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# Optimum proportions for the design of suspension bridge

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**Abstract**

Among different types of large span bridges, the suspension type structure is one of the most common. In the present study several suspension bridges with fixed central span and variable dimensions are investigated for dead load and traffic load. Study of dynamic response due to wind and earthquake loading is outside the purview of the study. The variations in dimensions that are considered are the changes in cable sag, girder depth, cable diameter and hanger diameter. The consequences of these variations on the principal design factors such as the central and side span moments (positive and negative), shears, cable and hanger stresses and central span deflections are investigated. AASHTO lane loading for bridges is applied and STAAD/Pro software is used for the finite element analysis. The graphical charts are prepared to show the effect of different cable sag, girder depth, cable and hanger diameter on the design factors. The interpretations of the graphical charts are used to find the tentative optimum dimensionless ratios for a suspension bridge like cable sag to central span ratio, girder depth to central span ratio, cable diameter to central span ratio and hanger diameter to central span ratio. The findings of the study can be used for approximation of optimal cable sag, girder depth, cable diameter and hanger diameter for a given bridge span.



*Keywords*: Suspension Bridge, Cable Sag, Girder Depth, Cable and Hanger Diameter.

## 1. Introduction

A bridge may be defined as a means of carrying traffic over an obstruction. A complete bridge includes deck, the primary structural system that supporting the deck and spanning between the piers and the substructure (Heins et al., 1979). Suspension bridge is a type of bridge that reigns supreme for central span in excess of 610m (Heins et al., 1984). However it is generally regarded as competitive for spans down to 305m and even spans below this figure are common. A suspension bridge works by hanging (suspending) the deck of the bridge from flexible chains or ropes. The simplest form is made of wood and rope and can be seen where a simple footbridge has to hang over a crossing (Frankland, 1995). Large versions carry heavy traffic over long crossings and use very large chains or cables.

This study concentrates on the effect of different cable sag, girder depth, cable diameter and hanger diameter on the key design factors such as the design moment, design shear, cable force, hanger force and deflection. It attempts further to provide the designers a set of guidelines to select approximate optimal cable sag, girder depth, cable diameter and hanger diameter for a given span of a suspension bridge. These optimum ratios are based on numerical values of different major design parameters that are obtained from structural analysis of different suspension bridges having different dimensions of major bridge elements, i.e., cable sag, girder depth, cable diameter and hanger diameter. Economic aspects related to the variation of these structural elements are not considered in this case.

## 2. Modeling and assumptions

The task of structural modeling is arguably the most difficult one facing the structural analyst, requiring critical judgment and a sound knowledge of the structural behavior of the bridge components and assemblies (Cook, 1992). An attempt to analyze a suspension bridge and account accurately for all aspects of behavior of all the components and materials, even if their sizes and properties were known, would be virtually impossible. Simplifying assumptions are necessary to reduce the problem to a viable size.

Although a wide variety of assumptions are viable, some are more valid than the others; the ones adopted in forming a particular model will depend on the arrangement of the structure, its anticipated mode of behavior, and the type of analysis. The assumptions adopted in this study are as follows.

### *2.1 Materials*

The material of the structure and the structural components are linearly elastic. This assumption allows the superposition of actions and deflections and, hence, the use of linear methods of analysis.

### *2.2 Participating Components*

Only the primary structural components participate in the overall behavior. The effects of secondary structural components and nonstructural components are assumed to be negligible. This assumption is generally valid and yields conservative results.

*Floor Slab:* Floor slabs are assumed to be rigid in plane. This assumption causes the horizontal plane displacements of all vertical elements at a floor level to be definable in terms of the horizontal plane rigid body rotation and translation of the floor slab. Thus the number of unknown displacements to be determined in the analysis is greatly reduced. Although valid for practical purposes in most structures, this assumption may not be applicable in certain cases in which the slab plan is very long and narrow, or it has a necked region, or it consists of precast units without a topping.

*Negligible Stiffness:* Component stiffness of relatively small magnitude has been neglected. These often include, for example, the transverse bending stiffness of slabs and cables, the minor-axis stiffness, and the torsional stiffness of columns and beams. The use of this assumption should be dependent on the role of the component in the behavior of structure. For example, the contribution of a slab bending resistance to the lateral load resistance of a column-beam rigid frame structure is negligible, whereas its contribution to the lateral load resistance of a flat plate structure is vital and must not be neglected.

*Negligible Deformations:* Deformations that are relatively small, and of little influence, are neglected. These include the shear and axial deformations of beam, in-plane bending and shear deformations of floor slabs, and the axial deformations of columns.

*Finite Element Modeling:* Suspension bridge is a composite type of structure. It consists of supporting towers, bridge deck, hanger, suspension cable, anchorage etc. For the modeling purpose three types of elements, one for beams and columns, one for slabs and the other one for suspension cables and hangers are selected for the numerical analysis. The following STAAD elements have been used in the investigation,

1) Beam element
2) Cable element
3) Plate element

The details of the bridge superstructures used in the numerical modeling are shown in Table 1. Figure 1 shows a schematic view of the bridge.

*Loading Condition:* The loads considered in the present study are the superimposed dead load and live load. Two types of live load are used for bridges. These are equivalent truck loading and lane loading. One of these loads is used depending on the span length of the bridge. Up to 17 m of span equivalent truck loading produces the greater bending moment and for spans longer than 17 m the equivalent lane loading produces the greater bending moment (AASHTO). The concentrated load in equivalent lane loading is different for moment than for shear. Only one concentrated load is used in a simple span or for a positive moment in continuous spans. Two concentrated loads are used for a negative moment. AASHTO equivalent lane loading and corresponding concentrated load for shear and moment are used in the analysis of the present study.

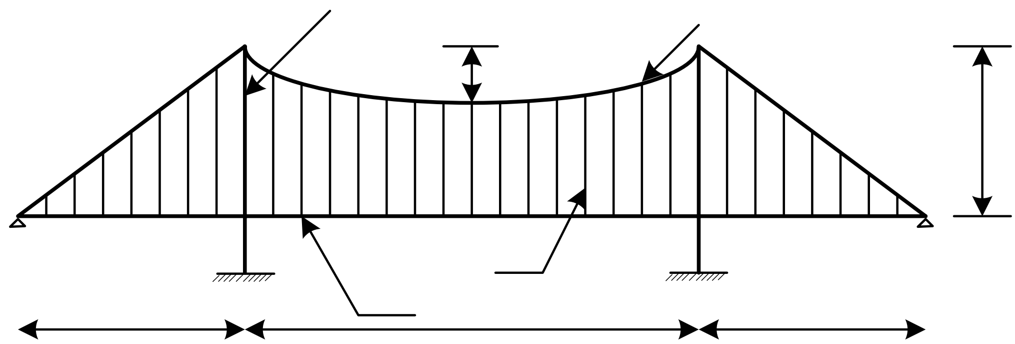

Fig. 1: Suspension Bridge

Table 1
Modeling of bridge superstructure

| Structure | Element used | Range of Parameters | Material properties |
|---|---|---|---|
| Tower | Beam element | Two vertical elements of circular cross section at each support (concrete),<br>Diameter = 3.65 m<br>Height = 91.5 m ~ 152.5 m | E = 21725 MPa<br>μ = 0.17 |
| Longitudinal girder | Beam element | I-section (steel)<br>Flange width = 1.2 m<br>Flange thickness = 600 mm<br>Web thickness = 600 mm<br>Total depth = 1.85 m ~ 4.5 m | E = 200000 MPa<br>μ = 0.3 |
| Transverse beam | Beam element | Rectangular section (concrete)<br>Width = 0.6m<br>Depth = 1.5 m | E = 21725 MPa<br>μ = 0.17 |
| Deck | Plate | Slab (concrete)<br>Thickness = 457 mm | E = 21725 MPa<br>μ = 0.17 |
| Cable | Cable | Wire (steel)<br>Diameter = 300 mm ~ 900 mm | E = 200000 MPa<br>μ = 0.3 |
| Hanger | Tension only Element | Circular solid cross section (steel)<br>Diameter = 150 mm ~ 375 mm | E = 200000 MPa<br>μ = 0.3 |

## 3. Selection of variable parameters

The major elements of a suspension bridge are cable used as flexible cord and hanger, the deck and the longitudinal girder (Connor, 1995). The cable sag has a large effect on different design factors particularly on side and central span moments. The overall cross-section of girders and diameters of cables used as hangers and flexible cords have significant effects on design moments and stresses, respectively. The deck has its effect on especially on moments and shears. In the present study all the major elements of a suspension bridge except the deck are considered as variable parameters.

## 4. Parametric study

In this study, several suspension bridges with fixed central and side spans but of variable other dimensions are analyzed. Finite element method is used here for performing the analysis. Computer software STAAD/Pro is used for this finite element analysis.

After performing the analysis, the variations of central and side span moments and shears, cable and hanger stresses and central span deflections with the changes in cable sag, girder depth, cable diameter and hanger diameter are plotted. The interpretations of the graphical charts are made to find the tentative optimum dimensionless ratios like cable sag to central span ratio, girder depth to central span ratio, cable diameter to central span ratio and hanger diameter to central span ratio for a suspension bridge.

### *4.1 Effect of cable sag*

Cable sag is one of the most important geometric features for suspension bridge, which has pronounced influence on design factors of a suspension bridge. The effect of cable sag on moments, shears, stresses and deflections are discussed below.

In the analysis different cable sags are considered for a constant central span length of 366 m with side spans of 150 m on each side of central span. The cable sag is varied from 45 m to 105 m. The width of the deck is kept constant (15 m). The other parameters kept constant are indicated in the respective figure.

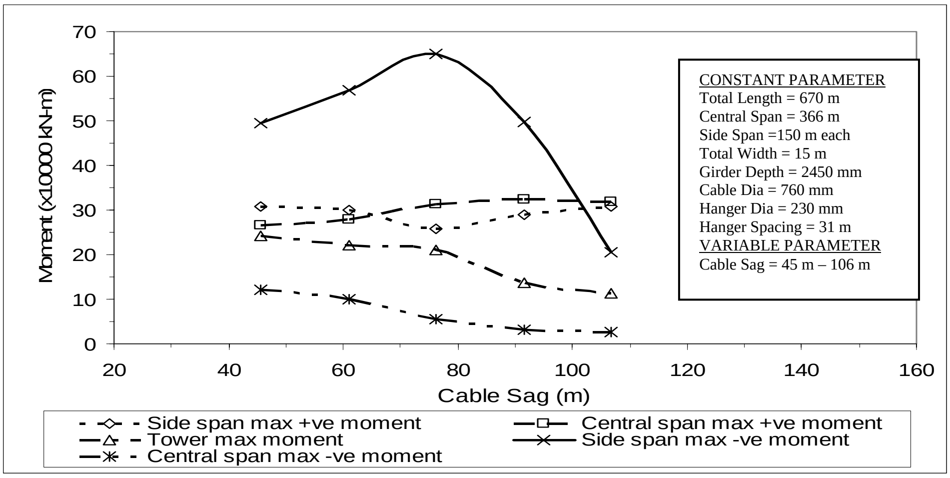


Fig. 2. Variation of maximum tower, central and side span maximum moments with cable sag

Figure 2 shows the variations of tower, side and central span moments (both positive and negative) with different cable sag. Negative moments in the central and side spans and also in the tower show significant change with variation of cable sag. The negative moment in the side span is the most dominant in magnitude and shows significant variation with changes in cable sag. Tower moment shows marked decrease in the range of 76 m to 90 m cable sag. The other negative moments decrease constantly with increase of cable sag. Positive moments, both in central and side spans, show only a moderate change with variation in cable sag.

Figure 3 shows the variation of cable and hanger stresses in both central and side spans. All the stresses decrease with an increase in cable sag. The rate of decrease in cable stress is high up to cable sag of 76 m and beyond this the rate of decrease is much lower. The hanger stresses both in side and central span decrease with the increase in cable sag.

From the above observation based on examination of figure 2 and figure 3, it appears that for large cable sag, practicable under other constraints, such as tower height, would produce the minimum design moments and stresses.

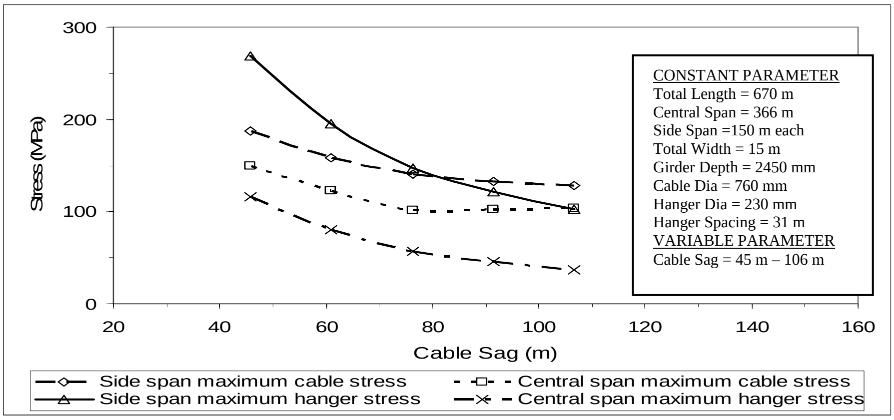


Fig. 3. Variation of central and side span maximum cable and hanger stress with cable sag

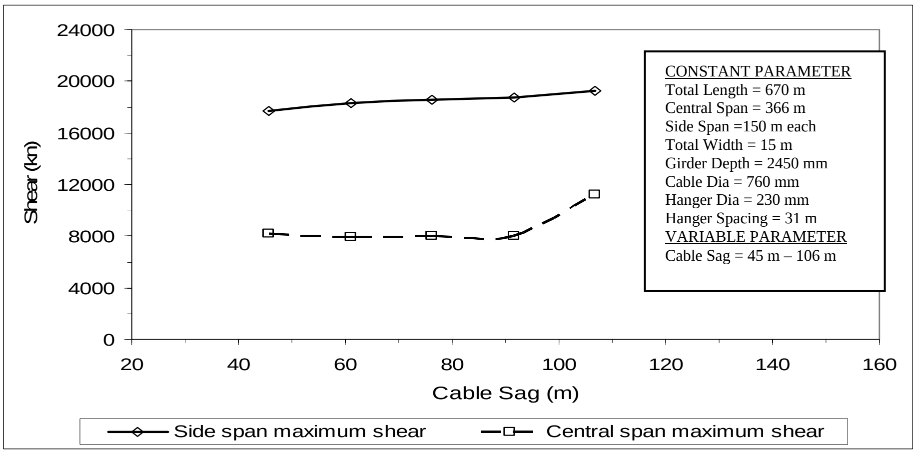


Fig. 4. Variation of central and side span maximum shear with cable sag

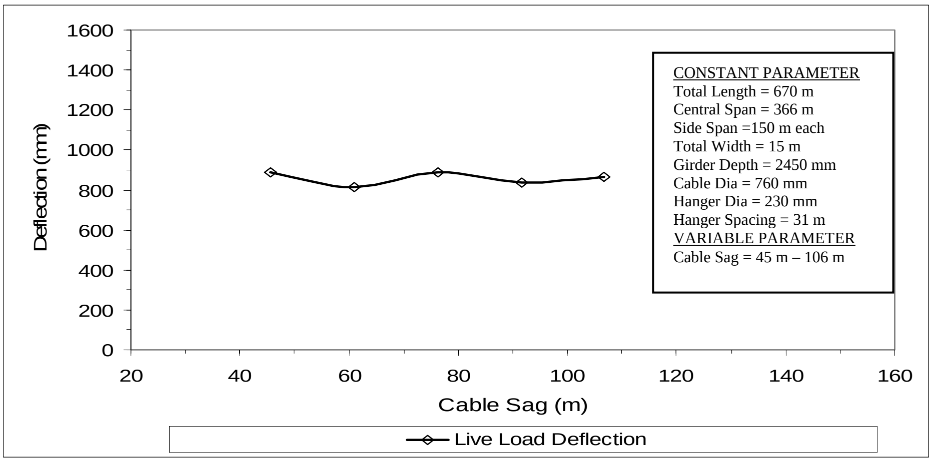


Fig. 5. Variation of maximum live load deflection with cable sag

Figure 4 shows the changes in central and side span maximum shear force. The variation in side span shear is negligible. For central span shear the change in shear with the change in cable sag is up to cable sag of 91 m is insignificant but beyond cable sag of 91 m there is a sudden increase in central span shear.

Figure 5 shows the effect of cable sag on the maximum live load deflections. It is clear from the evidence that the live load deflection remains almost constant with the variation in cable sag.

The maximum negative moment in side span has the highest magnitude at cable sag of 76 m. The maximum positive moment in the side span is the lowest at cable sag of 76 m but its value is rather small in comparison with the side span negative moment. Though the maximum positive moment is the lowest at cable sag of 45 m, at this value of cable sag both cable stress and hanger stress are quite high. Up to the sag of 76 m there is a significant decrease in cable and hanger stress. The minimum negative moment occurs at the cable sag of 106 m but the maximum positive moment also occurs at this cable sag. At cable sag of 91 m the values of all the design factors are of moderate magnitude.

From an overall consideration of all the design factors cable sag in the range of 76 m to 91 m appears to be the optimum from design point of view. The effect of shear and deflection may be ignored, as their influence is almost negligible. So, it can be tentatively concluded that the optimum cable sag to central span ratio for a typical suspension bridge is 1:4 to 1:5.

### *4.2 Effect of Girder Depth*

In this analysis, the girder depth is varied from 1800 mm to 4500 mm. The other parameters kept constant are indicated in the figure.

Figure 6 shows the variation of different moments with girder depth. Tower negative moment decreases significantly whereas the side span negative moment increases moderately with an increase in girder depth. The central span negative moment remains almost constant up to the girder depth of 3050 mm and beyond this the moment increases at considerably higher rate. Side span maximum positive moment decreases whereas central span positive moment increases with an increase in girder depth.

Figure 7 shows the variation of side and central span maximum cable and hanger stress with the change in girder depth. Side and central span maximum cable stress and central span maximum hanger stress increase at a very lower rate with the increase in girder depth. The rate of increase of side span maximum hanger stress with the increase in girder depth is relatively higher.

Figure 8 shows the variation of maximum central and side span shear with girder depth. The change in both side and central span shear with the increase in girder depth is not so significant.

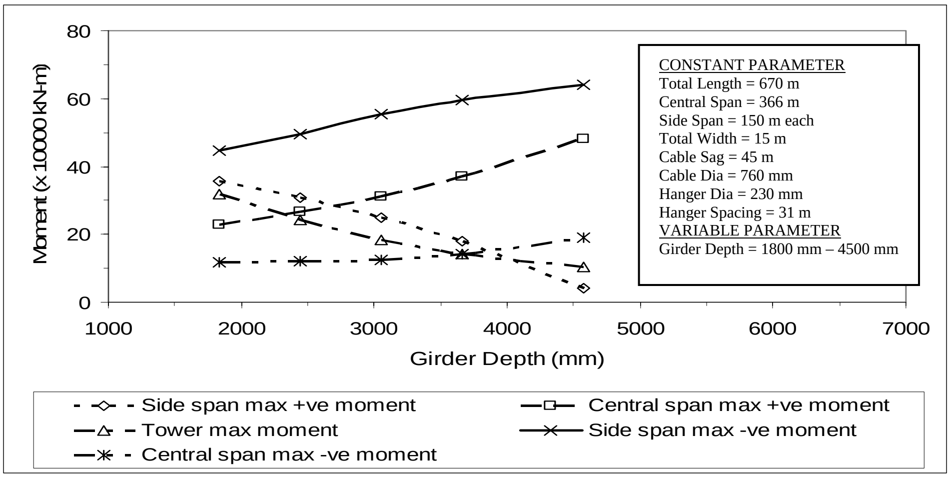


Fig. 6. Variation of maximum tower, central and side span maximum moments with girder depth

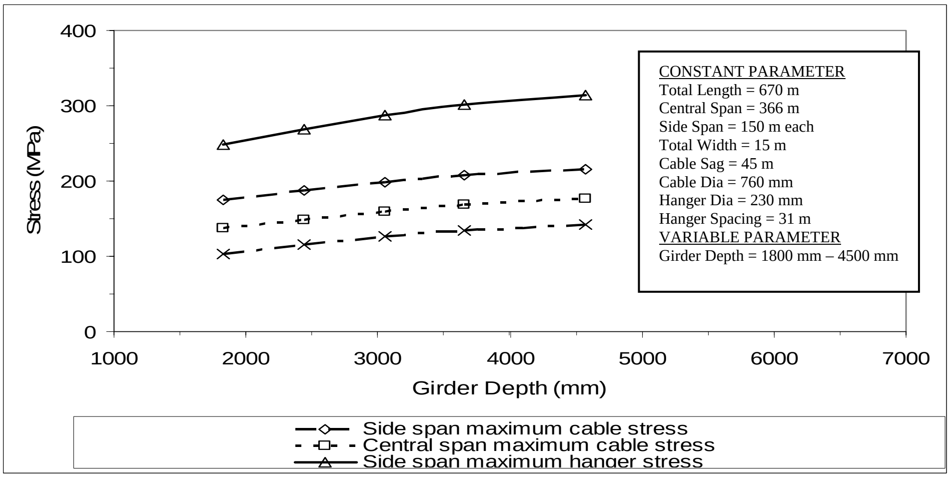


Fig. 7. Variation of central and side span maximum cable and hanger stress with girder depth

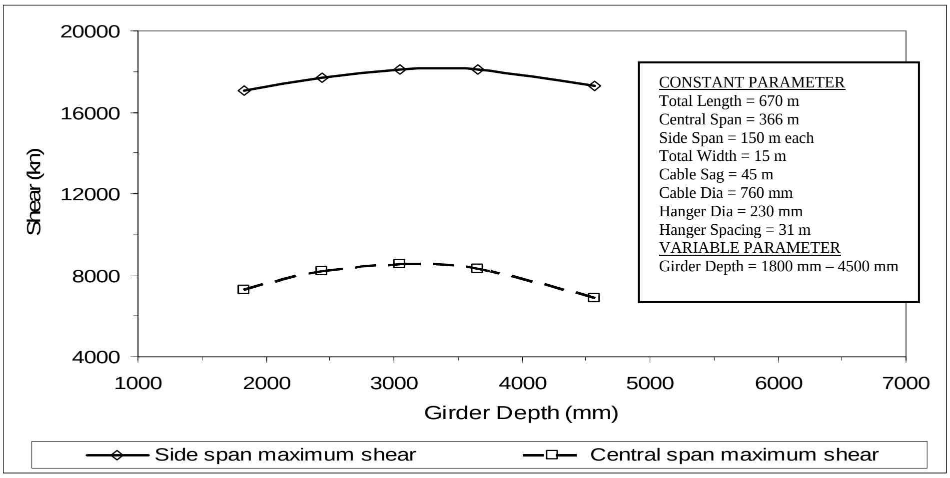


Fig. 8. Variation of central and side span maximum shear with girder depth

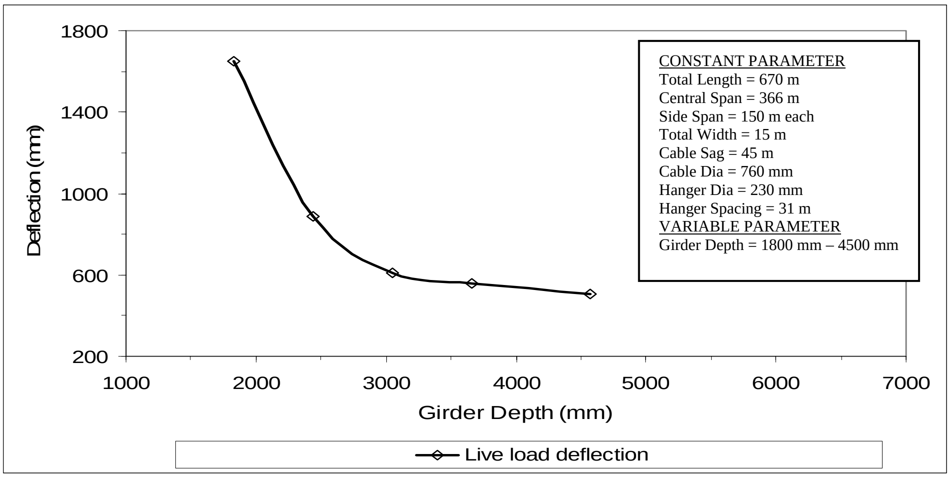


Fig. 9. Variation of maximum live load deflection with girder depth

Figure 9 shows the changes in maximum live load deflections with the change in girder depth. The deflection falls rapidly with the increase in girder depth within the range of 1800 mm to 3050 mm of girder depth. Beyond that the changes in deflection with girder depth is not significant.

Assessment of figure 6 to figure 9 reveals that increase of girder depth decreases side span positive moment, tower moment and deflection. Other design factors in general increase with increasing girder depth. The most significant effect of increase of girder depth is the considerable reduction in deflection. Thus, it appears that deflections, rather than moments and stresses, would determine the optimum depth of girders. However, in general, lower girder depths as far as practicable would result in the optimum design.

### *4.3 Effect of Cable Diameter*

In this case cable diameter is varied from 305 mm to 915 mm. The other parameters kept constant are indicated in the figure.

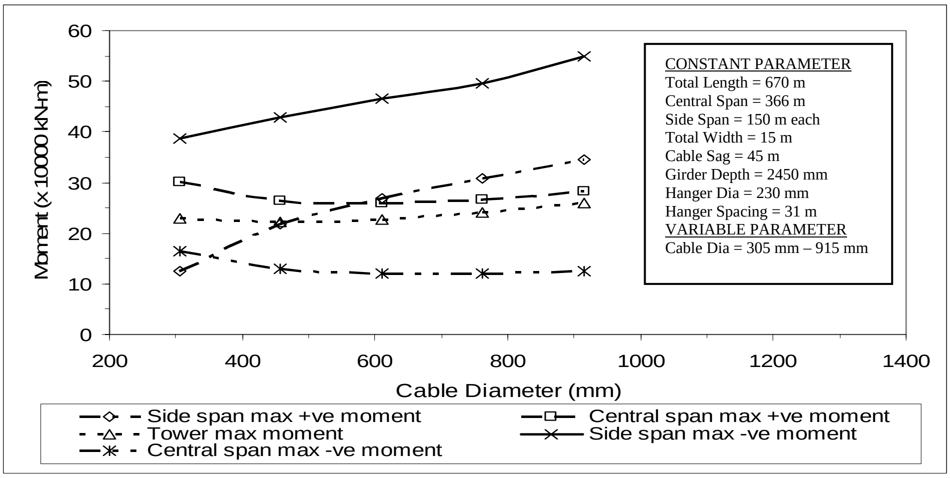


Fig. 10. Variation of maximum tower, central and side span maximum moments with cable diameter

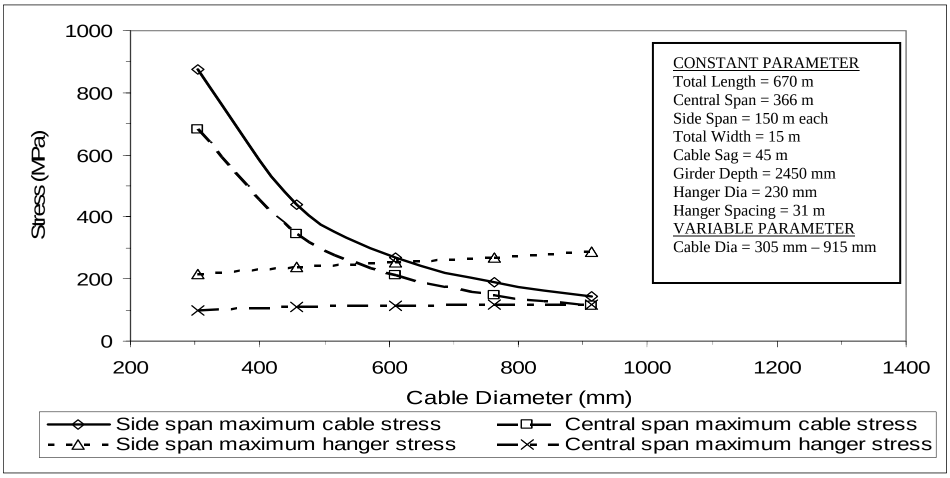


Fig. 11. Variation of central and side span maximum cable and hanger stress with cable diameter

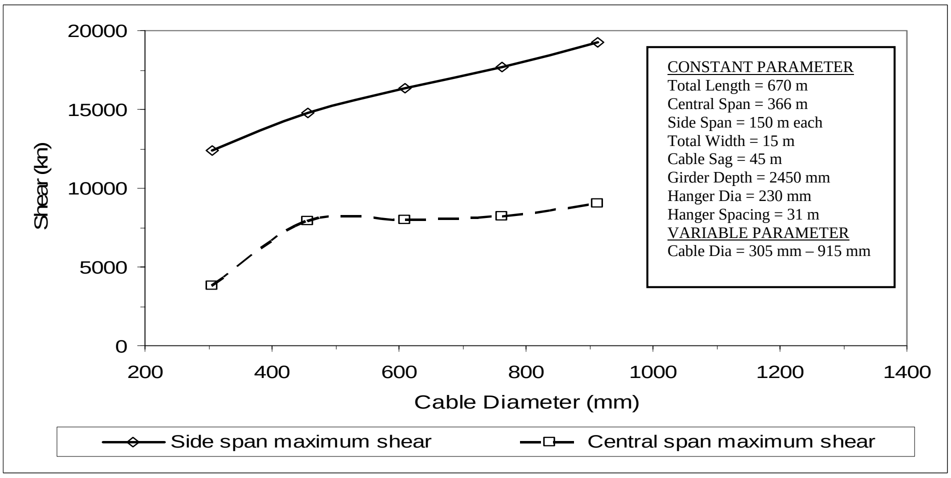


Fig. 12. Variation of central and side span maximum shear with cable diameter

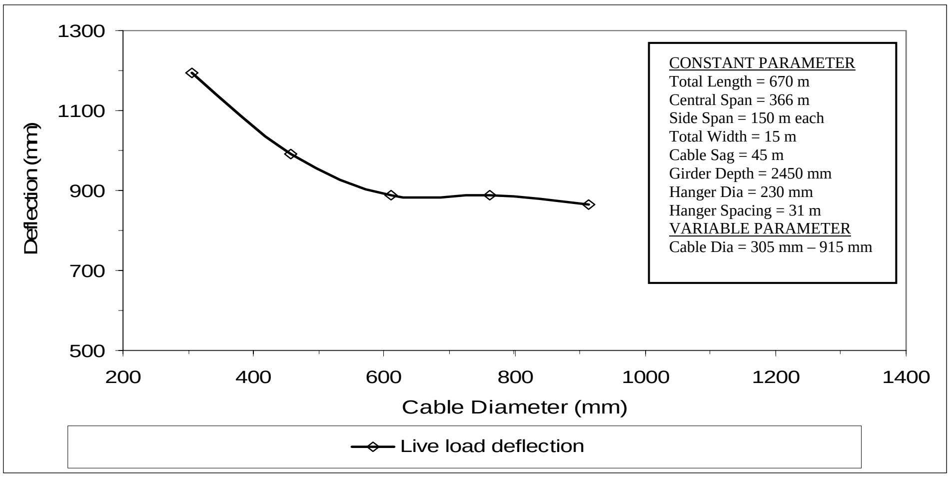


Fig. 13. Variation of maximum live load deflection with cable diameter

Figure 10 shows the variation of different moments with cable diameter. Side span positive moment and side span negative moment increase with the increase in cable diameter. The change in central span positive moment with the variation of cable diameter is not so significant. Tower negative moment and central span negative moment show small change with change in cable diameter.

Figure 11 shows effect of cable diameter on maximum cable and hanger stress. Both side and central span maximum cable stress decreases rapidly up to the cable diameter of 610 mm and then at a lower rate with the increase in cable diameter. The effect of cable diameter on side and central span maximum hanger stress is not much significant.

Figure 12 shows the variation in side and central span maximum shear with the change in cable diameter. Side span maximum shear increases almost linearly with the increase in cable diameter. In case of central span maximum shear, it increase very sharply up to the cable diameter of 455 mm and then remains almost unchanged with the change in cable diameter.

Figure 13 show the variation of maximum live load deflections with the variation of cable diameter. The live load deflection remains nearly constant with the change in cable diameter.

It is evident from figure 10 to figure 13 that cable diameter has considerable effect on side span positive and negative moment, side and central span cable stress and side span shear. Other design factors show small change with the change in cable diameter. It is apparent from the figures that cable stress rather than other factors would decide the optimum diameter of cable. The side and central span cable stress reduce sharply up to cable diameter of 610 mm and beyond this the change in stress is considerably small. Thus it appears that the cable diameter of around 610 mm would produce the optimum result from design point of view. So it can be tentatively concluded that the optimum cable diameter to central span ratio for a typical suspension bridge is around 1:50.

### *4.4 Effect of Hanger Diameter*

The hanger diameter is another important geometric feature of a suspension bridge. In this analysis hanger diameter is varied from 150 mm to 380 mm. The other parameters kept constant are indicated in the figure.

Figure 14 shows the variation of different moments with hanger diameter. Both side and central span positive moment show a little change with variation of hanger diameter. The variation of tower, side and central span negative moment with increase in hanger diameter is almost negligible.

Figure 15 shows the effect of hanger diameter on maximum cable and hanger stress. The variation in both side and central span cable stress with the change in hanger diameter is not worth mentioning. The effect of hanger diameter on maximum hanger stresses is very predominant specifically on side span hanger stress. The side span maximum hanger stress decreases very sharply with the increase in hanger diameter. The central span maximum hanger stress also decreases quite rapidly with the increase in hanger diameter but the rate of decrease is not as sharp as of side span hanger stress.

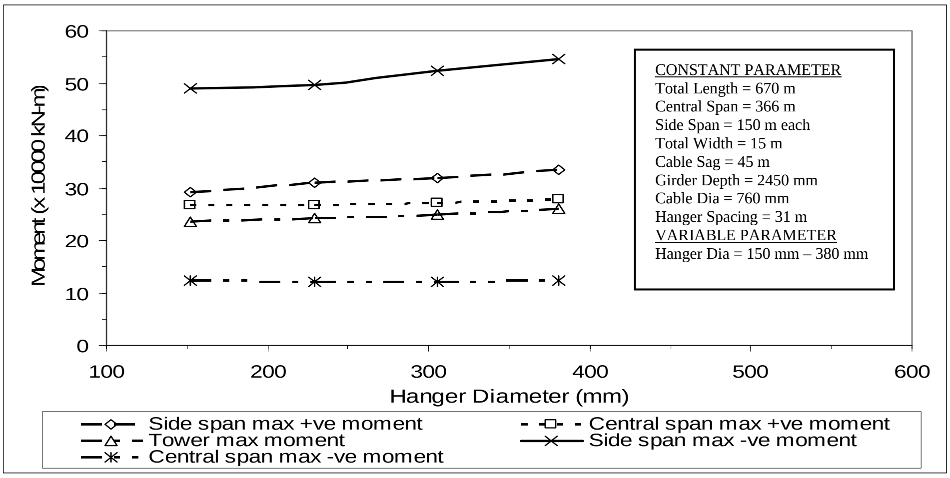


Fig. 14. Variation of maximum tower, central and side span maximum moments with hanger diameter

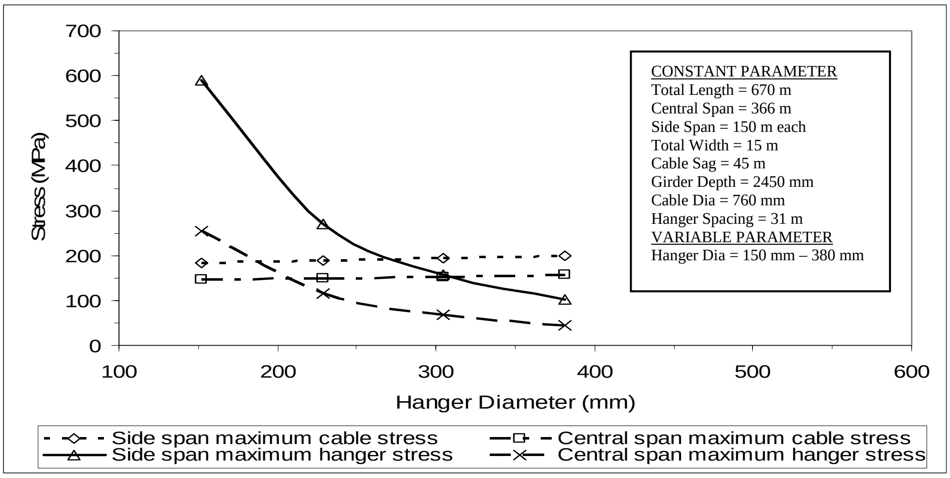


Fig 15. Variation of central and side span maximum cable and hanger stress with hanger diameter

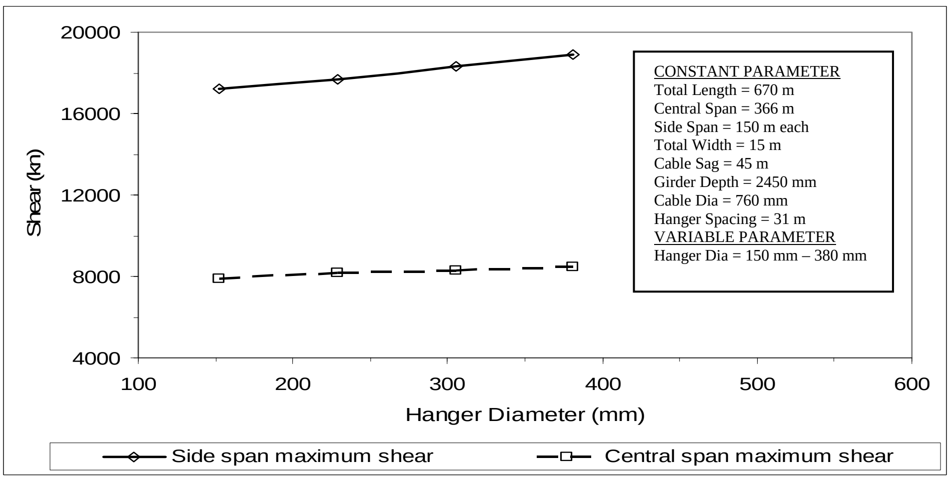


Fig. 16. Variation of central and side span maximum shear with hanger diameter

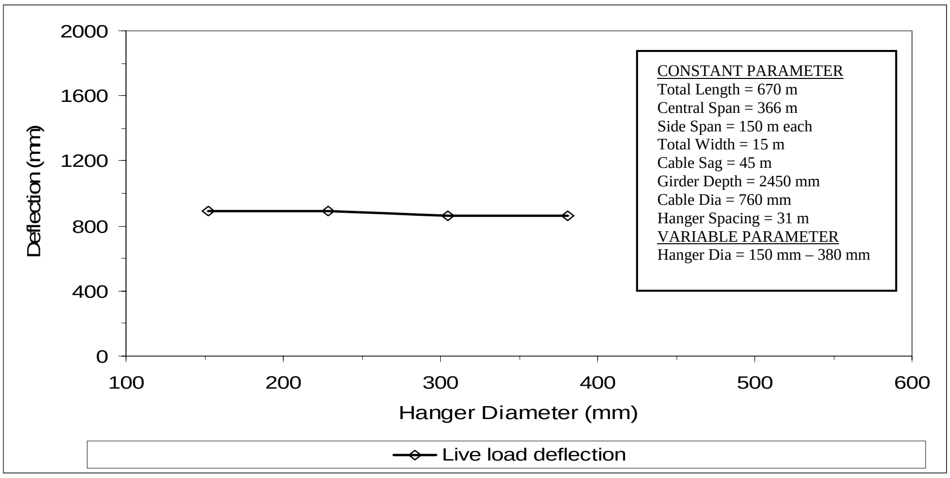


Fig. 17. Variation of maximum live load deflection with hanger diameter

Figure 16 shows the changes in maximum side and central span shear with the change in hanger diameter. Both the side span and central span maximum shear show very little change with the change in hanger diameter. Thus the effect of hanger diameter on shear is negligible.

Figure 17 shows the variation of maximum live load deflections with the change in hanger diameter. It is clearly visible from the figure 17 that the deflection remains nearly invariable with the increase in hanger diameter.

Thus, it is obvious from figure 14 to figure 17 that the effect of different hanger diameter predominantly reflects on hanger stress and cable stress. The changes in moment, shear and deflection with the changes in hanger diameter are almost negligible. Particularly hanger stress would establish the optimum hanger diameter for design consideration. From Figure 15 it can be said that hanger diameter of 305 mm produces the optimal hanger stress. So it can be tentatively concluded that the optimum hanger diameter to central span ratio for a typical suspension bridge is about 1:100.

## 5. Conclusions

From the above study the following conclusions are drawn:

The effect of variation in cable sag on side span and central span moment (both positive and negative), cable stress and hanger stress is significant. The change in shear with change in cable sag is not substantial. The effect of cable sag on bridge deflection is almost negligible. Thus, when cable sag to be selected in the design of a suspension bridge, considering its influence on moment (positive and negative), cable stress and hanger stress the optimum value of cable sag to central span should be in the range of 1.4 to 1.5.

The effect of variation in girder depth on side span and central span moment (both positive and negative) and deflection is considerable, especially on deflection. The hanger stress varies considerably with the variation of girder depth. The effects on shear and cable stress is not significant. Thus, when girder depth is under consideration in the design of a suspension bridge, the key considering parameters would be moment (both positive and negative) and deflection to select optimum girder depth and depending on the influence of girder depth on major design factors the tentative optimum ratio of girder depth to central span should be about 1:120.

The effect of variation in cable diameter on moments, side span shear and cable stress is significant. The main span shear and hanger stress changes at much lower rate with the change in cable diameter and can be ignored in selecting optimum cable diameter. The effect of cable diameter on deflection is almost negligible. Hence the principal considering parameters would be moment (both positive and negative) and cable stress to select optimum cable diameter and the tentative optimum ratio of cable diameter to central span of 1:600 can be suggested.

The effect of variation in hanger diameter on hanger stress and cable stress is considerable. The variation in moments, shears and deflection is not significant and almost negligible and can easily be ignored. So hanger and cable stress should be considered in selecting the hanger diameter of a suspension bridge during design. Considering the influence of hanger diameter on hanger and cable stress, a tentative optimum ratio of 1:1200 of hanger diameter to central span can be selected.

Design graphs are also prepared for different cable sag, girder depth, cable diameter and hanger diameter of a particular type of suspension bridge to assess the effect of these parameter on different design factors of a suspension bridge. The suggested optimum ratios can be used for any suspension bridge as these optimum ratios are dimensionless quantity. Using these design graphs and optimum ratios one can easily choose tentative optimum design parameters for a suspension bridge if the central span of the suspension bridge is known. It is noteworthy to mention that these optimum ratios are just a guideline for selecting different design parameters of a suspension bridge during the initialization of its construction but these parameters may change depending on further in depth analysis, geometry of the bridge, local conditions etc.

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