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EARTHQUAKE BEHAVIOUR OF CONTINUOUS MULTI-SPAN CABLE-STAYED BRIDGE

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SUMMARY

The earthquake behaviour of a continuous multi-span cable-stayed bridge across the Jamuna River in Bangladesh is investigated. The proposed bridge has a total length of 12 km and consists of a series of cable-stayed bridges with a span of 350 m. The bridge is located in a seismic region whereby an earthquake with magnitude 8.7 occurred in 1897 within an epicentral distance of 200 km. A comparison is made between the earthquake behaviour of different types of cable-stayed bridge systems. The bridge is modelled as a plane frame structure with the piers attached to the rigid foundation. Small-amplitude oscillations and linear material behaviour are assumed. Both the horizontal and vertical earthquake components are considered.

JAMUNA MULTI-SPAN CABLE-STAYED BRIDGE

The Jamuna River (Brahamaputra) divides Bangladesh into two parts on a north-south axis. The government has given high priority to the integration of the eastern and western zones of the country, therefore a long multipurpose bridge is considered which carries road and rail traffic, a gas pipeline and electricity across the Jamuna River. The importance of this project is reflected in the fact that the government of the People's Republic of Bangladesh established a special authority called Jamuna Multipurpose Bridge Authority. Schemes are already underway to collect funds for financing this prestigious project, which according to first estimates will cost US$ 600 million. The foundation stone for the bridge was laid on February 2, 1988.

Eighteen alternative bridge schemes for crossing the Jamuna at Sirajganj were designed to a level sufficient to establish the feasibility and cost of each scheme. Truss, concrete box girder, cable-stayed and suspension bridges were considered with spans ranging from 80 to 800 m. A multi-span cable-stayed bridge of 300 to 350 m span, with a total length of 12 km, was among the best schemes for the Jamuna crossing (Fig. 1), however, finally, preference was given to a prestressed continuous girder bridge.

The potential of multi-span cable-stayed bridges for crossings of very wide rivers with bad foundation conditions and large scour depth, for instance, like the rivers Indus, Ganga, and Brahmaputra with 200 to 300 m spans, so that the carrying capacity of the very large and deep caissons (depth between 50 to 70 m) can be fully exploited, has been discussed by Leonhardt and Zellner [2].

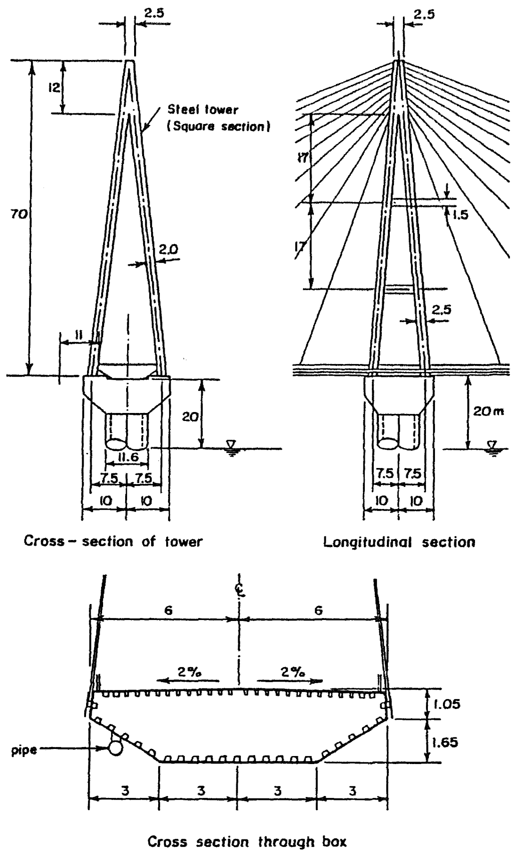


Fig. 1 Details of pylon and deck girder of the proposed cable-stayed bridge scheme across the Jamuna River in Bangladesh.

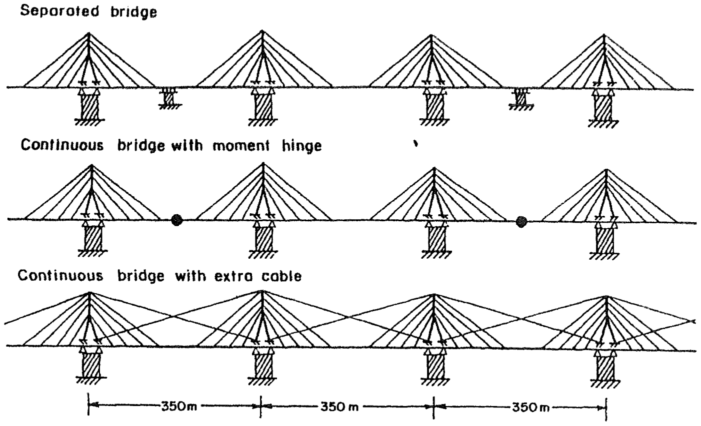


Fig. 2 Different types of multispan cable-stayed bridge systems.

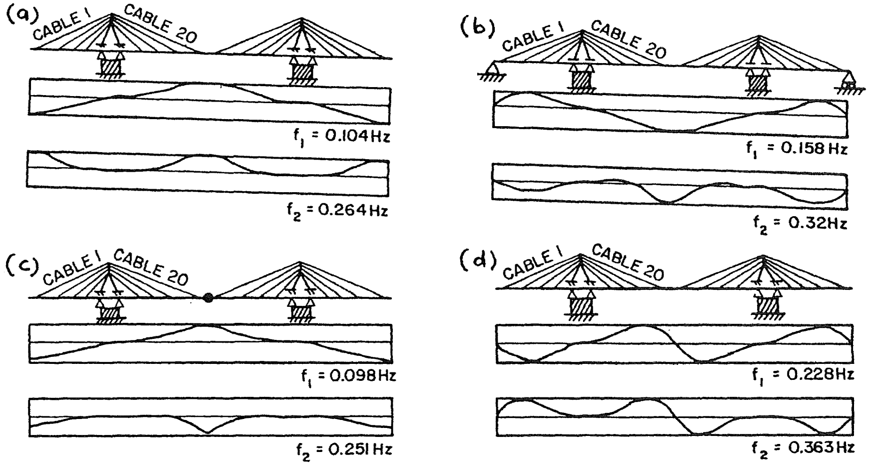


Fig. 3 Eigenfrequencies and mode shapes of different bridge schemes: (a) to (c): symmetric modes; (d) antisymmetric modes (identical for all systems).

METHODOLOGY

Assumptions A typical interior segment of the multi-span cable-stayed bridge with a span of 350 m is considered, which is modelled as a plane frame system on rigid foundation, using beam elements for the deck and pylons, and truss elements for the cables. Inertial properties of the bridge are lumped at nodes. In addition, linear-elastic material behaviour is assumed and second order effects in pylons and girder are neglected. The nonlinear effect due to sagging of the stay cables is taken into account by an equivalent modulus of elasticity [2]:

$$E_{eq} = E/[1 + (\rho g L')^2 E/(12\sigma^3)] \qquad (1)$$

where E: modulus of elasticity of straight cable;
L': horizontal projected length of cable;
ρ : mass density of cable;
g : acceleration due to gravity ($9.81\ m/s^2$); and
σ: tensile stress in cable.

The effect of time-varying cable tension on the cable stiffness is disregarded. The vertical and horizontal support movements are taken into account, which due to symmetry of the bridge will excite symmetrical and antisymmetrical modes respectively.

Equations of Motion Assuming small-amplitude oscillations, the equations of motion for a cable-stayed bridge discretized by finite elements and subjected to the same horizontal and vertical components of the ground excitation at all supports, can be written in the form [3]:

$$\underline{M}\,\underline{\ddot{u}} + \underline{C}\,\underline{\dot{u}} + \underline{K}\,\underline{u} = -\underline{M}\,\underline{E}\,\underline{\ddot{u}}_g \qquad (2)$$

where $\underline{M}$, $\underline{C}$ and $\underline{K}$ are the mass, damping and stiffness matrices respectively; $\underline{u}$ is the relative displacement vector; $\underline{E}$ is an influence matrix; and $\underline{\ddot{u}}_g$ a vector consisting of the horizontal and vertical components of the support excitation. For proportional damping, eq. (2) can be solved by the mode superposition or response spectrum methods using standard computer programs for the dynamic analysis of linear systems. In the present study the response spectrum method with the square-root-of-sum-square superposition of modal maxima has been used [1].

Bridge Systems Four different alternative types of cable-stayed bridge systems have been considered (Fig. 2):

(i) continuous bridge over total length;
(ii) continuous bridge with moment hinge in alternate spans;
(iii) separated bridge consisting of a series of cable-stayed bridges with central span of 350 m and side spans of 175 m; and
(iv) continuous bridge with extra cables connecting the pylon top with adjacent pylon at deck level.

Figure 1 shows a cross-section of the steel deck and a view of the tower together with the initial cable arrangement. In Fig. 3, the first two symmetrical and antisymmetrical mode shapes for systems (i) to (iii) are plotted. The antisymmetrical modes are the same for all systems. The mode shape along the deck is essentially the same as for the continuous bridge. The only noticeable difference is in the tower deflection. A further alternative would be a bridge with hinges (expansion joint) at the towers. In this case, the whole deck would be subjected to tension, which might cause constructional problems. In addition, individual spans would be interconnected in such a way

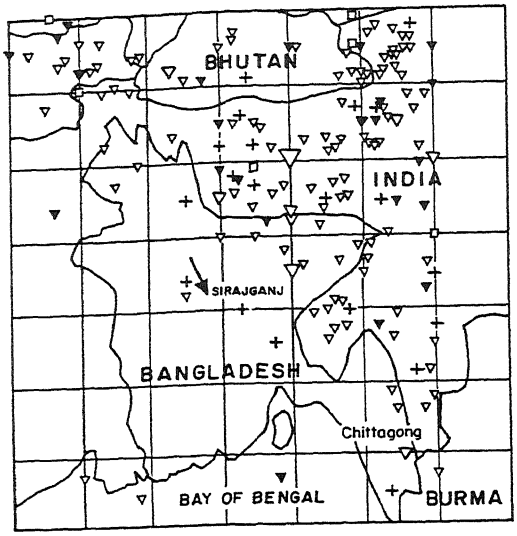
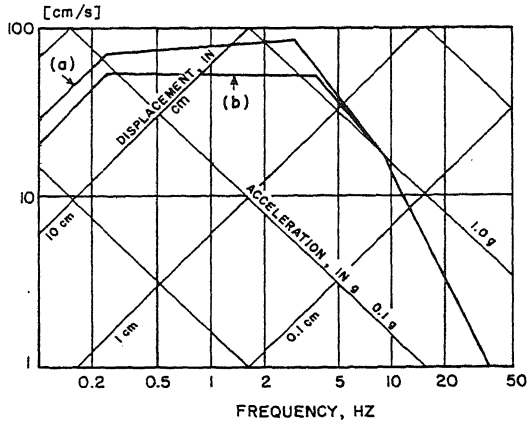


Fig. 4 Epicenters in Bangladesh and adjacent region for period 1897-1985, 230 earthquakes plotted.



(a) HORIZONTAL SPECTRA (b) VERTICAL SPECTRA

Fig. 5 Design response spectra for horizontal and vertical earthquake component for Jamuna Bridge site (damping ratio: 0.5%).

that the bridge would become susceptible to progressive failure. However, this alternative has not been investigated

Seismicity of Bridge Site At the bridge site, earthquakes may cause strong ground shaking and there is a possibility of foundation failure due to liquefaction. A catalog of earthquake data of Bangladesh and the neighbouring countries has been received from the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado (Fig. 4). 230 earthquakes which occurred between 1897 to 1985 were listed. The strongest earthquake with a magnitude of 8.7 occurred in 1897 about 200 km away from the bridge site. Based on a statistical analysis of earthquake data [3], an earthquake with average return period of 100 years has a magnitude of 7.5. The epicentral distance and focal depth have been assumed as 45 and 20 km respectively; this coincides with the location of the earthquake recorded closest to the bridge. Using McGuire's attenuation laws [3], the peak acceleration and displacement at the site are estimated as 0.216 g and 0.27 m respectively. The same peak values are assumed for the horizontal and vertical earthquake components. Subsequently, smooth design response spectra were constructed for a damping ratio of 0.5% following the U.S. Atomic Energy Commission Regulatory Guide 1.60 (Fig. 5).

DISCUSSION OF RESULTS

Dynamic Characteristics A damping ratio of 0.5% has been assumed in the dynamic analysis. This is a rather low value, which, has been selected based on measurements reported in the literature. For example, for the Annacis bridge in Canada [4] the measured damping ratios of the first flexural and torsional modes of vibration for small amplitudes up to 0.10 m were 0.46 and 0.30% respectively and cable damping ratios varied from 0.27 to 0.52%.

The fundamental eigenfrequency of the cable-stayed bridge systems (i) to (iii) is 0.104, 0.098 and 0.158 Hz respectively (symmetrical mode). The extra cable (system (iv)) has no effect on the first mode shape and eigenfrequency.

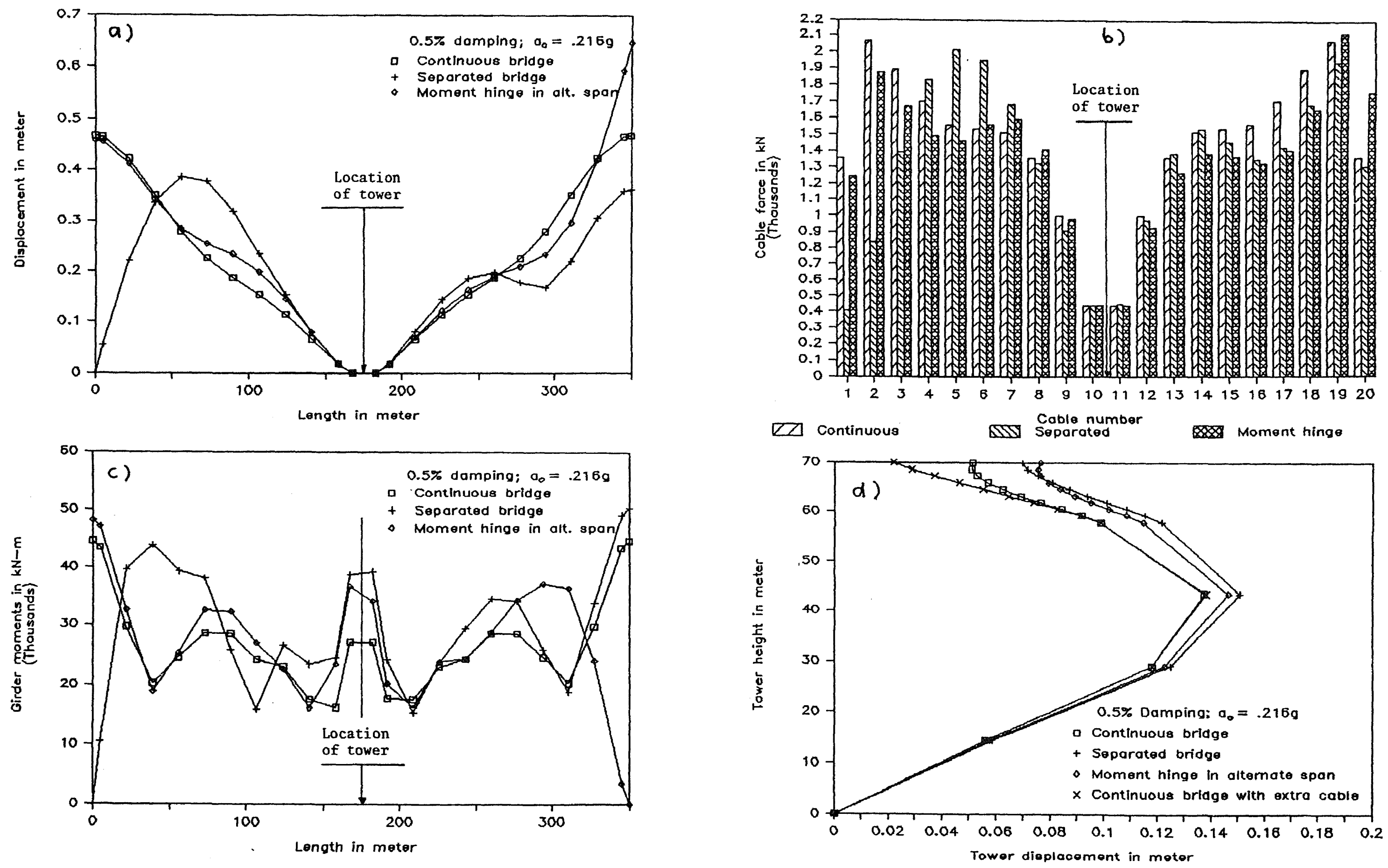


Fig. 6 Comparison of absolute maximum dynamic response for different cable-stayed bridge systems with a damping ratio of 0.5 % subjected to horizontal and vertical components of design earthquake (a: girder deflection; b: cable forces; c: bending moment in girder; d: horizontal deflection of tower)

Earthquake Response As shown in Fig. 6, the dynamic response of the bridge due to the horizontal and vertical components of the design earthquake depends on the type of cable-stayed bridge system. The maximum values of the deflection, bending moments and cable forces vary considerably. The extra cable (case (iv)), however, leads to the same response in the girder as the continuous bridge (case (i)). The only marked difference is in the deflection of the tower in the top region. In terms of the deflection response, the separated bridge has advantages compared to the other bridge schemes. Results carried out by the first author [3] indicate that the type of cable (locked-coil cable, parallel wire cable) and the cable area have only a minor effect on the overall dynamic behaviour of the bridges considered.

CONCLUSIONS

1. Due to a design earthquake with a peak acceleration of 0.216 g, the bridge with moment hinges in alternate spans and the continuous one will experience maximum deflections of 0.65 and 0.47 m respectively.
2. Dynamic cable forces in individual cables vary between 400 to 2100 kN.
3. The addition of an extra cable in a continuous bridge has a very small effect in the deck response, but the tower displacement at the top is reduced by more than 50% as compared with the other alternatives.
4. The maximum dynamic cable forces are significantly less than the initial cable forces due to prestress and dead load.
5. Multi-span cable-stayed bridges of the different designs considered in this study can easily cope with the earthquake actions at the proposed bridge site; however, a special investigation is necessary to assess the bearing capacity of the foundations under earthquake actions.
6. The earthquake behaviour of the superstructure should not be a critical factor for the selection of the optimum cable-stayed bridge system.

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