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ROLE OF HYDRAULIC MODEL STUDIES IN BRIDGE DESIGN

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SUMMARY

Bridge construction requires careful planning and in-depth study as no undue risk should be taken in its design and construction. Hydraulic consideration in the bridge design comprises several aspects such as selection of site, determination of waterway, assessment of scour for design of foundation of piers and abutments, design of guide banks, approach banks, protection works, etc. Undermining of the piers due to excessive scour could become a potential cause for bridge failure. Mechanism of scour around bridge pier, factors affecting scour, estimation of depth and extent of scour, scour protection measures and some case studies conducted in this regard in Central Water and Power Research Station (CWPRS), Pune, have been discussed in this paper.

1. INTRODUCTION

1.1 River Characteristics

Indian rivers in flood plains are shallow and flow in a wide alluvial belt with meandering and braiding characteristics. The river Brahmaputra is intensely braided about 30 km upstream of Guwahati with a width of about 10 km. Thereafter it naturally constricts to 1.5 km at Saraighat bridge and again widens to 18 km at about 30 km downstream of this bridge. In 1980, construction of a 17 span road bridge at Tezpur was started on the river Brahmaputra from the hill located at the right bank. By the time construction progressed the deep channel shifted considerably towards the left and the bridge had to be completed with additional 7 spans on the left side to accommodate the lateral shift in the river regime. Before formulating any hydraulic project, it is therefore essential to understand the behaviour of the river in the vicinity of the project area including upstream and downstream stretch of the river regime.

Bridge construction requires careful planning and in-depth study as no undue risk should be taken in its design and construction. Study made by Smith on the failures of 143 bridges constructed between 1847 and 1975 indicated that majority of the bridges have failed due to scour around the piers and abutments. Other causes were defective design, overloading, adoption of inadequate or unsuitable erection techniques, earthquake forces and use of material or type without taking into account certain salient aspects which are critical or not known to be critical at the time of design and construction.

2.0 HYDRAULIC ASPECTS

Hydraulic aspects of bridge design consists of selection of site, optimum orientation and waterway, location of abutments, design of guide banks, approach embankments and design of bridge piers. As far as possible bridges are to be located on straight reaches and with alignment normal to the flow. Nodal points are ideal for locating bridges. High cost of bank to bank bridges and bank protection required on the upstream and downstream stretches of the river made the engineers to look for constricted bridges with guide banks and approach embankments. Waterway design depends upon the design discharge, type of river, whether aggrading or degrading, and nature of river such as braiding or meandering, etc. The empirical relation evolved by Lacey for stable width in alluvial rivers is widely used to determine the waterway for bridges. Inadequate waterway can result in excessive velocities across the bridge causing deep scour at the piers and the guide banks in addition to an undesirably high afflux on the upstream side. Excess waterway causes slackness in the flow thereby causing aggradation, promoting the formation of shoals resulting in non-uniform flow distribution and oblique approach of the flow to the bridge. Deviation from Lacey waterway becomes imperative in some cases to take care of special site conditions.

In constricted bridges, the abutments are provided with guide bunds (also called guide banks) and approach embankments. The guide bunds which ensure smooth passage of the river flow through the bridge, are so designed that, a safe marginal distance is available between extreme swing of deep channel with possible worst loop.

Bridge piers are founded on wells or in some cases on piles. When rocky strata is not available at a considerable depth and river bed is highly erodible, well foundations are suitable. When rocky strata is available at 6-20 m below bed level, pile foundation is preferred. In Karnataka and Goa, most of the bridges of Konkan Railway are located in the reaches of rivers affected by tidal variations (estuarine conditions) and strata comprises of marine silt or clay followed by dense sand, sandy clay, soft rock, etc. Pile foundations were considered suitable for these bridges. Speed of construction, economical and accurate construction and elimination of problems of tilting, shifting, etc. are the advantages of pile foundations over the well foundations.

- Undermining of the piers by scour is a potential cause of failure of bridge foundations. Local scour that is scour which occurs due to the presence of an obstruction to the flow causes a decrease in the bed elevation only in the area surrounding the obstruction. The dominant feature of the flow around a bridge pier essentially comprises the system of vortices. The most important of these are the horse-shoe vortex and wake vortex system (Fig.1). As the flow approaches the pier a stagnation plane is formed. Because of the vertical velocity profile a pressure gradient is formed along the stagnation plane on the pier. This gradient produces a downflow in front of the pier, which acts like a vertical jet in eroding the bed material. The indentations and downflow combine to excavate a hole at the leading edge of the pier. The incoming flow separates at the edge of the scour hole, creating a circulation or roller within the scour hole. The downflow divides at the bottom of the scour hole and spirals downstream past the pier. This together with the ground roller forms a horse-shoe vortex. It is very efficient in transporting dislodged sediment particles away from the pier. Wake vortices form at the downstream side of piers and are the result of flow separation at the sides of the pier. The wake vortices dissipate as they move downstream. The frequency of periodical vortex shedding downstream is directly proportional to the approach velocity and inversely proportional to the pier diameter.

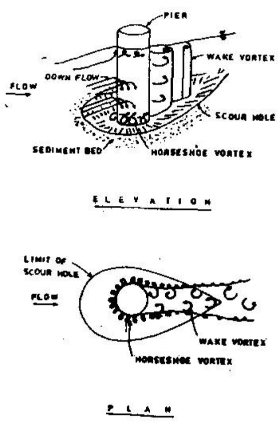

FIG. 1 FLOW PATTERN AT CIRCULAR PIER

  Depth of scour depends on a number of variables such as depth, velocity and angle of attack of flow, width of obstruction, soil strata and sediment size. In the case of non cohesive materials the characteristics of bed material which affect scour include sediment density, median size and standard deviation. Since lighter sediment will move at lower mean velocity or shear, greater scour can be expected. When the channel is not transporting sediment, the bed around the pier will continue to lower until the shear in the scour hole is critical.

- Clays are transported by water and after flocculation get deposited in main river channel on flood plains and in lakes and estuaries. When sandy material is mixed with silts and clays in different percentages, the material, exhibits a certain amount of cohesion. Adequate information is not available to determine scour depth around bridge piers in cohesive soils. Kand suggested that Lacey's silt factor be increased in the case of cohesive soils by using the relation. $f_C = F\ (1+C^{0.5})$ where f_C is Lacey silt factor for cohesive soils, C is cohesion in Kg/cm^2 and F is a coefficient based on angle of internal friction Ø. F = 1.5 for Ø = 11° to 15° and F = 2.0 for Ø = 5° or less. If Ø is greater than 16° and $C \geq 0.2\ kg/cm^2$, it is sandy soil with clay binding, and can be treated as sandy.

- Very limited data are available on scour around bridge piers in gravel bed rivers. The bed material of these rivers is usually characterised by relatively large mean size. It is during relatively large flood that all the particles in the bed material move, as the discharge reduces the coarser particles which cannot be moved, accumulate on the bed surface and form a layer of non-movable particles on the bed. This is known as protective armour layer or paving. When a bridge pier is constructed in a gravel - bed river as the scour progresses during the flood, coarser particles will accumulate in the scour hole and armouring effect will be increased. As a result, the scour depth will be much smaller than that in an alluvial river with relatively finer and uniform materials.

- Estimation of maximum scour can be grouped under three components viz., (a) general scour due to design flood, (b) scour due to constriction and (c) local scour due to pier obstruction. Laboratory studies are useful in predicting more accurately the third part i.e., local scour due to pier obstruction. Lacey-Inglis method of estimating scour around bridge piers is commonly used in India for piers placed in alluvial rivers and is recommended by the Indian Road Congress and Indian Railways. Inglis advocated maximum scour depth D_s below HFL, around a bridge pier as $D_s = 2\ D_L$ where D_L is the general scour depth below HFL suggested by Lacey as $1.34\ (q^2/f)^{1/3}$ where q = maximum discharge intensity in cum/s/m and f is silt factor = $1.76\ m^{0.5}$, where 'm' is the mean diameter of the bed material in mm. This method is meant for sandy rivers of meandering type.

- In an estuary or a tidal river where flow is subjected to periodical change in direction, the scour of the river bed occurs mostly during ebb tide (seaward flow). During flood the scour of the tidal river bed is supposed to be nominal because the increase in discharge is being accommodated mostly by rise in water level rather than by lowering of the bed levels by scouring. The phenomena of the scour depend considerably upon the order of velocity which persists for a prolonged period in the tidal cycle which occurs generally at the mean tide level (MTL). Therefore, for computations of regime depth D in the tidal river, the normal depth of water should be measured from MTL and not from high flood level (HFL). Also the computations of discharge intensities and mean velocity should be undertaken at the mean tide level. The regime depth is thus obtained using Lacey's empirical regime formula which is applicable to alluvial river. In tidal river of this kind, the maximum natural depth of scour is obtained by using a multiplying factor of 1.25 to 2.7 to the regime depth.

- The criteria for scour protection and the level of foundation are different for the deep and shallow types. For deep foundations, usually no scour protection is provided. But there are many cases where a shallow type pier foundation has to be selected. This type of foundation is greatly subjected to scour risk and therefore adequate design allowance and scour protection are required.

Stones for scour protection (Fig.2) are laid over filters which help in arresting the leaching of finer base material or river sediment through the rip-rap primarily due to upward hydraulic gradient and turbulence within the rip-rap layer. The filter should be fine enough to prevent the base material from entering

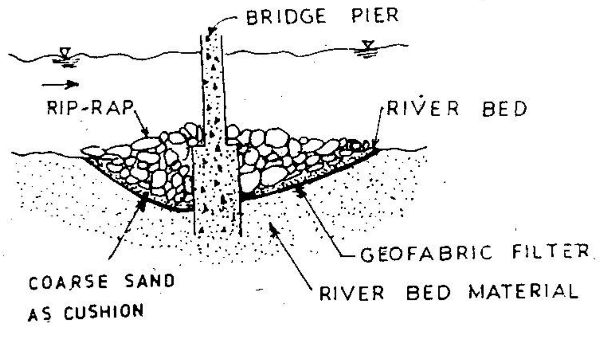

FIG 2. SCOUR PROTECTION FOR A BRIDGE PIER

and it should be much more permeable to water than the base material. Using geofabric filter is a relatively new and modern development and is advantageous both in terms of economy and ease of construction as compared to the graded filter. In order to prevent damage to the geofabric filter while placing the stones, a 15 cm thick layer of coarse sand should be provided over the filter as a cushion.

3. NEED FOR MODEL STUDIES

In spite of availability of many empirical formulae associated with analysis of certain river parameters in the vicinity of the bridge, it has been found that model studies either physical or mathematical would be valuable in optimising the design parameters to suit the specific site conditions, thereby reducing the risk of bridge failures. Morphological studies of the river upstream and downstream would help to understand the river behaviour, changes in the river channel alignment, formation and development of shoals, bars, islands, bank erosion, etc. Information analysed under pre-bridge conditions would help to estimate the likely morphological changes in the river under post-bridge conditions. CWPRS has conducted physical, mathematical and morphological studies for various bridges to derive optimum design parameters or to solve certain problems faced by the engineers.

4. CASE STUDIES

4.1 The Toka Bridge

The Toka bridge is situated across the Godavari river on Pune-Aurangabad sector of State Highway No.27. The construction of the bridge was completed in the year 1961. Safety of the bridge was required to be ascertained in view of the construction of a dam downstream of the bridge at Paithan. On the basis of the analysis of data for 9 years, the permissible scour level to achieve the required grip length was worked out which was more or less equal to the existing average river bed level. It was, therefore, necessary to provide proper protection at the existing river bed level for preventing local scour thereby maintaining the design grip length. It was therefore suggested to provide 0.6 m X 0.6 m X 0.45 m cement concrete blocks over a granular filter in 6.40 m width around the piers with top of the protection flush with the river bed level (Fig.3). Since laying of the granular filter under flowing water was difficult, project engineers laid cement concrete blocks in two layers with staggered joints to minimise loss of bed sand through the gaps. After the construction of protection works, heavy flood occurred and the performance was reported to be satisfactory except that a few blocks at the edges of the protection were disturbed.

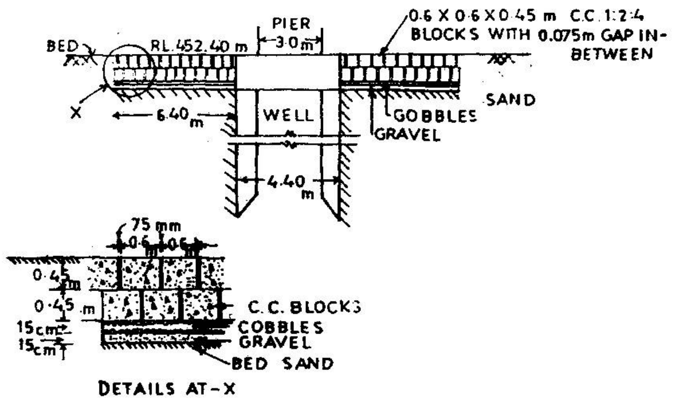

FIG:3. TYPICAL PIER PROTECTION AT TOKA BRIDGE

4.2 The Alamuru Bridge

The Alamuru bridge is situated across the Godavari river downstream of the Dowlaiswaram anicut on the stretch of National Highway between Vijaywada and Visakhapatnam. The width of the river at this location is 2441 m. On the basis of model studies conducted at CWPRS for the design discharge of 56,600 cum/s, a bridge with waterway of 1454 m with suitable guide bunds was suggested to achieve uniform distribution of flow in various spans. However, in the year 1967, a bridge with total waterway of 2341 m was constructed.

During the year 1978, deep scour developed at the second pier from the left abutment resulting in its tilting. At that time the discharge was only 13,000 cum/s which was much less than the design discharge of 56,600 cum/s. However, excessive waterway had resulted in the formation of islands which led to the concentration of flow with an oblique approach. Based on some measurements at site, the discharge intensity at the affected pier was estimated to be about 71 cum/s/m with an obliquity of 25° to 30° and the observed scour level was (-) 16.15 m. The bottom level of wells was at RL (-) 25.0 m.

The general scour level corresponding to the discharge intensity of 71 cum/s/m worked out to be RL (-) 0.6 m. However, analysis of data after the floods indicated that the deepest bed level had shifted from pier No.2 to 4 and was at RL (-)2.0 m. It was difficult to do the excavation of 4 m in the water and therefore protection at RL (-) 2.0 m over a width of 11.5 m around the pier was suggested (Fig. 4). At other locations, the bed level was higher where the protection was not needed immediately.

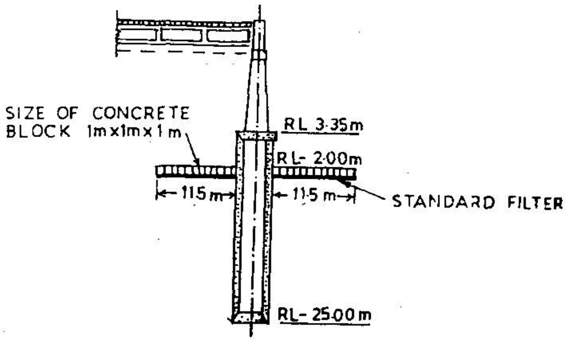

FIG. 4. DETAILS OF PROTECTION AT ALAMURU BRIDGE PIER NO. 4

4.3 The Delhi-NOIDA Bridge

50 km of river Yamuna traverses through the National Capital Territory of Delhi. In the urban area of Delhi, i.e., within 25 km three barrages and four bridges exist, most of which have been constructed based on the model studies and recommendations of the CWPRS. During the last 10 years, proposals for four more bridges were studied in the CWPRS. NOIDA is on the left bank of the river. In order to connect NOIDA with Delhi, a road bridge (Fig. 5) was proposed in between Nizamuddin road bridge and Okhla weir.

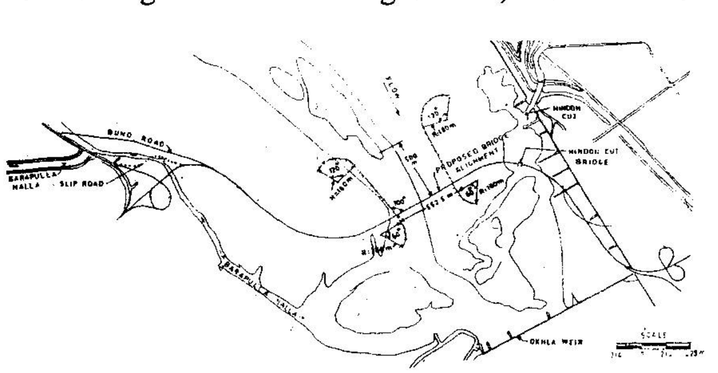

FIG. 5 DELHI NOIDA BRIDGE SITE PLAN

Model studies were carried out to study the scouring pattern and to compare the scour around the group of piles with that around the well foundation of the bridge pier for similar flow condition (Fig. 6). Studies were carried out in a flume and the scour development in both the cases were studied and compared. It was found that depth of scour was more for the well foundation as compared to that for the foundation with group of piles. Studies conducted with normal flow and obliquity of flow indicated more depth of scour with oblique flow compared to that with normal flow.

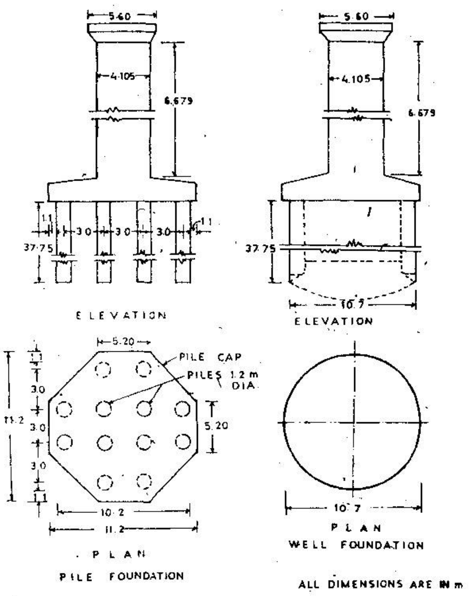

FIG 6. DETAILS OF PIER FOUNDATION

4.4 The Gouranga Bridge Near Nabadwip

The Gouranga bridge is situated on the river Hooghly about 160 km upstream of Calcutta (Fig.7). The left bank of the river upstream of the bridge had been eroding for the last few years and there seemed to be a possibility of the bridge being outflanked. Due to concentration of flow the second pier from the left abutment was experiencing deep scour. In order to avoid further deterioration of the situation and limited time available before the onset of the next monsoon, short term measures were suggested on the basis of site inspection and available data. To avoid the danger of the bridge being outflanked, protection was recommended in the upstream embayment for a length of 160 m. In addition, porcupines were suggested at the toe in the further upstream reach of about 100 m. For control of scour at the endangered pier, provision of two layers of 50 kg stones in a 60 m width all around the pier at the existing river bed over geo-jute/nylon bags was suggested. For evolving long term measures, studies were subsequently conducted on a physical mobile bed model constructed to a horizontal scale of 1:300 and vertical scale of 1:50 reproducing a river reach from 3.50 km upstream to 2 km downstream of the bridge. These studies revealed the necessity of providing continuous protection from 100 m downstream of the bridge to 100 m upstream of the embayment along the left bank with stones weighing 40 kg or more in two layers over a synthetic filter. For the protection of the toe of the left bank, 15 m wide apron consisting of two layers of 40 kg stones over a synthetic filter was recommended.

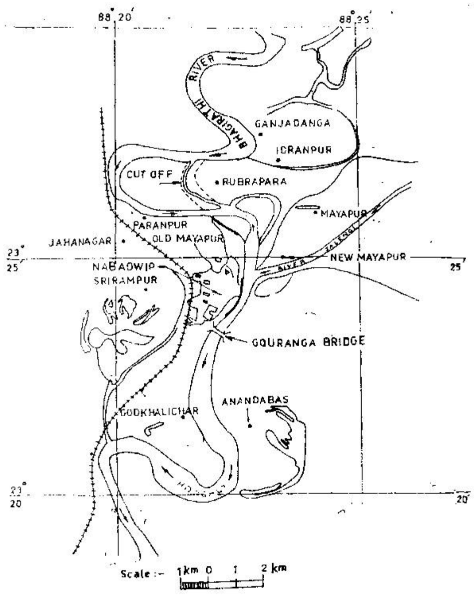

FIG 7 LOCATION OF GOURANGA BRIDGE AND THE CUT-OFF DEVELOPED

5. CONCLUSIONS AND FUTURE STUDIES

- When the river is degrading, bridge scour should be monitored for scour and when necessary, protection by way of garlanding should be provided.

- River plan form changes can be monitored with the help of Remote Sensing data. This analysis would help to estimate change in discharge intensities across a bridge which in turn help in estimating the maximum scour.

- Adoption of pile foundation for bridge pier can reduce local scour and this may therefore be adopted when feasible.

- Understanding of soil-structure interaction, scour and fill process in a river with a boulder-bed are some of the grey areas where considerable research including field monitoring, need to be taken up. In India scour observations at hydraulic structures during floods are very rarely taken due to non-availability of suitable instruments. Sometimes observations are taken when the flood recedes and scour pockets get filled up by bed material. The scour observations are taken by sounding from bridge decking which are affected by drifting due to high velocities. For scour observations during floods, it is very much essential to install automatic recording type instrument. Such instrument should be compatible for installing at the bridge pier. It should give a clear indication of the depth of scour under all flow conditions. The system should record the onset of scour, maximum depth of scour and filling of scour holes following high flow events.

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