The Effect of Deflector Toe Block Geometry on the Scour Downstream of a Stepped Spillway

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تأثير الشكل الهندسي للقدمة الحارفة علي النحر خلف مفيض سد مدرج

خلاصة

يهدف البحث إلى معرفة تأثير أبعاد القدمة الخلفية (الطول والميل العلوي) على النحر الحادث خلف مفيض سد مدرج. لذا فقد أجريت سلسلة من التجارب المعملية علي مفيض مدرج حيث تتكون قفزة هيدروليكية حرة اسفل السد علي قاع من الحصى ذي قطر متوسط ٧,٤٠ مم. أجريت هذه التجارب في معمل الهيدروليكا بجامعة سالفورد بإنجلترا. استخدم التحليل البعدي لتحديد المتغيرات المهمة للحصول علي العلاقات التي تربط بينها. ولقد تم الحصول علي معادلتين تربطان بين كل من طول النحر وعمق النحر وأبعاد القدمة تحت ظروف السريان المختلفة للتجارب المعملية. كما تم استعراض العلاقات التي تربط بين المتغيرات المختلفة.

Abstract

A series of experiments were performed downstream of a stepped spillway with a free hydraulic jump formed on a gravel bed apron. The experimental work was conducted in the Hydraulic Laboratory of the Civil Engineering Dept., Salford University, England. The effects of flow rate, tailwater depth, difference in the water levels upstream and downstream of the spillway, and the toe block geometry were investigated to see how they influenced the maximum scour depth and the corresponding scour length. Two empirical equations for scour depth and scour length were concluded. Dimensional analysis was used to obtain relationships between both the scour depth and scour length, and related flow and toe block geometry variables, and relationships between the different variables are presented, (1).

Introduction

The scour of the bed downstream of a dam spillway is very serious as it directly affects the stability of the structure. Therefore, it is necessary to dissipate much of the energy, and to return the water to the normal depth appropriate to the stream below the dam. One of these energy dissipators is the deflector block, Fig. (1). This block directs the flow away from the bed and causes it to form a surface jump.

The main objectives of the investigation were, to study the changes in the scour hole parameters using different upper surface slopes and different lengths for the toe block with respect to the rate of discharge. Hence to develop empirical relationships between the variables involved and to prepare equations that express the scour hole parameters under various flow conditions.

A few previous studies have accounted for the effect of the energy dissipator geometry on the scour downstream the structure, (2), (4), (5) and (6).

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Dimensional Analysis

Due to the complexity of the problem and also the lack of theoretical explanation for the development of scour below the toe of spillways, the employment of dimensional analysis is suggested both to reduce the number of variables and to assist in the experimental design. Scour geometry depends on many variables that characterize the deflector block, the scour hole, the bed material and the flow.

By using Pi-theory and after many variables were eliminated because of their secondary importance or because they were held constant in the experimental work, the maximum scour depth, d_s, can be written as follow, see Fig.(1)

$$d_s = f\ (q,\ g,\ y_1,\ y_t,\ H,\ a,\ L_t,\ T) \tag{1}$$

and finally,

$$d_s/y_1 = f(\ F_r,\ y_t/y_1,\ H/y_1,\ a/y_1,\ L_t/y_1\ ,\ qT/y_1^2\ ) \tag{2}$$

and for the scour length,

$$l_s/y_1 = f\ (F_r,\ y_t/y_1\ ,\ H/y_1,\ a/y_1,\ L_t/y_1,\ qT/y_1^2\ ) \tag{3}$$

Experimental Work

A designed rectangular recirculating flume was used, Fig.(3). The overall length of the 60cm wide, flume was about 22.25 m. Downstream of the spillway there was an apron filled with gravel. A tail gate was used to control the tailwater depth, in order to achieve the required hydraulic jump just downstream the deflector toe block. The main slope of the stepped spillway ramp was 1:2.5 for a length of about 10.40 m, the spillway crest being 4.5 m above the original bed level. The ramp changed to a flat slope of 1:6 for a distance upstream of the toe of about 1.25m.The shape and dimensions of the wedge blocks (3), which represented the roughness of the spillway, are shown in Fig.(2). The deflector block was made from wood and could be adjusted horizontally to change the toe length and vertically to change the upper slope of the toe block. The maximum flow rate used in this study was 145 l / s. One type of gravel was used which had a mean diameter of 7.40 mm.

Flow measurement was carried out using a non-contact ultrasonic transducer (1), measuring the depth of water passing over the spillway crest, and calculating flow rate from a calibration equations. A specially developed Gauge Contact Time Indictor was designed by the Experimental Hydraulic Research Group at Salford University, England, to embellish the accuracy of the depth measurement The use of the contact time indictor eliminated the "personal error" inherent in point gauge measurement in high velocity flows. A long bar point gauge with a sharp edged end was used to measure the tailwater depth. Another point gauge with flat circular end was used to measure the scour depths.

One hundred and fifty runs were carried out, (1), using the deflector toe block, with different geometry as an energy dissipation downstream of the spillway. The run time was taken as 30 minutes in all experimental tests. The range of discharge was from 55 to 145 l/s. Different toe slope angle of 0°, 4°, 6°, 8°, 10°, and 12° were used with various values of the discharge and constant toe length. To study the effect of the change of toe length on the scour hole, toe lengths of 50, 60, 70, 80, and 90 cm were carried out with various values of the discharge and a constant upper slope.

Experimental Results

Scour contour maps were drawn for each of the one hundred and fifty tests for the scour area occurring downstream the stepped spillway. Samples of contour lines are shown in Fig.(4). A longitudinal section was drawn on the line passing through the point of maximum scour depth, d_s. Fig.(5) represents samples of the longitudinal sections of the scour hole. Also, cross sections were drawn on the line of maximum scour depth and Fig.(6) shows some samples of them.

The following parameters were recorded for all test, q, y_1, y_t, d_s, l_s, l_m, a, H and L_r. Also, some other terms and ratios have been calculated from the measured data such as, F_{r1}, $n\%$, d_s/y_1, l_s/y_1, y_t/y_1, H/y_1, a/y_1, L_r/y_1, qT/y_1^2

Analysis of Results

Observations of the scour area can be concluded as follow.

- Two deposition areas were formed, the bigger one occurred after the toe end and the smaller one formed downstream of the scour hole.
- The maximum scour depth and the scour length are directly proportional to the flow rate.
- The maximum scour depth in nearly inversely proportional to the toe upper slope angle.
- The contour lines and cross sections are symmetrical.

Also, some relationships were drawn as follow:

- The relationship between the maximum scour depth and the scour length for different toe lengths, Fig.(7).
- The relationship between the Froude number and the ratio between the maximum scour depth and the scour length at the deepest point is shown in Fig. (8). It is obvious from figure that, the ratio (d_s/l_s) is directly proportional to the supercritical Froude number of the flow on the toe block.
- Also Fig.(9) shows the relationship between relative maximum scour depth (d_s/y_1) and the ratio (qT/y_1^2). Also, the toe length of 50 cm is represented by the highest curve and gives the greatest values of (d_s/y_1), whist, the toe length of 80 cm is represented by the best curve because it gives the smallest values of ratios (d_s/y_1) and (qT/y_1^2).
- The relationship between the Froude number and the efficiency $(n\ \%)$, Fig. (10) where, n is the efficiency between the upstream and downstream sections of the jump. Equation (4) represents the best fit line for this relationship,

$$n\% = 3.20 F_{rl}^{1.62} \tag{4}$$

It is clear that, the toe block geometry has very little effect on this relationship.

- The Equations (5) and (6) represent the relationship between the total scour depth (t) and both tailwater depth (y_t) and the difference in water levels (H) respectively, where t is the summation of the maximum scour depth and the tailwater depth, see Figures (11) and (12),

$$t = 0.648 y_t^{1.10} \tag{5}$$

$$t = 7.63 - 1.68H \quad (\, t \text{ and } H \text{ in m} \,) \tag{6}$$

All the above curves were obtained by using the best fit method.

The main objective of this model study was to examine the effect of the toe block geometry on the scour hole but it was also possible to develop equations to describe the geometry of the scour hole. Variables such as the tailwater depth and the energy dissipator geometry are not usually included in most equations presented by previous researches, (2) and (4), in this field when defining the maximum scour depth. The equations presented here related to a mean diameter of 7.4 mm of the gravel tested. However, a gravel definition parameter, such as d_{50} is often indicated.

After the regression analysis of the dimensionless pi-terms is applied, the following empirical power equations are obtained,

$$d_s = 0.6273 \left(\frac{q^{1.576} L_t^{0.267} y_t^{1.049}}{g^{0.788} H^{0.835} a^{0.338} y_1^{1.507}} \right) \tag{7}$$

$$l_s = 15.539 \left(\frac{q^{0.760} L_t^{0.206} a^{0.278}}{g^{0.380} H^{0.232} y_t^{0.156} y_1^{0.236}} \right) \tag{8}$$

To examine the accuracy of the equations (7) and (8), the comparison of predicted values of the scour depth and length with the observed values is shown in Figures (13) and (14), a good degree of fit is achieved.

Conclusions

The following conclusions can be drawn under the flow conditions from the results of the present study,

1- The use of appurtenances such as a deflector block downstream of a spillway is helpful in increasing the percentage of energy dissipation and in distributing the velocities more evenly through out the structure.

2- By increasing the upper slope of the toe block the scour length increases and the maximum scour depth decreases. Also, the big toe slope needs a high tailwater depth to form the surface hydraulic jump. It is found that, the toe length of 90 cm and toe slope of 12° give the smallest values of the scour depth and the greatest values of the scour length.

3- Relationships between variables that affect this study are represented by curves and equations, these curves are drawn by using best fit method, see Figures (7) to (12) and Equations (4) to (6).

4- Two power empirical equations are developed to describe the geometry of the scour hole downstream the stepped spillway including the effect of the toe block geometry. These equations related to a fixed mean diameter of the sediment. The equations describe the most important dimensions of the scour hole, the maximum scour depth and the scour length, see Equations (7) and (8), they help in predicting the values of (d_s) and (l_s) of the scour hole. A good degree of fit is achieved for these equations, Figures (13) and (14).

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Notation

a : Difference between the upper lip of the toe block and the original bed level.

d_s : The maximum scour depth.

F_{rl} : Froude number due to y_l.

g : Acceleration due to gravity.

H : Difference between the water level upstream the spillway and the tailwater depth.

l_s : Length of scour at the point of maximum scour depth.

L_s : The total length of the scour at the point of maximum depth.

L_t : Length of the deflector block.

η : Efficiency between the upstream and downstream sections of the jump.

q : Discharge per unit width.

t : The maximum water depth in the scoured hole.

T : Run time.

y_t : Tailwater depth.

y_1 : The supercritical flow depth at the toe

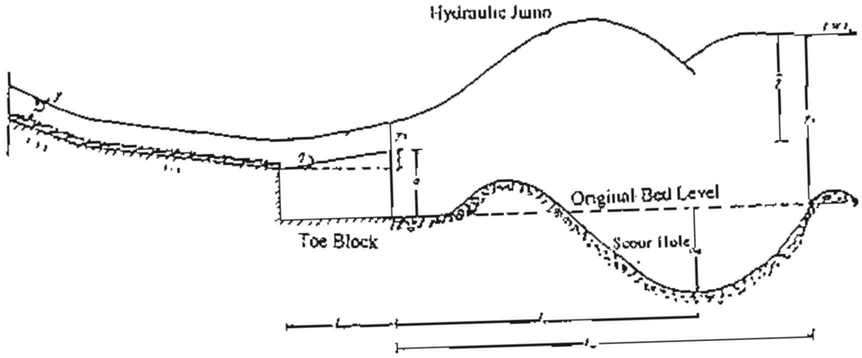

Fig. (1) Definition Sketch

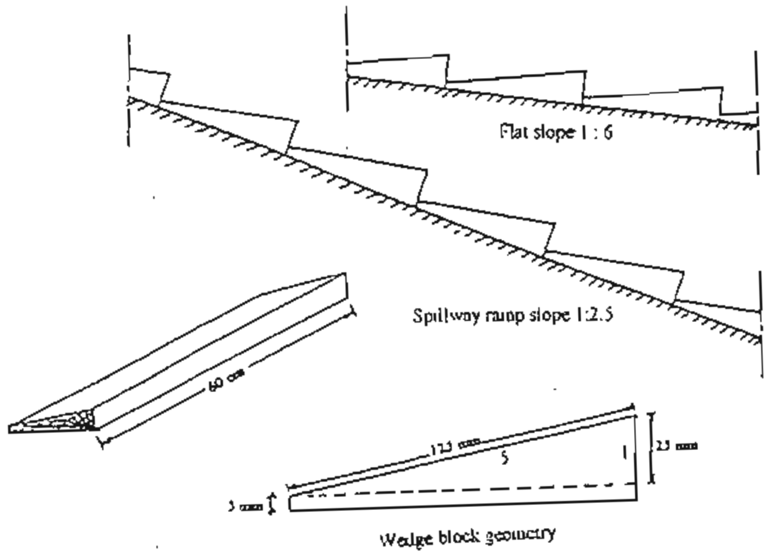

Fig. (2) Wedge Block Used in the Investigation

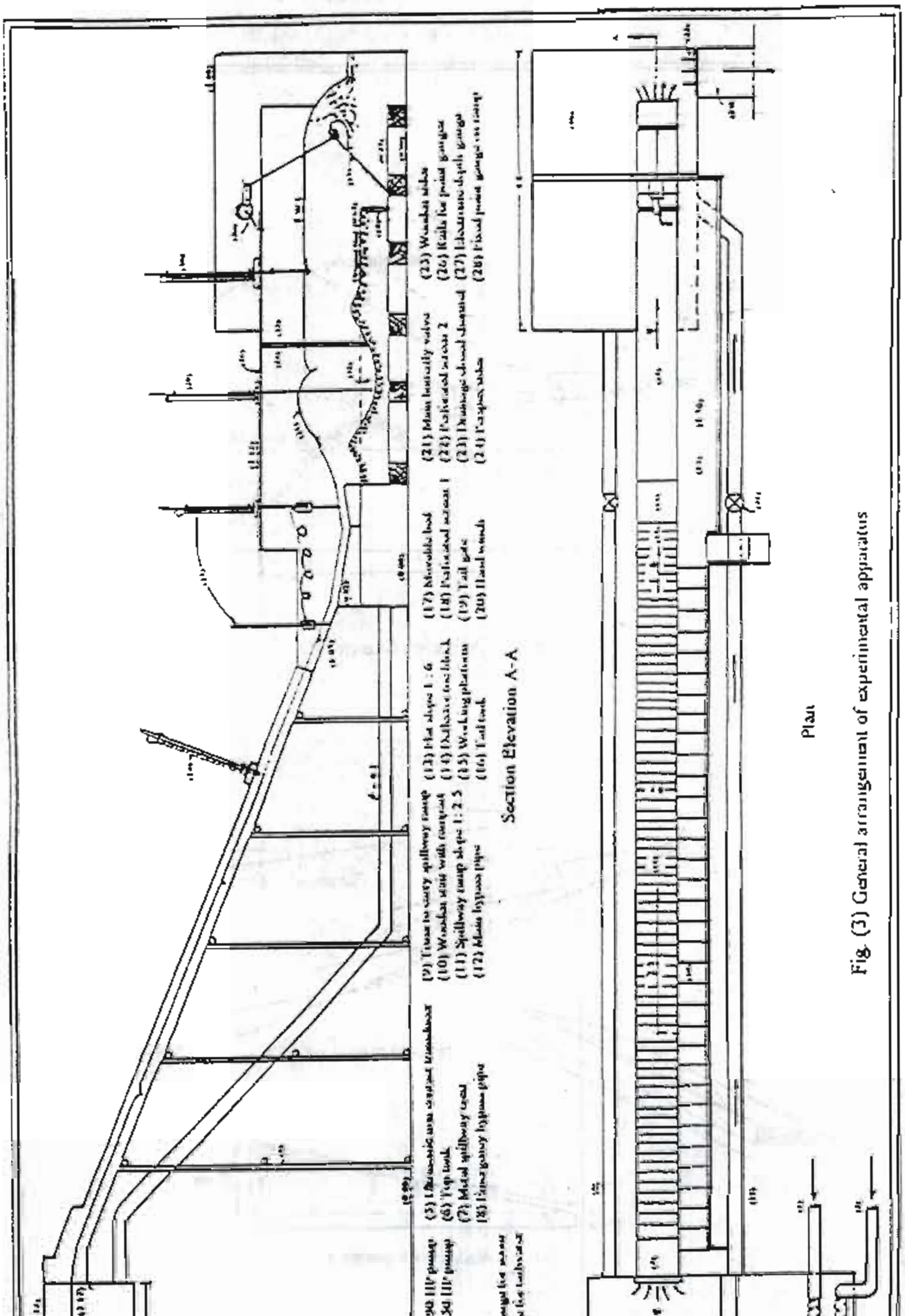

Fig. (3) General arrangement of experimental apparatus

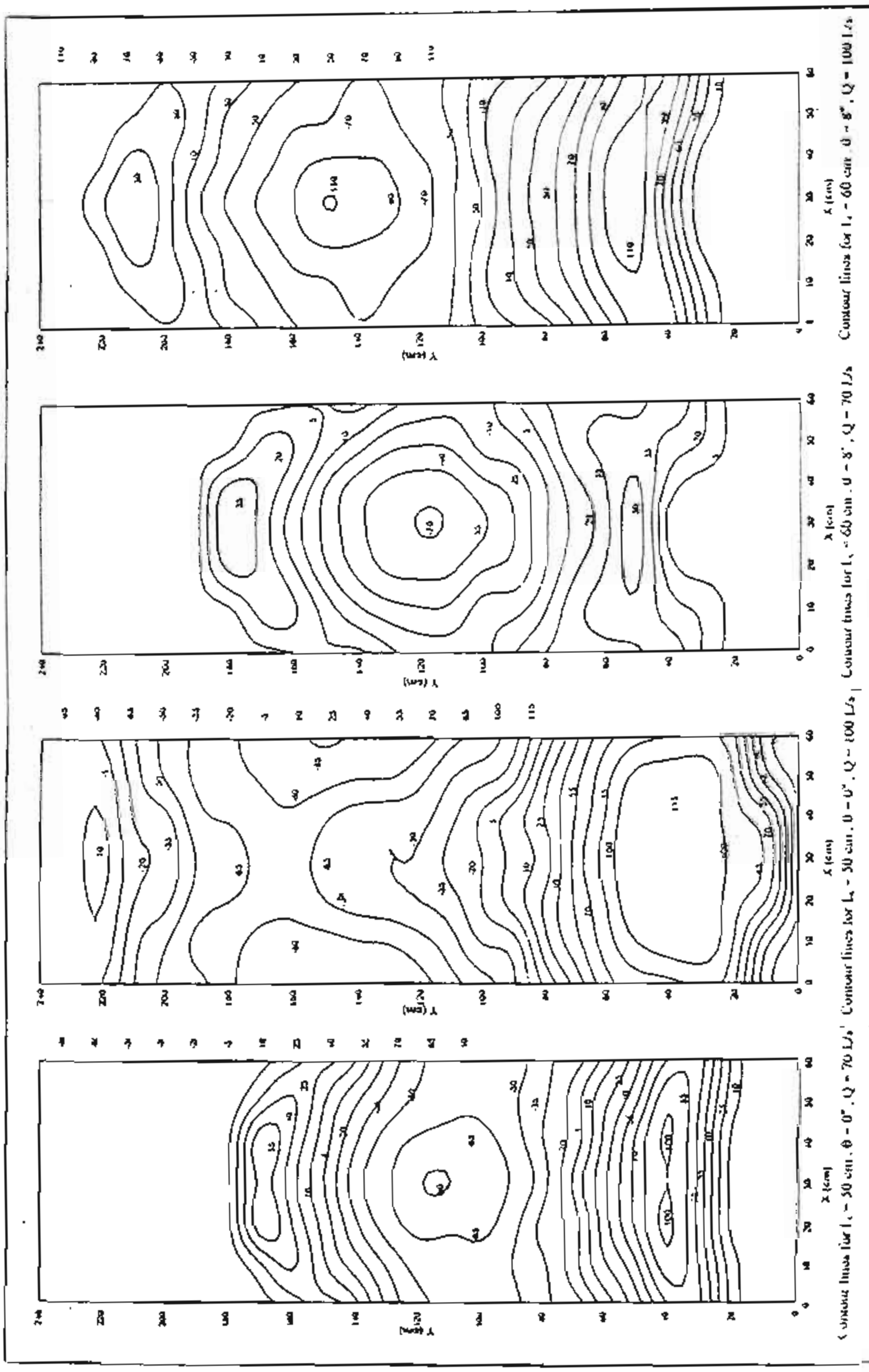

Fig. (4) Samples of Contour Lines for the Scour Area

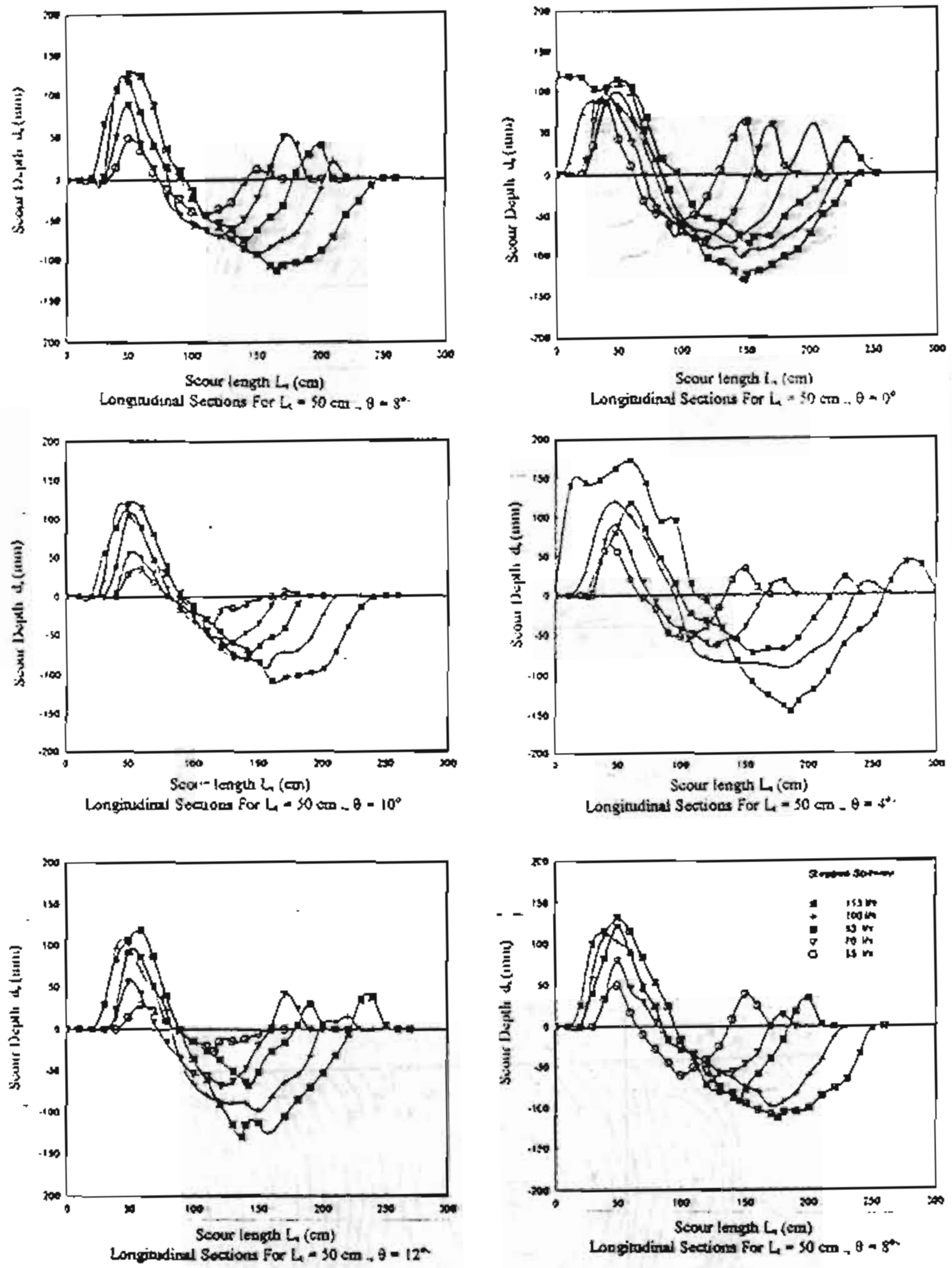

Fig. (5) Samples of Longitudinal Sections of the Scour Hole

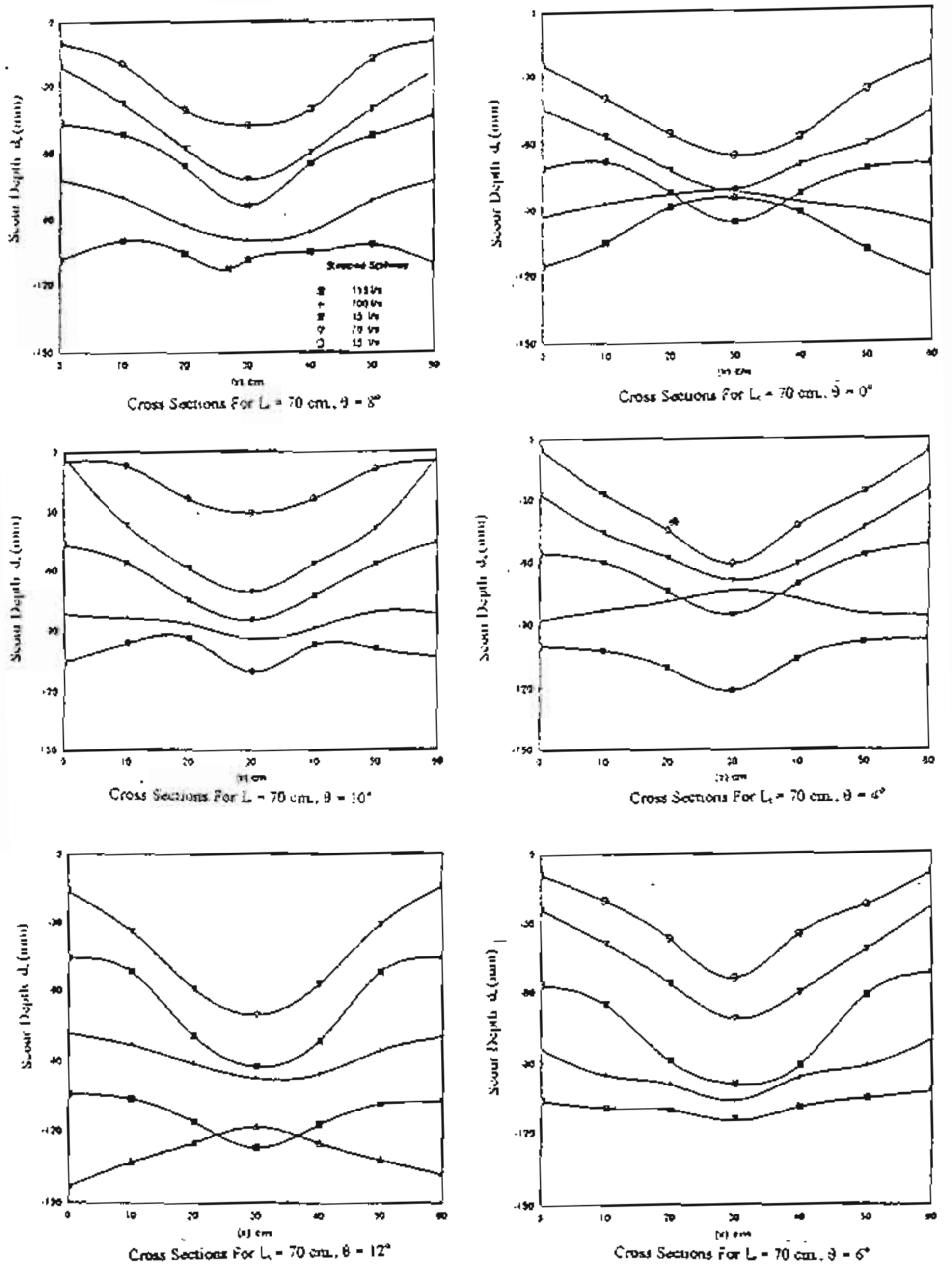

Fig. (6) Samples of Cross Sections of the Scour Hole

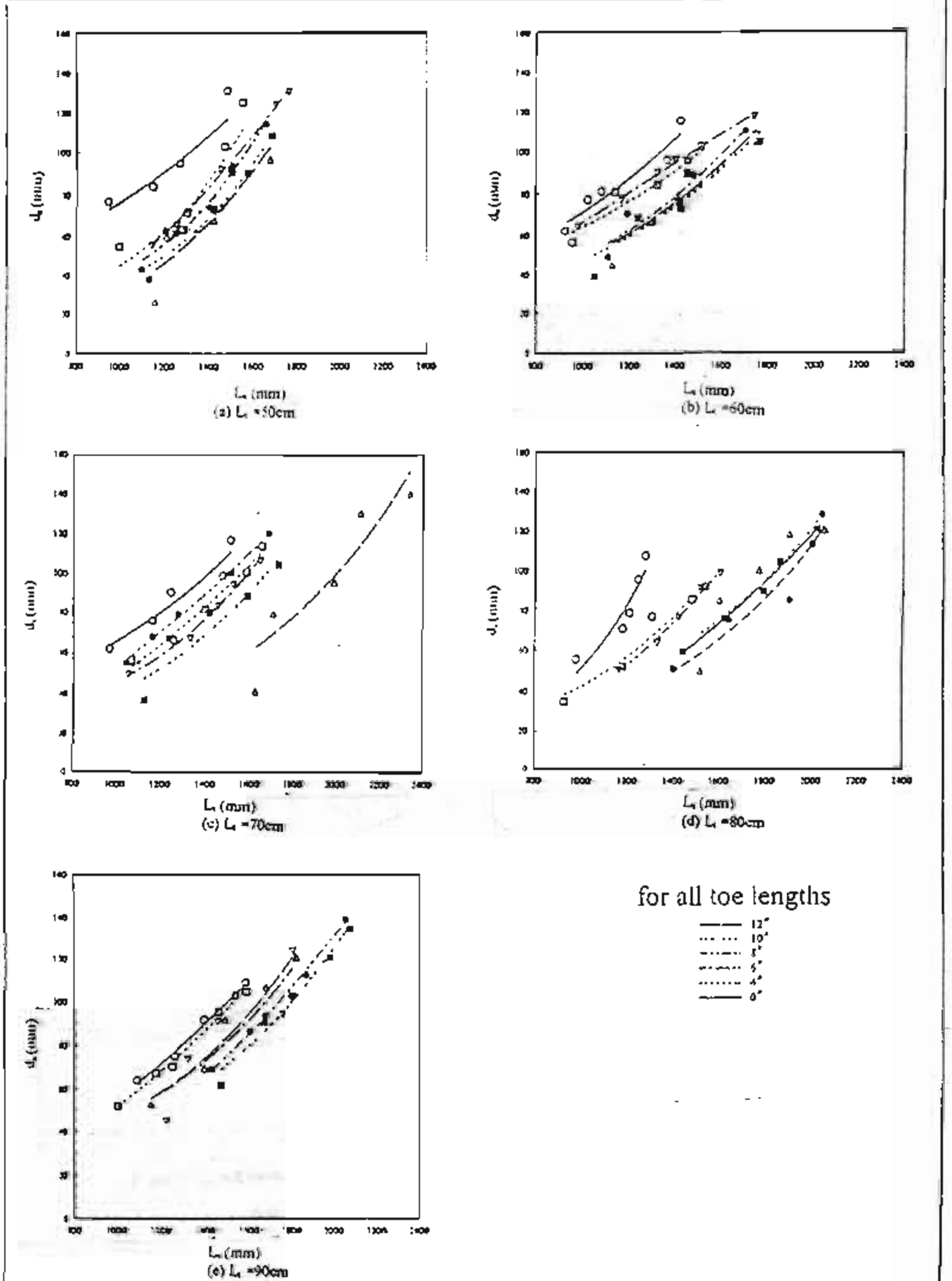

Fig. (7) The Relationship Between the Maximum Scour Depth and the Scour Length for the Stepped Spillway at Different toe Lengths

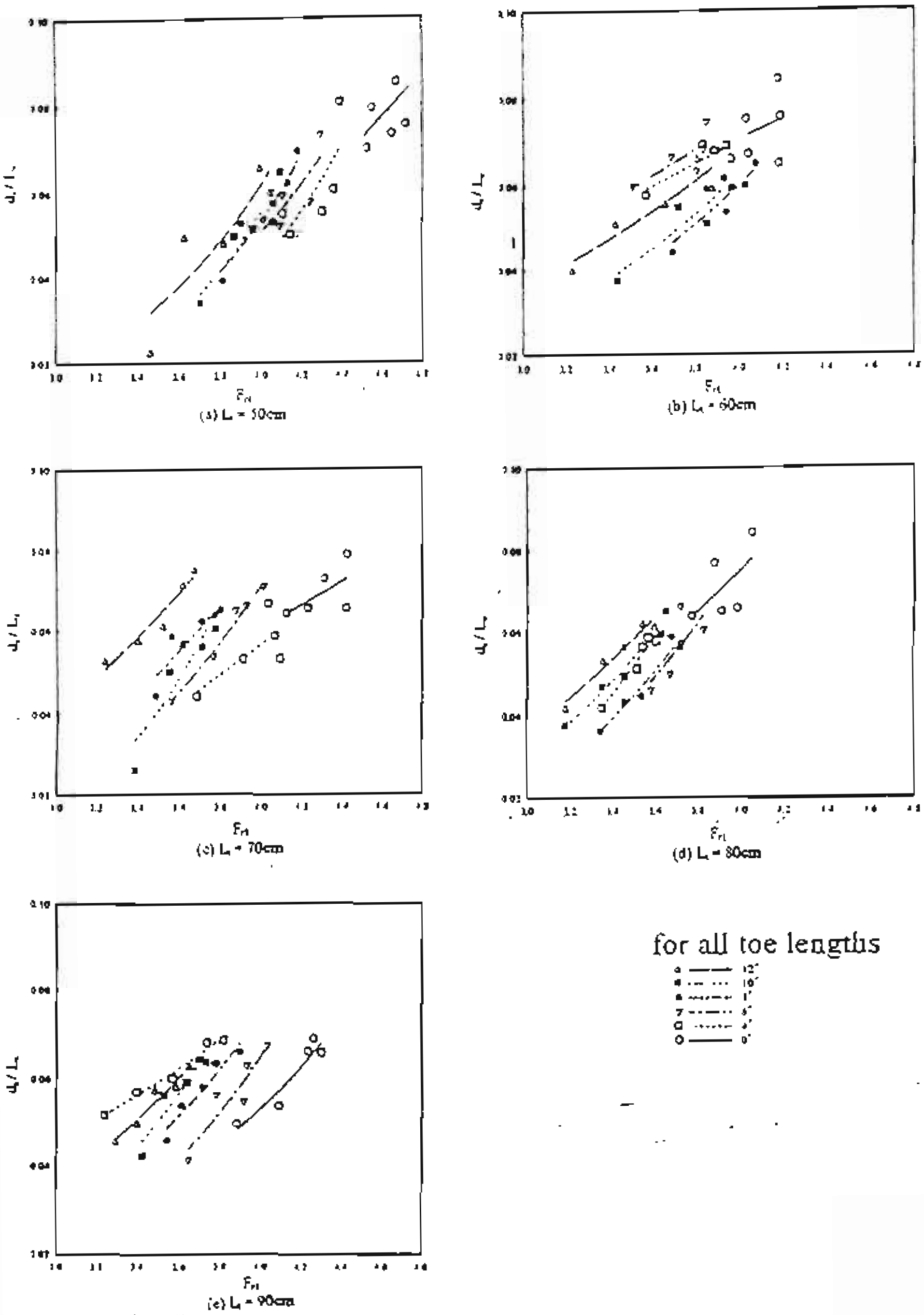

Fig. (8) The Relationship Between the Froude Number and the Ratio (d_L / L_t) for the Stepped Spillway at Different Toe Lengths

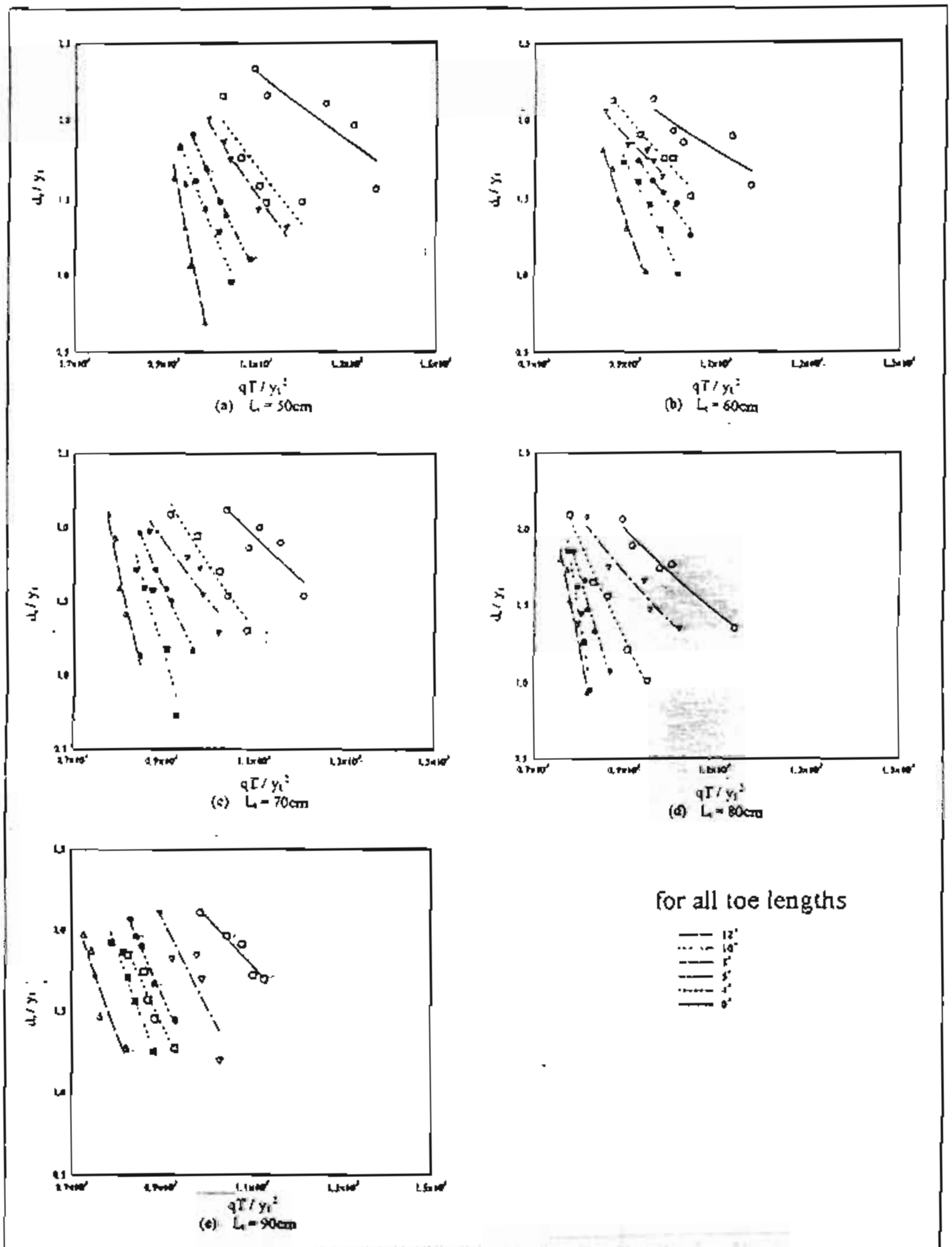

Fig. (9) The Relationship Between the Relative Maximum Scour Depth and the Ratio (qT/y_1^2) for the Stepped Spillway at Different Toe Lengths

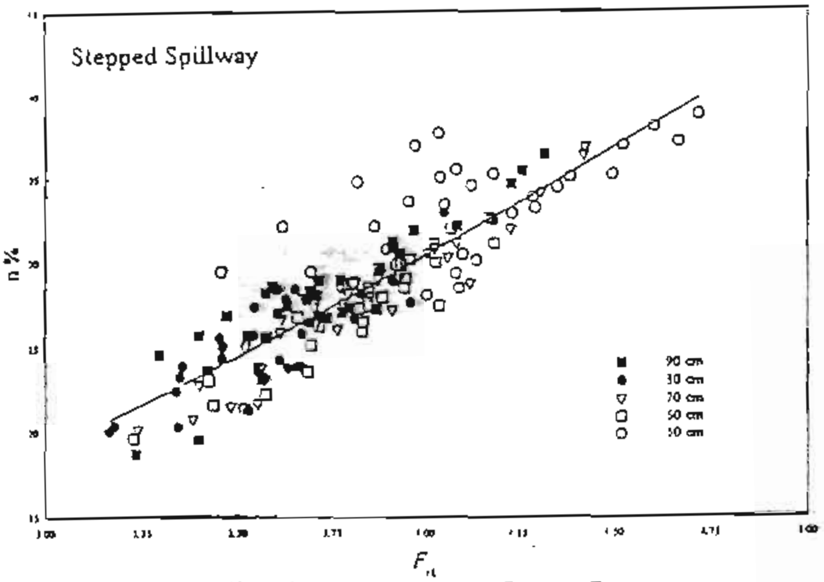

Fig. (10) The Relation Between F_{r1} and n %

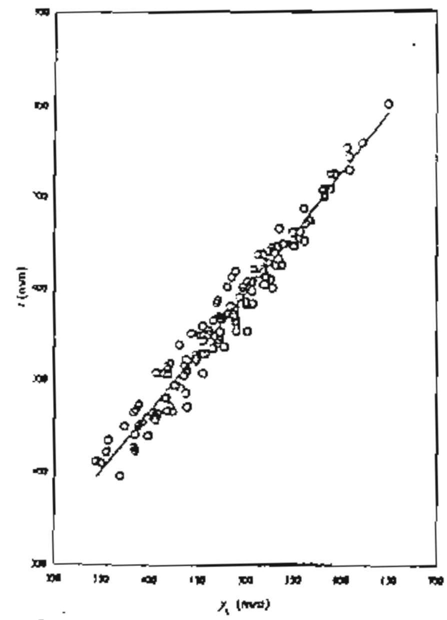

Fig. (11) The Relation Between t and y_c for Stepped Spillway

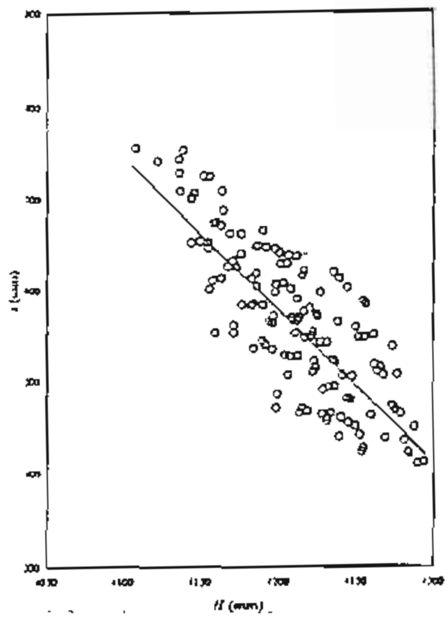

Fig. (12) The Relation Between t and H for Stepped Spillway

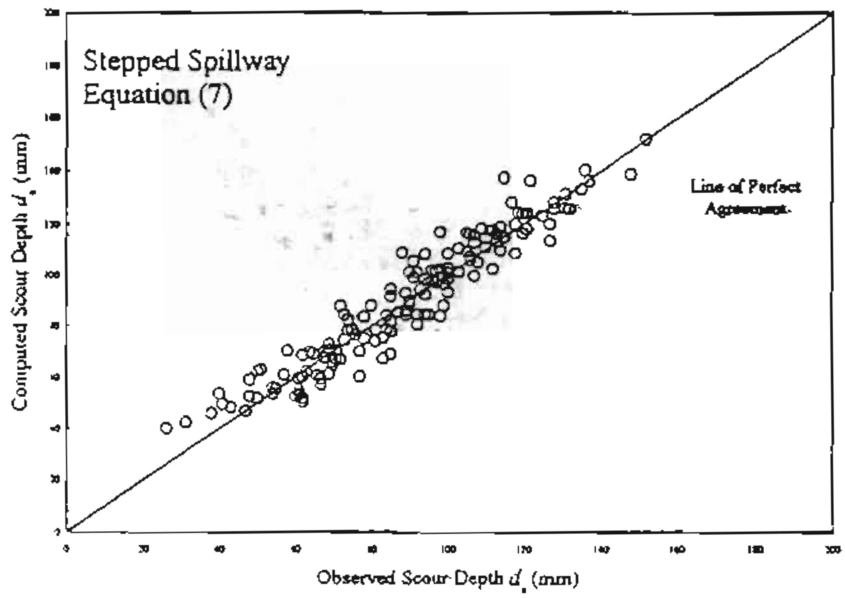

Fig. (13) Comparison Between Calculated and Measured Depth of the Scour Hole

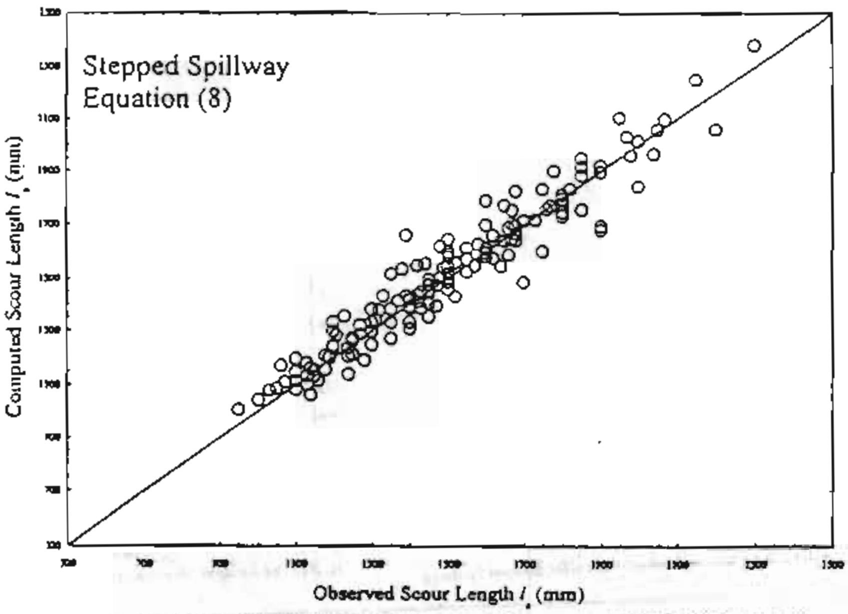

Fig. (14) Comparison Between Calculated and Measured Length of the Scour Hole