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CASE STUDY AND RISK ASSESSMENT OF SCOUR AROUND BRIDGE PIERS

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ABSTRACT

Scour around bridge piers has been the source of concern for the safety of road and railway bridges in many countries of the world. A number of bridge collapses due to scour have occurred causing damage and loss of lives . More bridges are vulnerable. emphasising the urgency of attention to be given to this subject and the need for further research. In the present research a case study was first carried out on the scour downstream of the circular pier of Tahrir bridge on the river Nile in Cairo. A model of the bridge pier was then constructed and experiments were carried out using Laser Doppler Anemometery. The aim of these experiments was to measure the velocity distribution in the model and to study and analyse the flow pattern around the pier and determine its relationship with the scour configuration. A number of useful conclusions were deduced. Moreover a method of risk assessment for bridge scour has been developed and briefly presented in the paper.

KEY WORDS

River hydraulics. bridge scour, flow pattern, risk assessment. Laser Doppler Anemometer (LDA).

INTRODUCTION

The subject was studied by the author which included the studies of the works of other scholars and carrying out a research at the University of East London (U.K) during 1994-96 period. The paper provides useful information on the subject.

An understanding of the flow pattern around bridge piers is important in the study and analysis of bridge scour. The pattern of flow approaching a bridge changes as it passes the piers. It may be due to the increase in flow intensity as a result of bridge constriction, increase in sediment transport capacity and consequent changes in the structure and configuration of the stream bed around the piers. However in a wider context, the factors affecting the flow pattern are the characteristics of the approaching flow, sediment transport, river bed material, debris, changes in river bed around the piers with respect to time as well as type, shape, size and spacing of the piers. The analytical indicators of change in the flow pattern are changes in the velocity distribution, its magnitude and direction. Scour around bridge piers is related to the flow pattern. Different patterns of scour around piers are obtained with different pier characteristics even under the same approaching flow. Several researchers including Carsten et al [1], Johnson [4], Melville & Sutherland [9], Raudkivi [10], Riddell [11], Stevens et al [12] and few others have pointed out to the formation of the horse-shoe and wake vortices around cylindrical piers and their relation with the equilibrium depth, pattern and time rate of scour depending on clear water and live-bed-scour conditions. In this research, the data of flow around piers obtained from the full scale tests was analysed and was followed by experiments on small scale models in the

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laboratory flumes to study the flow pattern on the piers of same shape as that of the pier in the case study.

There is an absence of awareness about the importance of monitoring and risk assessment of bridges for scour. The bridges and its users are left at the mercy of nature which sometimes takes a heavy toll by damaging the bridge due to scour. Scour failures tend to occur suddenly without prior warning or signs of distress to the structure. At its worst, it has resulted in complete collapse of bridges, sometimes with loss of life and damage to the environment. It is useful to develop and adopt effective strategies for monitoring and risk assessment. The basic concept of risk assessment is to analyse the extent of probable damage which can occur at a bridge site due to various factors acting individually and also simultaneously and then to compare this damage with the protection measures and strength of the structure provided at site and evaluate the degree of risk involved, often followed by quantifying probable consequences as stated by Johnson [5,6]. The risk assessment of bridges due to scour is based on a number of factors including the characteristic features of the river and the bridge as well as the extent of risk associated with these factors, as stated by Meadowcroft et al [7]. Probabilties of failure can also be analysed through detailed simulation process as explained by Charles [2] For monitoring bridge scour, several methods have been developed and used at different sites with varying degrees of success. As the scour holes formed at a bridge site tend to fill up after the floods, a rather instant method using sensors fixed with the bridge piers has been found to be more effective in monitoring bridge scour.

This paper consists of three parts. The first part includes the case study of scour downstream of Tahrir bridge using the results obtained from the field observations. The second part contains the physical model testing of flow pattern around bridge piers and its relation to scour with a pier similar to that in the case study. In the third part, two methods of risk assessment of scour around bridge piers have been presented along with methods of monitoring bridge scour. The first method was practised by the British Rail and the second one was developed in this research.

CASE STUDY OF TAHRIR BRIDGE

A case study was carried out on the scour which occurred downstream of the circular pier of Tahrir bridge existing across the river Nile upstream of the Aswan Dam in Egypt. Information obtained from Hydraulic Research Institute, Delta Barrage, Egypt was studied and analysed to study the flow pattern around the bridge piers and its relation to scour. Tahrir bridge, built in 1931 across the river Nile in Cairo, Egypt, spans 354m. It has seven piers, one circular (diameter 15m) and others rectangular with semi-circular nose. The circular pier has a 21m wide floating fender built around it projecting up to 50m on both sides from the face of the pier and ending with a pointed nose. The total depth of fender is 1.2m, with 0.7m above the water surface and 0.5m below. The bridge plan is given in Fig.1 and a part plan with details of bed contours surrounding the circular pier is given in Fig.2.

TABLE 1 SCOUR HOLES D/S OF CIRCULAR PIER OF TAHRIR BRIDGE

Sl. No	Date	Deepest point of scour holes from surface (Metres)	Distance of centre of scour holes from bridge-axis (Metres)	Distance of centre of scour holes from right bank of river (Metres)
1	Apr 1981	10.00	84.00	98.00
2	Mar 1983	9.00	80.00	90.00
3	Dec 1984	8.00	78.00	90.50
4	Oct 1986	7.00	75.00	92.50
5	Nov 1988	7.00	75.00	92.00
6	Dec 1989	7.22	75.00	92.00

Frequent scour occurred downstream of the circular pier of Tahrir bridge with scour holes sometimes forming upto 8 metres below the river bed (Table 1). Scour holes formed at other piers were not so deep. The scour hole in Fig.2, formed in October 1986 upto 7m below bed surface and maximum depth of 11m with reference to the average river bed level. The deepest point of scour was 76m from the bridge axis and 16m from the axis of the fender.

FIELD OBSERVATIONS

The cross-section surveys, velocity distribution measurements and preparation of contour plans were carried out on the river Nile at bridge site by a team of the Research Institute, Dellta Barrage, Egypt. The contour plans downstream of the bridge given in Figs.1 & 2 show the full scale scour pattern along with details of the piers and the fender around the circular pier. Cross sections of the river Nile upstream and downstream of the bridge with values of velocities measured at 0.2Yo, 0.5Yo and 0.8Yo (Yo= total depth of flow) in each vertical. Cross section of the river through deepest points of scour holes downstream of bridge were also prepared. The maximum depths and locations of scour holes downstream of circular pier which were observed during high flow periods were as presented in Table 1. The downstream cross section and velocity distribution were used to calculate the total discharge Q and the average velocity, Vo, of the river. The total discharge of the river downstream of Tahrir bridge in March 1983 was 878.39 cumecs and the average velocity was 0.270 m/s with the river water surface level at El.16.80m above mean sea level.

PROPOSED THEORY OF SCOUR

Based upon the above description, it appears that at Tahrir bridge, the fenders have a definite role in effecting the shape and position of the scour holes downstream of the bridge piers. As the fender is closed at both ends, vortices are formed in the two circulation zones downstream of the fender and each one extending downstream, on either side of the centre line, to a distance of 6B, where B is the distance between the fender and the centre line of the pier as shown in Fig 3. Here it can be seen that the flow vortices downstream of the fender produce two well-defined scour holes corresponding to the two circulation zones. The recirculation zone on the water surface of the river has been shifted by a distance approximately equivalent to the length of the fender downstream of the pier. In this way the deep scour holes which are normally formed around the pier are shifted away from its foundation. Also, the back flow towards the pier has moved the sand bed material upstream and raised the bed level of the river by about 5m of deposited material. The maximum depth of the scour hole is approximately 14m below the 5m contour line.

At another bridge Imbaba, also on the river Nile, the fender is open at the downstream end and therefore, the recirculation zones downstream of the bridge pier again extend 6B in length, but appear to move the vortices inside the fender as near as possible to the bridge pier. The wake vortices are strongest near the middle of the circulation zone at about 3B downstream of the fender end. The two recirculation zones appear to interact and produce alternating wake vortices which travel downstream and cause the single scour hole as shown in Figs 1and 2.

In order to understand and confirm the above theory, physical model experiments were carried out in the laboratory on a model of a pier 60mm diameter. Fenders were placed on each side of the pier. The model showed very clearly that the pattern of the recirculation and the formation of the large scale eddies and vortices extended to a distance of 6B downstream of the fender end. There is no doubt that the length of the recirculation zone downstream of the fender is approximately 6 times the radius of the pier (approximately equivalent to the distance between the fenders) and the position of the stagnation point is at a distance equal to the length of the fender plus the length of the recirculation zone. From these field and laboratory observations, it appears that the fenders create complex recirculation zones which affects substantially the pattern of scour around the bridge piers. Previous observations on bridge pier without fenders have all shown that the scour hole is centred around the pier itself. The positions of stakes for the fenders may also affect the vortices depending upon their size and spacing. The importance of fenders in controlling scour hole around bridge pier has become a subject of research and studies in order to develop guidelines not only to predict the position of the scour hole on the basis of the geometry of the bridge pier and the fender but also to investigate different shapes and depth of fenders which may reduce the amount of scour.

No evidence was found to prove that the adjacent slim bridge pier near to the large circular pier had any substantial effect on the pattern of scour downstream of the main pier. The small train of vortices shown in Stevens et al [12] and radiating from small pier can not be formed in practice unless there is considerable cross flow in the river. While the previous research has made contribution, the case studies described in this paper do not reveal any appreciable effect on the scour hole which appear to be related to the recirculation zones and the vortices which form inside these zones in the wake of the fenders and the bridge pier as explained above. The bridge pier foundation has been kept fully covered with bed material to a much higher level than the original river bed. Relocation of scour hole downstream of the pier is the most important role of these fenders. Undoubtedly further research and analysis is required to study this phenomenon.

For the other slim rectangular piers of 3m width and 18m length, it appears that the wake vortices formed immediately downstream of these narrow piers extend again to 6 times the half width of each pier which is a distance of approximately 9 metres. The scour hole should be approximately at a diatance of 9m but it is shown to be at a greater length. It is possible that the vortices are narrow in width, are much stronger and possibly extend and are interferred with by other vortices from other piers. The effect of each pier on the adjacent one needs again to be investigated and in particular in regards to the spacing of a number of piers across the stream and their effect on the depth and the distance of the scour hole downstream. Looking at the plan of the scour holes across the width of the river (Fig. 1) one observes another interesting phenomenon that is the big scour hole downstream of the circular pier has a pulling effect on the adjacent scour hole. This effect is transmitted to the smaller scour holes with decreasing effect. The line of vortices shown across the stream in Fig. 1 indicates this side effect very clearly.

PHYSICAL MODEL TESTS

The aims of these experiments were to study and analyse the flow pattern around the model pier and determine its relationship with the scour configuration. For this purpose, a number of tests were carried out with the model of a cylindrical bridge pier in two different set-ups. The first model consisted of a 60mm dia 400mm long cylindrical perspex pipe representing the central pier of Tahrir bridge of the case study mounted on 2000 x 305mm glass flume equipped with Laser Doppler Anemometer (LDA) for measuring the velocity distribution, a calibrated pump for maintaining constant discharge, inlet and outlet controls and a depth measuring gage. Froude's formulae for dimensional analysis were used to determine the model scale (1:250) and the dimensions of the model. Laser Doppler Anemometers are non-contact optical instruments for the investigation of fluid flow structure in liquids and gases. The unit used in this research was LDA04-combined flow and vibration measuring system. The complete system comprised a Frequency Shift Unit, a Doppler Frequency Tracker, a DISA Cootner Processor and an on-line computer for acquiring and analysing data observed through LDA system. The software provided by the suppliers for analysis was ' Attraktion'. In the second set up, the cylindrical pier was erected on a sand bed ($D50<0.7$ mm) in a flume 610 mm wide with the length of sand bed as 1800mm in a total flume length of 4000 mm fitted with a gaged pump and depth measuring gauge.

DETAILS OF EXPERIMENTS

Velocity distribution of flow over an area of 305 x 260 mm around the cylindrical pier in the model was observed with LDA along 14 cross sections at 20 mm intervals from a distance of 100mm upstream to 160mm downstream of the pier. At each of the 350 points in this area, 10 velocity observations were made in each vertical from $Y = 5$ mm to 50 mm. Depth of water and discharge were kept constant, as far as possible. The average total depth of flow and discharge were 57 mm and 1.97 litres/sec respectively. For visualisation of flow pattern, Aluminium and Timiron powders were used separately. In order to analyse the flow pattern around the cylindrical pier, V/Vo values obtained from the LDA for one test run ($Yo = 57$ mm $Q= 2$ lit/sec, approximately) for points at $Y/Yo = 0.78$ were plottted along 14 cross sections as shown in Fig.4. The flow pattern around the cylindrical pier obtained from the LDA results (Fig.4) shows the velocities increasing on both sides of the pier as the flow proceeds downstream, occurrence of reverse flow in the wake of the pier and the stagnation point was located at a distance of about 160 mm (= 5.33R), i.e within the range of 5R to 6R (radius of the pier, R = 30 mm) from the centre of circular pier with formation of vortices in the wake of the pier. However no special pattern was recorded at upstream face of the pier. In the second set up the supply pump was started and clear water from the source continued to flow through the model for 45 minutes. The flow pattern was continuously observed during this period. Plastic and paper particles were used for visualisation of the flow pattern. After stopping the flow, photographs of the scour pattern were taken and measurements of its contours were carried out and plotted to obtain the scour pattern around the cylindrical pier. During visualisation of flow pattern, formation of vortices similar to horse-shoe vortex was noticed at the upstream face of the pier which was also explained by the creation of scour hole around the pier. Wake vortices were also formed and were responsible for scour on the downstream side.

A side view of the model of circular bridge pier, standing in water in the glass flume of the hydraulic laboratory, used for the case study is shown in Fig 5 and an end view of the flume, also showing the circular bridge pier is given in Fig 6.

RISK ASSESSMENT OF BRIDGE SCOUR

Studies and analyses of uncertainties, variabilities and risk associated with aspects of social and economic importance have become the subjects of special attention and emphasis in recent times. The probability of occurrence of scour at a bridge site due to environmental or technical reasons warns of a risk to structure and it is important to have a forehand risk assessment for necessary precautions. In plain terms, risk involves occurrence probability and occurrence consequences. In case of bridge-scour, the occurrence probability is influenced by natural factors e.g. river flows, sediment transportation, river bed structure, whereas the occurrence consequences include such effects as cost of damages, repairs and reconstruction. The risk assessment of bridge scour is based mostly on the characteristics of the bridge and the river as explained by Meadowcroft et al [7]. Analytical models for assessment of scour around bridge piers were used by Johnson Peggy A [5,6] and the estimated scour was compared with the available depth of pier foundation to determine the factor of safety. Later on, the following relationship between probability of failure and factor of safety was derived by the said researcher.

$$FS = C1 + C2\ PF^{C3} \tag{1}$$

Using factors of safety ranging from 0.8 to 1.8, the above equation was calibrated using a non-linear least-squares numerical optimization algorithm resulting in the following equation:

$$FS = 1.88 - 1.06\ PF^{0.212} \tag{2}$$

The above relationship was stated in the following form for use in risk assessment exercise in this paper.

$$PF = \{(1.88 - FS) / 1.06\}^{4.717} \tag{3}$$

The assessment can be made directly by evaluating the available factor of safety against the overall scour and estimating the corresponding probability of failure. A detailed risk assessment at a particular bridge will require hydraulic analyses and simulation studies as mentioned by Charles [2], using scour data collected through monitoring and field surveys.

EVALUATION OF BRIDGE SCOUR

The risk to a bridge associated with scour and erosion during the floods may include: undermining or loss of support to the pier due to scour of the river bed, undermining of the abutment due to bank erosion which causes a lateral shift in the course of the river, erosion at the toe of the approach embankment resulting in slope failure and erosion of ballast and embankment due to flows overtopping the embankment. There are three main processes of scour as stated below.

Progressive Degradation

Long reaches of a river may be affected by bed erosion. The cause of such erosion may often be far away from the bridge site and a simple quantitative assessment may not be possible. In such cases the predominant factorts should be identified for evaluating degradation and enhance awareness of the possible effects of works upstream and downstream of the bridge.

General Scour

Flow velocities generally increase due to the constriction at the bridge sites increasing the general bed scour. Presence of the river bends also cause general scour.

Local Scour

Scour adjacent to the bridge pier or abutment is caused due to the complex turbulent flow pattern at an obstruction. Local scour can further be classified into clear water scour and live-bed scour depending upon the sediment transport conditions of the approaching flow. Several formula for local scour have been developed by researchers which can be presented in the following general form:

$$ds = f(\rho, \nu, U, y, \rho s, d50, \sigma g, g, D, Sh, Al) \qquad (4)$$

$$ds / b = Ki \; Ky \; Kd \; K\sigma \; Ks \; K\alpha \qquad (5)$$

Few formulae proposed by various researchers have been given in Table 2.

TABLE 2 EQUATIONS FOR ASSESSING SCOUR AROUND BRIDGE PIERS

Following equations for assessment of scour around bridge piers were developed by various researchers:

1. Colorado State University (HEC - 18)

$$ds = 2.0y \; K1 \; K2 \; K3 \; (b/y)^{0.65} \; (F)^{0.43} \qquad (i)$$

2. Breusers et al (1977)

$$ds = b \; f \; K1 \; K2 \; [\, 2 \tanh(y/b) \,] \qquad (ii)$$

3. Hancu (1971)

$$ds = 2.42 \; b \; [\, 2 (V/Vc) - 1 \,] \; (Vc^{2} / g b)$$

(iii)

$$Vc = 1.2 \; [\, g \; D50 \; \{(\rho s - \rho)/\rho\} \,]^{0.5} \; (y / D50)^{0.2}$$

(iiia)

4. Izzor and Bradle (1958)

$$ds = 1.45 \; q^{2/3} \qquad (iv)$$

5. Jain and Fischer (1979)

$$ds = 2.0 \; b \; (F - Fc)^{0.25} \; (y/b)^{0.5}$$

(v)

(for $F - Fc > 0.2$)

$$ds = 1.85 \; b \; (Fc)^{0.25} \; (y/b)^{0.5}$$

(va)

6. Laursen & Toch (1956) and Neil (1964)

$$ds = 1.35 \; b^{0.7} \; y^{0.3}$$

(vi)

7. Liu and Skinner (1961)

$$ds = 2.15 \, (D/y)^{0.4} \, (Fo)^{1/3} \qquad \text{(vii)}$$

8. Melville & Sutherland (1988)

$$ds = K_I \, K_d \, K_y \, K_\alpha K_s \, b \qquad \text{(viii)}$$

9. Shen et al (1969)

$$ds = 0.00022 \, Re^{0.619} \qquad \text{(ix)}$$

General and local scour are influenced by a number of features of the bridge and the river which are known to affect the susceptibility to scour. For example, abutments founded on the flood plain near to the river channel are likely to be at greater risk from bank erosion if the river has a steep gradient than if the river has a shallow gradient. Checklist of features which influence scour risk are given in Table 3, which have been included on the basis of their importance in determining the risk of scour and on the ease of measurement and inspection. The assessment of risk due to scour can be made on a preliminary scale using direct method or it may be carried out in detail according to the magnitude of risk involved and priority of the case.

RISK ASSESSMENT BY METHOD OF RISK NUMBERS

The effect of various features (Table 3) were integrated and a scoring system with a Table of risk numbers was followed for analysis of risk assessment of bridges of the British Rail as explained by Riddell [11]. It helps to quantify indirectly certain characteristics of bridge and the river e.g. type of river (TR) potential scour severity (PSS) and foundation quality (FQ). The potential range of risk numbers is from -7 to +7 giving the risk classification as least risk, marginal and problem. The values of TR, PSS and FQ are built up from individual scores and weighting of these scores. When the overall weighted risk number is greater than 3, the bridge is at risk. This method is briefly stated here by assessing the risk of the Portrack viaduct of the British Rail, as mentioned below.

River Characteristics

Type of stream : perennial stream with considerable skewness in its alignment
Bank stability: mild erosion of banks; Flashiness: medium flashiness; Distance from river source to bridge =72 km, average channel slope upstream = 3.4m / km, channel width = 55m, channel width under bridge = 39m, channel constriction=70%, floodplain constriction = 10%, bed material = sand, depth of flow = 4.0m.

Pier Features

Pier width = 1.52m, pier length = 6.55m, angle of attack = 0, pier / abutment nose shape = rounded, depth of foundation provided =1.52m, load bearing material = sand. With these features, the wighted risk numbers were:

Risk Parameters		Risk Numbers
Probable scour severity	(PSS)	6
Foundation quality	(FQ)	1
Type of river	(TR)	0.69

Overall weighted risk number = PSS - FQ + TR = 5.69 > 3
The bridge is at high risk.

The method appears to analyse the risk on a broader perspective but it may incorporate errors due to numerous assumptions made in the exercise.

PRELIMINARY RISK ASSESSMENT

A method for preliminary risk assessment of bridge due to scour and erosion around piers is suggested with illustration. Firstly the data about the river and bridge characteristics be collected and features associated with risk to the bridge be identified. The overall probable scour due to various features should be evaluated and compared with the provided depth of foundation and determining the factor of safety should be determined. The assessment of risk should be done by using the following relationship between the factor of safety (F.S) and probability of failure (P.F), as mentioned earlier.

$$P.F = \{(1.88 - F.S) / 1.06\} \wedge 4.717 \qquad (3)$$

Example of Preliminary Risk Assessment

Risk assessment of the Portrack Viaduct of British Rail was carried out as follows to explain the above method.

Assessment of Scour and Factor of Safety

Progressive degradation = none; general scour = 0.15m; local scour = 1.45m,
Probable overall scour depth = 1.60m,
Factor of safety (F.S) =1.52/1.60 = 0.95

Risk Assessment

Probability of failure (P.F) = {(1.88 - F.S) / 1.06}^4.717 = 0.54 Risk = 54%

A risk of failure above 50% is a very high risk.

Risk Consequences

The probable consequences of above bridge failure include: Loss of the bridge structure,closure of the train services, investments in temporary measures and/or reconstruction and other losses due to interruption of economic activities associated with the train service using the damaged bridge After determining the risk probability, economic value of the risk can be estimated by quantifying the above losses in financial terms.

MONITORING OF BRIDGE-SCOUR

Bridge scour holes tend to fill up after the flood and it is necessary to follow an instant method for scour observation which will indicate, obtain and record information of scour holes at the time of its occurrence. Jain et al [3] used flexible strings, initially fixing them vertically in the foundation around the piers which after being exposed due to scour were buried under the sand indicating the level of scour. Riddell [11] mentioned the use of sensors for monitoring bridge-scour at a British Rail's bridge selected for these observations. The sensors were tied to the vulnerable piers at different foundation levels and were linked with recording devices (Fig.7). It gave warning of scour around the pier as it progressed through various stages during the flood and provided instant record of the scouring process.

TABLE 3 FEATURES FOR RISK ASSESSMENT OF BRIDGE-SCOUR

General Features	Specific Features	Effects on Scour
River and catchment features	Type of river bank stability	Affects final priority rating
Channel and floodplain dimensions	Constriction of channel Constriction of floodplain	Affects depth of general scour
Dimensions of pier in plan	Pier width Protrusion of abutment from bank Length of pier/abutment	Affects local scour
Bend in river	Severity of bend Pier/abutment on inside or outside of bend	Affects distribution of general scour
Depth of flow	Depth of flow at bridge relative to pier width	Affects local and general scour
Intensity of flow	Abnormal distribution of intensity of approaching flow along the cross section	Affects local and general scour
Angle of incidence of flow to pier	Angle of approach flow to elongated pier length/width ratio of pier	Affects local scour
Interaction of neighbouring columns	Centre-to-centre spacing of columns Diameter of columns Alignment of column group to flow direction	Affects local scour
Shape of upstream nose of pier	Plain shape, circular or rounded	Affects local scour
Debris trapped on pier	Type of bridge Catchment vegetation and topography History of debris problems	Affects local and general scour
Bed material properties	Range of sizes present Properties of material on which pier is founded	Affects depth of scour
Foundations	Foundation depth Foundation type	Affects susceptibility to scour
Scour protection	Stone/concrete invert Riprap scour protection	May prevent scour

DISCUSSION

At Tahrir bridge wake vortices were the main cause of formation of deep scour-holes downstream of circular pier. The fender has affected the shape and the position of the scour holes downstream of the circular bridge pier. The vortices produce two well defined scour holes where the recirculation zones are formed. The recirculation zone on the surface of the river hasshifted by a distance equivalent to the length of the fender downstream of the pier. The deep scour holes which are formed are shifted away from the foundation of the pier and cause a backflow towards the pier moving the sand upstream and raising the bed level of the river. The two recirculation zones interact and produce alternating vortices which travel downstream and cause single scour hole downstream of the pier. In small scale model, the pattern of the recirculation and the formation of large-scale eddies and vortices extended a distance of 6B downstream of the fender end.

The length of the recirculation zone downstream of the fender is approximately 6 times the radius of the pier and the position of the stagnation point is equal to the length of the fender plus the length of the recirculation zone. The fenders create complex recirculation zones which affects substantially the pattern of scour around bridge piers which in the past had concentrated simply on the scour hole around the bridge pier. Relocation of the scour hole downstream of the bridge pier is the most important function of the fenders. Series of scour holes across the river downstream of the circular pier indicates that the big scour hole downstream of the circular pier is pulling the adjacent scour holes further downstream and that effect is transmitted to other scour holes with decreasing effect. The line of the vortices going across the river indicates this side effect very clearly. There is no evidence that any small bridge pier has any substantial effect on the pattern of scour downstream of the main pier. The fender plays an important role in erosion control of bridge piers. Experiments are needed to study this phenomenon further and possible develop guidelines not only to predict the position of the scour hole from the geometry of the bridge pier and the fender but also to investigate different shapes of fenders which may reduce the amount of scour.

CONCLUSIONS

Change in the flow pattern occurs around bridge piers, which is related to the occurrence of scour. At Tahrir bridge the unsymmetrical distribution of the intensity of approaching flow was one of the causes of excessive scour. The 18m wide floating fenders around the circular pier extending 78m both ways and upto a depth of 0.5m as well as according to Carsten [1], the largeness of the pier (diameter=15m) stopped the formation of the horse-shoe vortex. The centre of the scour hole was 76m from the bridge axis which is 10 times the radius of the circular pier. Wake vortex, becoming more active with additional increment in flow intensity, was the main cause of formation of deep scour-holes downstream of circular pier. Wake vortices generated at the right side of the pier next to circular pier and deflected towards downstream of the circular pier, also intensified the concentration of wake vortices there, resulting in deeper scour holes. In small scale experimental model studies of flow around cylindrical bridge pier with LDA flume, reverse flow was observed downstream of the pier with the stagnation point located at 5.33 times the radius of the pier. Wake vortices were observed to form in the wake of the pier but due to absence of erosion around the pier, formation of horse shoe vortices was not noticed. Local scour, whether in case of clear water or live bed, initiated the formation of those irregularities in the flow domain which consequently caused further scour around the piers, as well as on its downstream side. Risk assessment of bridges due to scour could be made from relation between the available factor of safety of the bridge pier foundation and probability of failure due to scour.

Remedial Measures

Following remedial measures could be considered to deal with the scour problem at Tahrir bridge:

The existing un-symmetrical distribution of intensiy of approaching flow at Tahrir bridge could be normalised by constructing suitable river training works upstream of the bridge e.g guide banks, spurs and dykes.

Divide walls could be constructed downstream of all bridge piers extending up to a suitable distance to stop the deflection of wake vortices, avoiding the effect of split-flow condition and streamlining the flow downstream.

However it is necessary to carry out model tests before actually taking up any construction work.

NOTATIONS

b=pier width
C1,C2,C3=constants
D50=media sediment size
Fc=critical Froude Number
g=acceleration due to gravity
K1, Ks=correction factors for pier shape
K2=correction factor for angle of attack of flow
Ki=flow intensity factor
P.F=probability of failure
ρ s=density of sediments
V=velocity
Vc=critical velocity

B=bias factor
ds=scour depth
F=Froude Number
F.S=factor of safety
K=symbol for correction factor
Yo = total depth of flow
K3=correction factor for bed condition
Kd=sediment size factor
ρ=density of water
Re=Reynold's Number
Vo=mean velocity
Y=flow depth

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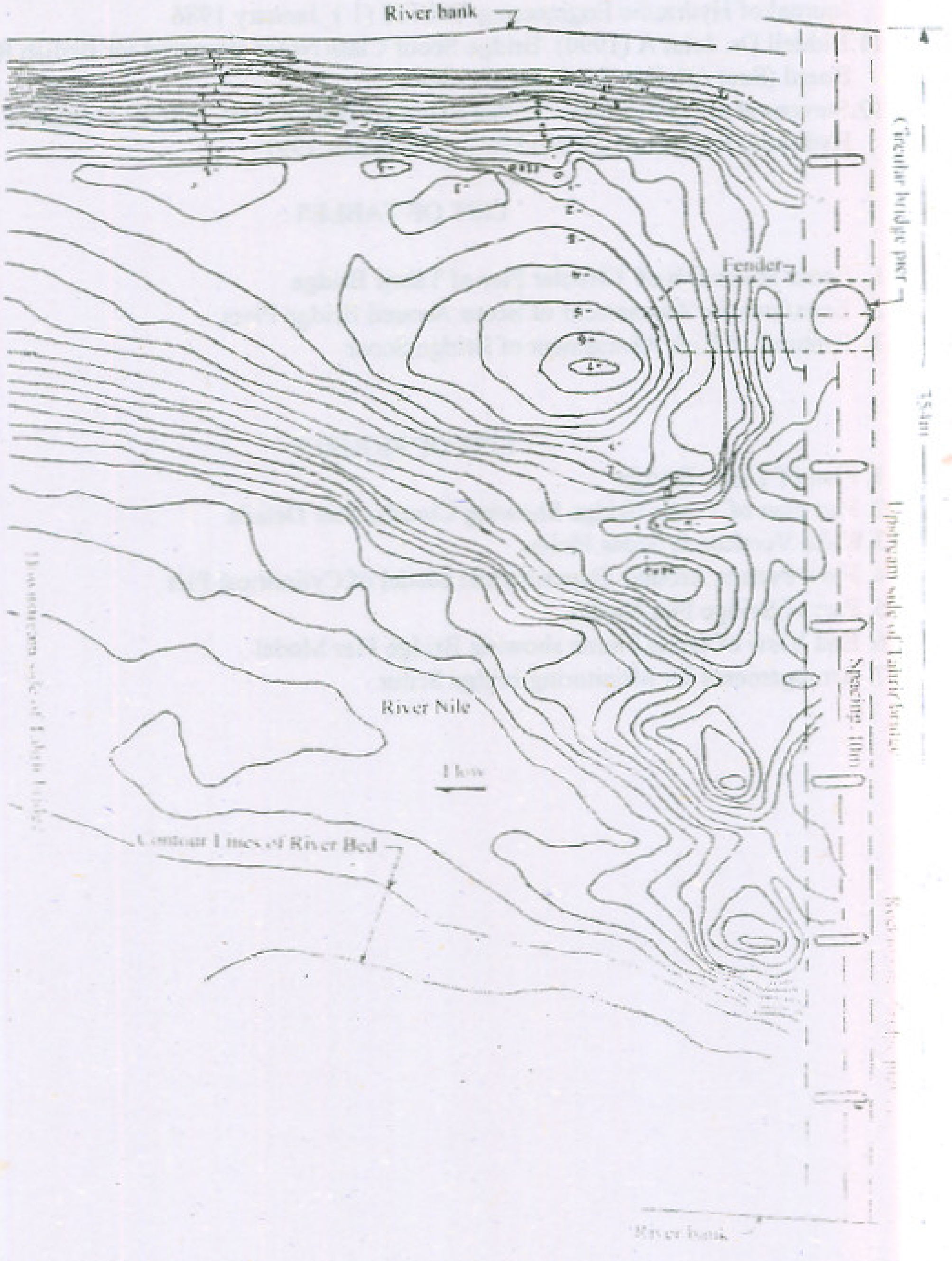

Fig.1. Plan of Tahrir Bridge

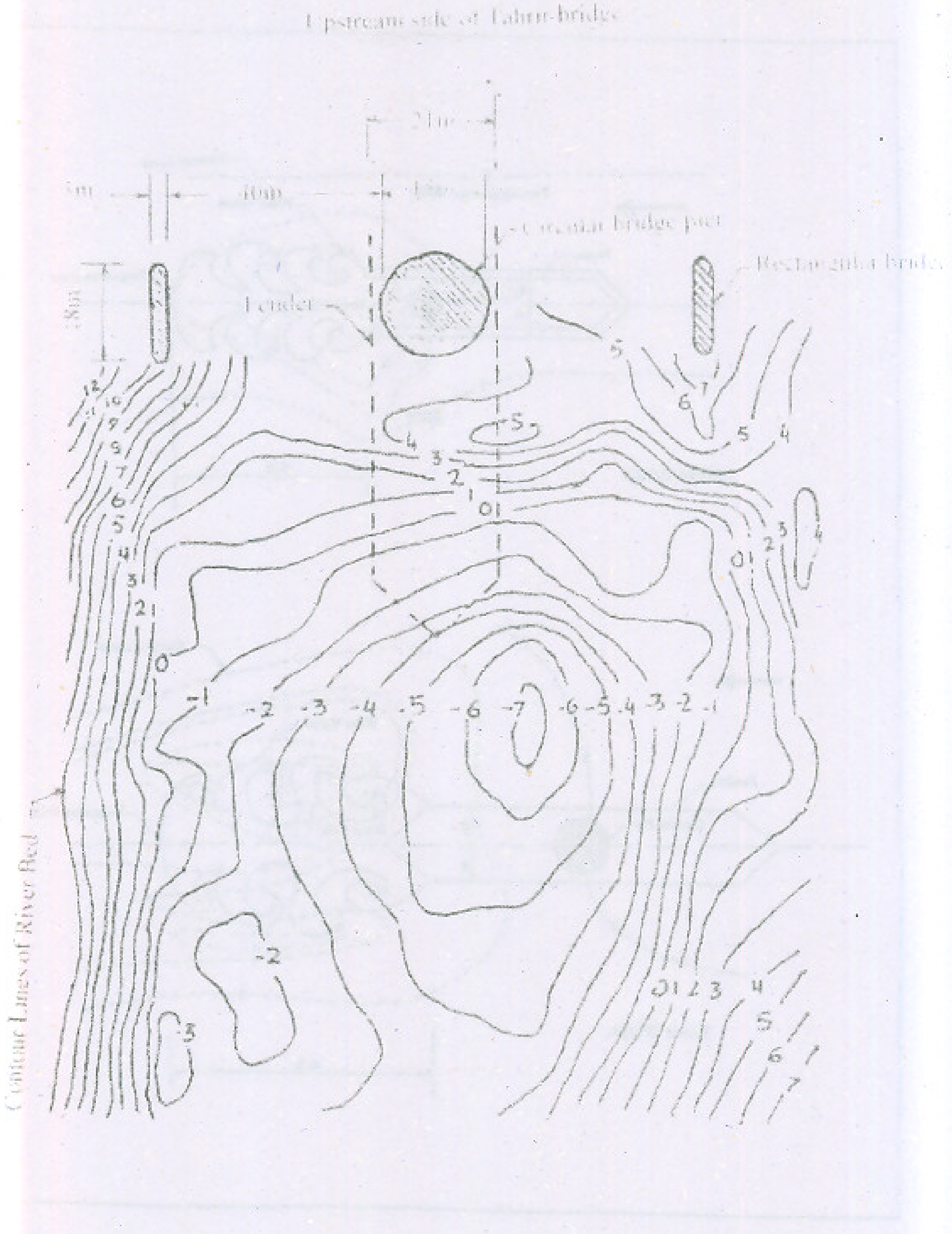

Fig.2. Part plan of Tahrir Bridge Showing Circular Pier Details

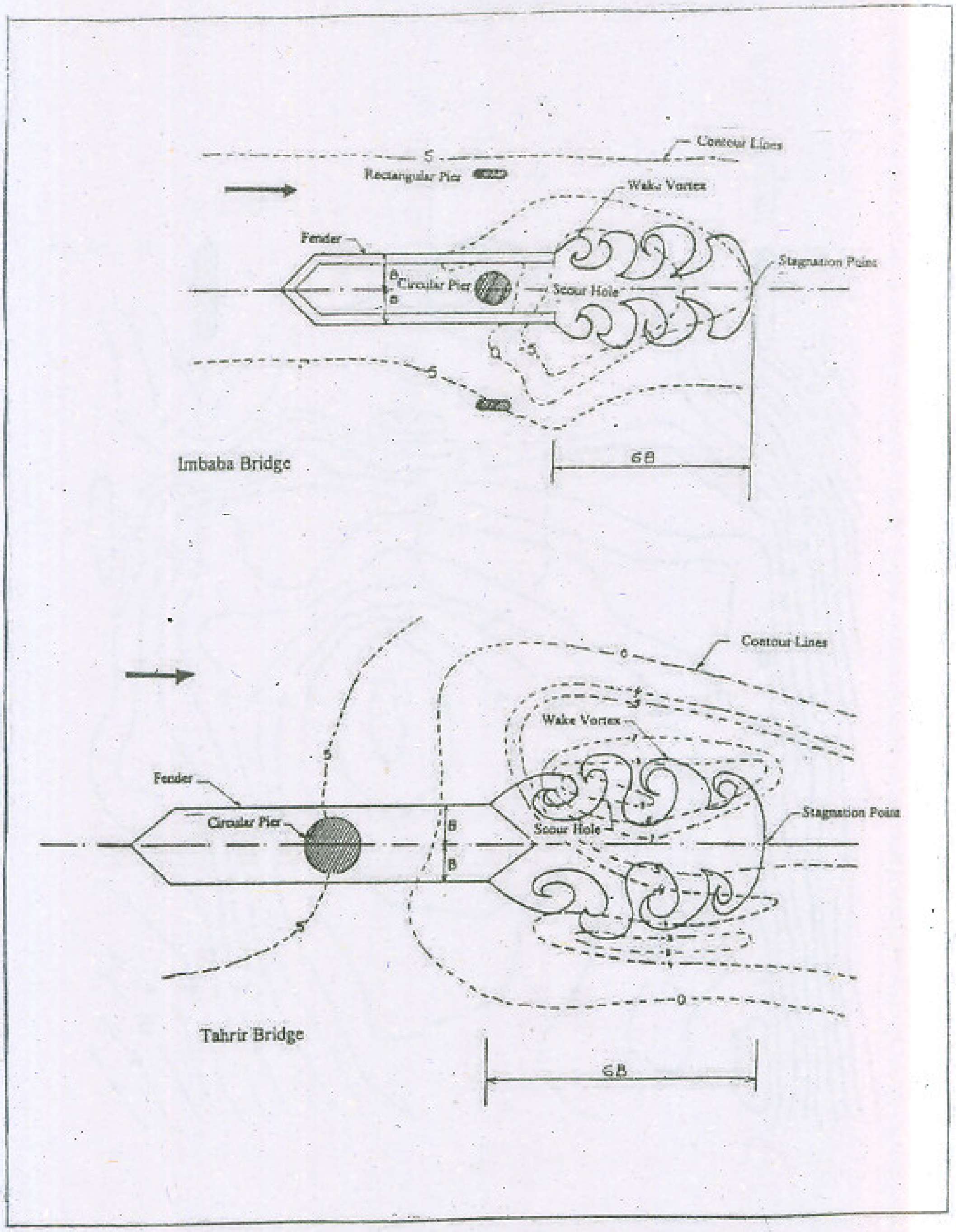

Fig.3 Wake Vortices & Scour Holes

Legend:

V - Velocity observed at any point by means of Laser Doppler Anemometer
Vo - Average Velocity of Flow in the laboratory flume
Z - Distance measured across the flume of the laboratory
X - Distances measured along the length of flume of the laboratory from one end.
Zo - Total Width of the laboratory flume

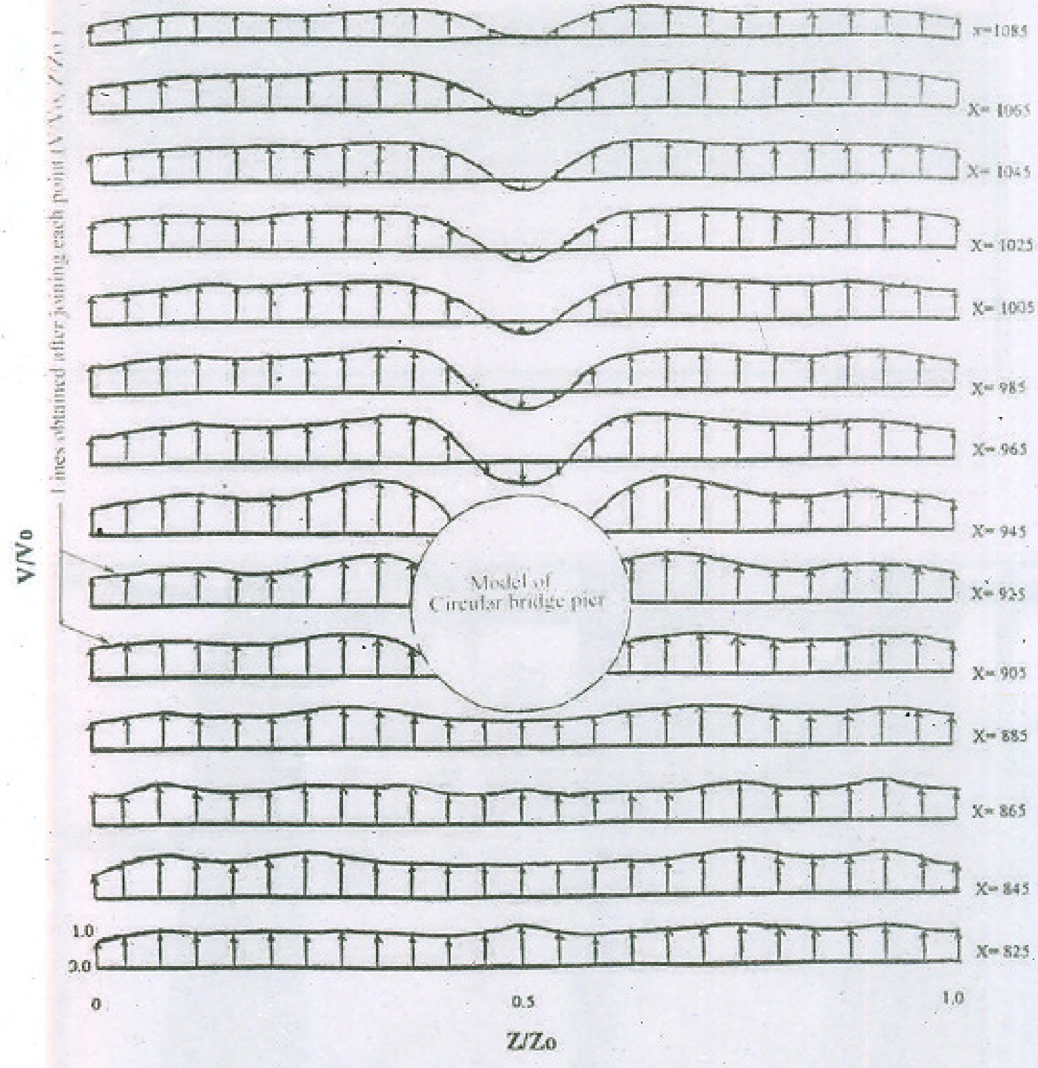

Fig.4 Flow Pattern Around Experimental Model of Gylindrical Pier

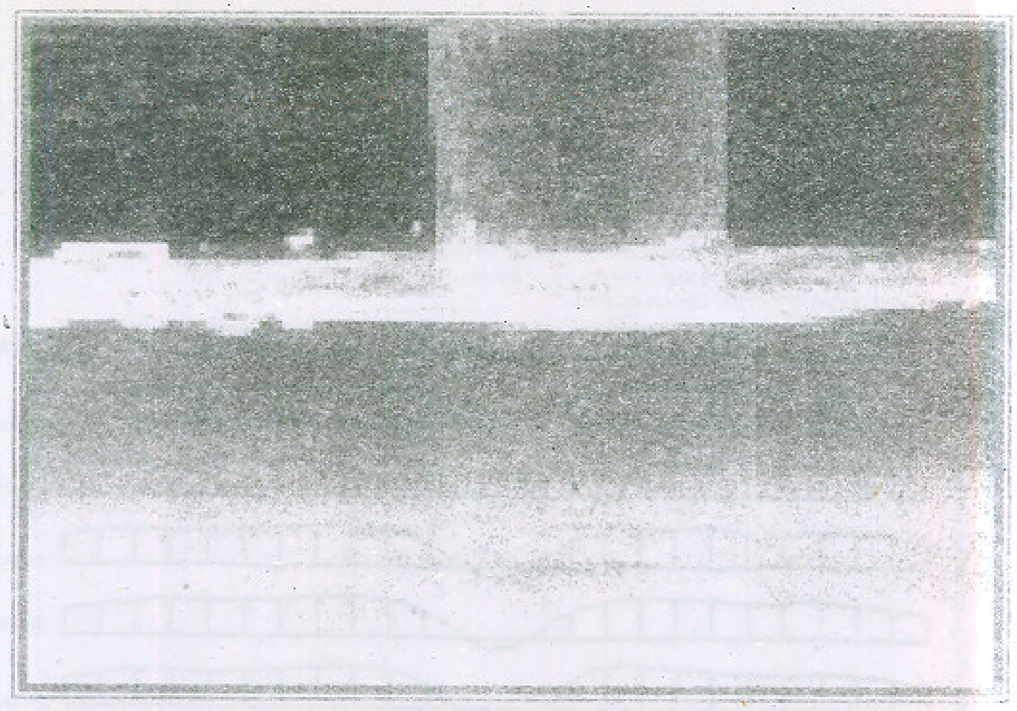

Fig 5. Part of Bridge Pier Model erected in the Glass Flume of the Hydraulic Laboratory

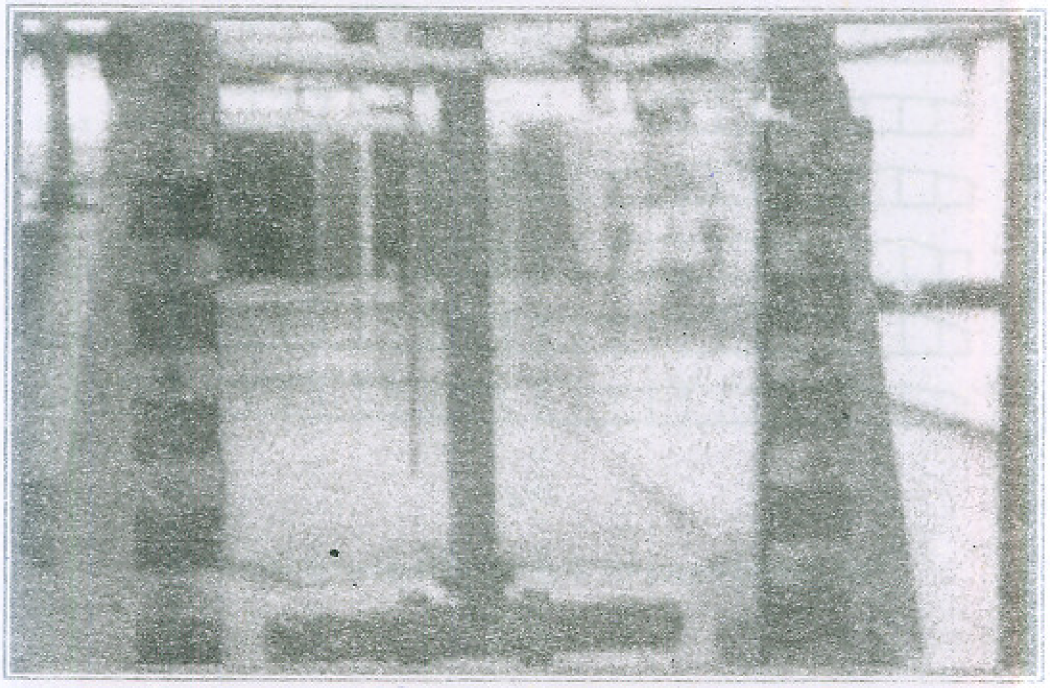

Fig 6. End View of Glass Flume showing the Bridge Pier Model and Gauge for Measuring Water Level in the Flume

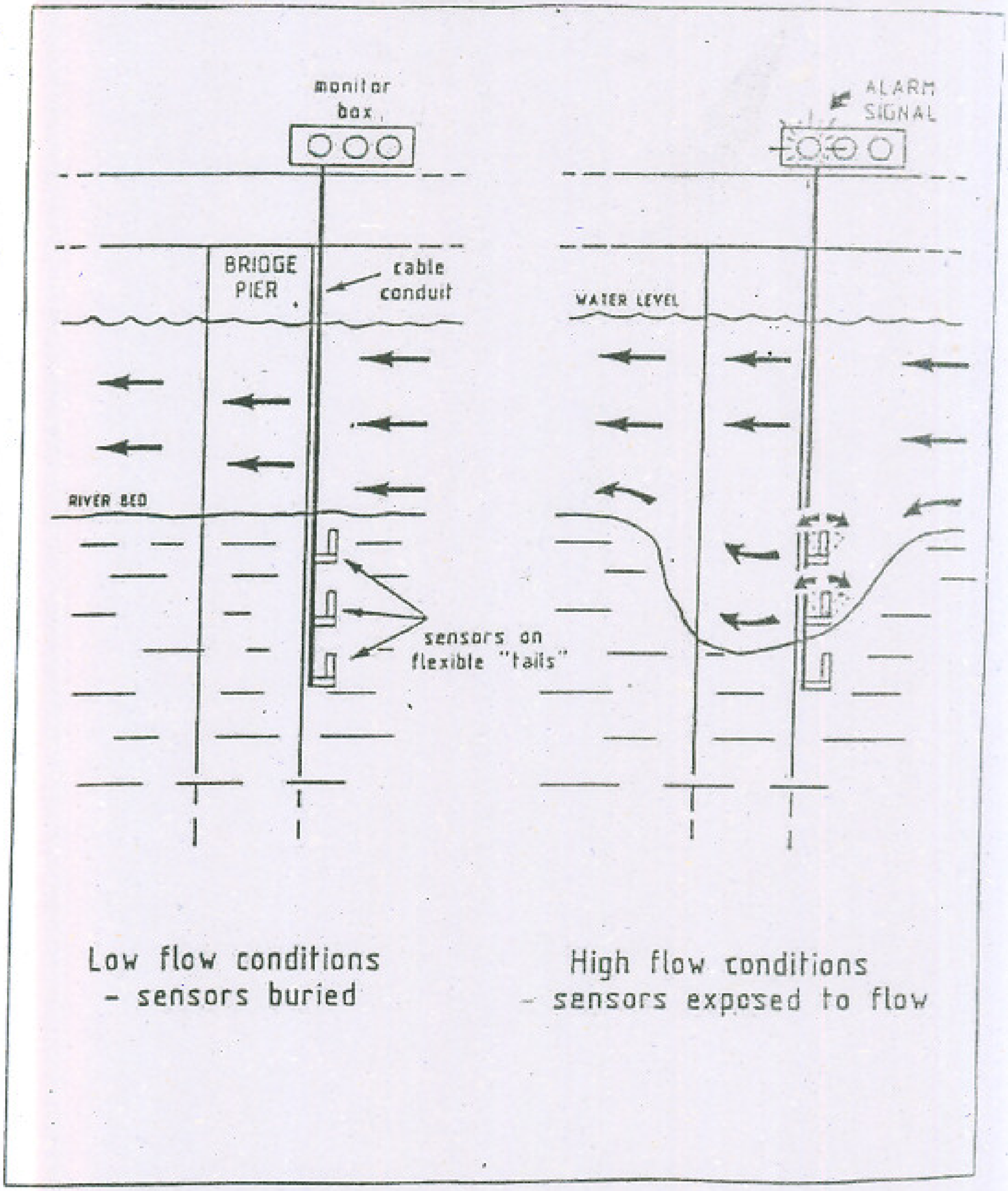

Fig 7 Arrangement Showing Monitoring of Bridge Scour With Sensors