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Extensive cracks were noticed in concrete arches of Sukkur Barrage in April 1964. A high level committee was appointed to investigate the damages and submit their recommendations regarding remedial measures. The structural investigation of the arches as a part of total investigations is the subject of this paper.

Formerly known as Liyod Barrage, the Sukkur barrage is the first barrage on the river Indus. It was constructed in 1932 and is situated about 225 air-miles North-East of karachi. Sukkur barrage project completed at a cost of Rs. 20 crore is considered to be the World's largest single unified irrigation scheme. The barrage feeds seven canals which irrigate 69 lac acres of cultivable area. The irrigation channels off-taking from Sukkur Barrage hold a key position in the rural economy and prosperity of southern West Pakistan.

The right undersluices, the central weir portion and the left under sluices are the three main divisions of the barrage. In all there are 66 bays, each having a clear span of 60 ft. The left and the right undersluices consist of 7 and 5 bays respectively, whereas the remaining 54 bays of middle weir portion are divided into 6 compartments of 9 spans each, separated by abutment piers. The lower level road bridge and the higher level gate bridge decks are supported on reinforced concrete arches.

The Gate bridge on the u/s side and the Road bridge on the d/s side are the two separate bridges supported by the piers. Both of these bridges transmit their load to the piers through reinforced cement concrete arches. The Gate Bridge rests on two separate series of arches on u/s and d/s sides having width of 8'-3" and 5'3" respectively with a springing level of RL. 219.0 and a rise of 15'. The Road Bridge arches, 25'-3" wide, have a springing level of RL. 201.0 and a rise of 10'. River training works, constructed to eliminate serious silt trouble on the right bank canals, reduced the flood capacity of the barrage from 15 to about 9 lac cusecs. Stone masonary voussoir arches, proposed for both the bridges in the original design in 1919, were changed to reinforced cement concrete arches in 1928 just before actual construction, in view of a higher strength of reinforced concrete, its suitability for longer spans, and quick and economical construction. Design of the intrados for stone arch profile was retained for both the bridges to avoid delay in construction.

The three sets of concrete arches were designed in 1919 for certain loads and temperature variation. For the Road Bridge, live load of 100 lbs per sq. ft with an impact factor of 13% in addition to the computed dead load and a steam roller load of 15 tons was taken as the design load. A graphical arch analysis yielded a maximum compressive stress of 316 psi in masonary at crown and 311 psi at joint of rupture. The Gate Bridge design load consisted of the dead load, a live load of 45 psf with 13% impact factor, 3 ton travelling crane with a laden weight of 15 tons and an impact factor of 33%. This lead produced maximum compressive stresses of 315 psi at crown and 313 psi at joint of rupture in the upstream arch and 316 psi and 313 psi respectively in the downstream arch at corresponding locations. During review in 1928, the original loads were considered inadequate and live load over the road bridge was changed to a succession of 16 ton lorries per 10 ft traffic lane. Ths case of a fully loaded arch with the heavier axle at the crown was considered to be the worst condition of loading. A static load of 40 ton gate standing on 4 bearers and a rolling crane load of 7 tons passing over the arches was accepted as the worst loading for gate bridge. A temperature variation of $^{+}$ 30°F was assumed for design. The reinforcement in concrete arches was provided with a concrete over of 22".

Crown moments, thrust and shear for loads and temperature effect were calculated by using summation equations for symmetrically loaded arches. One half of the arch was considered for analysis by putting live loads symmetrically about the crown. No effort was made for investigating an economical design. Concrete for arches had a ratio of 1:1.5:4 for cement, local lime stone, and stone metal without sand. The construction was continued in all seasons, without the help of vibrators, and field as well as laboratory tests.

Cracks were first reported in the barrage piers in 1949 and in cement concrete arches in December 1950. The Cementation Company, a British firm, was engaged to repair these arches by guniting but soon after the repairs the cracks reappeared in a number of arches in March, 1956. The Cementation Company made no serious attempt to treat the cracks and accept any responsibility, and advanced reasons which were not considered to be convincing. In view of the importance of the barrage, the need for extensive field and laboratory investigations was evident. The arches of the Road as well as Gate Bridge were tested for different loadings and with different assumptions which do not form the subject of this paper by the author. The design assumptions originally made were checked and shortfalls in original design procedures were taken due notice. The Author has included the detailed results in his paper for the interested readers.

Sukkur Barrage concrete arches are not of any regular shape and arch section is also not symmetrically reinforced. These arches are also fixed at the ends and 6 different equations are required for stress analysis of the structure. As these arches follow a complex shape and cannot be analysed by usual integral equations in addition to three equations obtained from moments and reactions. The solution of these six equations yielded many interesting results, the most significant being the increase in secondary stresses due to temperature and shrinkage with the thickening of the arch.

The first step in design check was aimed at comparison of design conditions with original computed values. The Road Bridge was further checked for present day loading conditions which, of course, represent higher loads than those originally assumed. The study yielded some significant findings like lack of thoroughness and precision in design, ignorance of sizeable shrinkage and rib shortening effect, incorrect splay effect, use of summation equations for computing M and T values without any appreciation of their basis, etc. Live load for maximum effect was placed on the arch, on the anology of maximum beam moments, by temperature influence, were increased to 70% of the critical moment values whereas live load contributed only 7 to 12%.

An isolated radial crack in an RCC arch is only a warning and is not a sign of failure. A through crack breaks the continuity of the arch and gives relief to the secondary effects of temperature and shrinkage. Consequently moments will become far lower than those when the arch was continuous and uncracked. Therefore the possibility of a sudden collapse may easily be ruled out. The arches, therefore, are not required to be replaced and may be rendered safe by suitable repairs. However a thinner arch having half the thickness of the existing section and half the quantity of steel of the existing arch would have been superior and stronger.

Structural investigations of Sukkur Barrage have brought out some errors and omissions of basic nature which point to the need for a Centralised Design Office where proper analyses by expert engineers would help in eliminting such serious drawbacks. Unfortunately the Central Design Office of the Irrigation Department at Lahore, after thirty years unmatched performance, was abolished in 1962 during Re-organisation of the Department. The present trend of relying on foreign Consultants to the extent of allowing them to direct our policies regarding sensitive technical decisions is fraught with danger. The trend is also likely to hamper the much needed growth of the engineering profession in Pakistan. The engineering talent in the country needs guidance and conducive working environment for which the Government as well as the Pakistan Engineering Congress should identify their roles and take immediate steps to check the worsening situation.