

1. Introduction

The construction of bridges has played a major part in the development of our society and civilization. The bridges nowadays are analyzed and designed very cautiously. The analysis part of the bridge system is much more impotent than the design part. The advancement in the stability analysis of the bridge system has reached the behaviour study of the abutments and the wing walls. Abutments are vertical structures, classified as substructure component of a bridge system. They are used to retain the earth behind the structure. The abutments are subjected to the dead loads, live loads from the bridge superstructure, and the lateral pressures mainly from the approach embankment. In a bridge, the wing walls are adjacent to the abutments and act as retaining walls. They can be parallel to the bridge deck or perpendicular or may at some angle, depending on the requirements. They are generally constructed of the same material as those of abutments. The walls can be independent or integral with the abutment wall. The integral wing walls have an influence on the behaviour of the abutment wall; hence, the length, thickness, etc., parameters are adopted carefully after proper design and checks. Wing walls are provided at both ends of the abutments to retain the earth filling of the approaches. The studies about configurations of the wing walls affecting the behaviour of the bridges integral with abutment have shown that the connection between the wing wall and the abutment creates a better stable system.
that can resist loads better [1–3]. Some of the studies are in the direction of seismic resistance of the integral abutment bridge and also the backfill soil effect [4–8].

The material used in the construction of the bridge system is also a very important part of the study and needs to explore more and more. When China clay (kaolin) is heated at a higher temperature, a by-product called metakaolin is created. Metakaolin is a very effective pozzolanic substance used in concrete. Metakaolin was effectively included in the concrete used to build a number of sizable dams in Brazil in the 1960s. To enhance certain qualities of cement concrete, metakaolin is utilized in place of OPC. The current hot topic in the construction material industry is the metakaolin geopolymer concrete. MGPC is a green construction material as it does not contain cement, and hence, the emission of CO₂ and other GHGs is nil. The use of this material in the construction of any big structure needs a thorough investigation and tests in the laboratories to prove its mechanical and engineering abilities [9–11]. The cube strength and other engineering properties of this material are calculated by various researchers, and here, in this study, those values are used to create the material in the software and then the material is used in further study.

2. Modelling and Analysis

2.1. General Design Data. This study will be done by analyzing an abutment with connected wing walls. The geometric parameters of the walls are calculated and are listed as follows:

(1) The density of soil, assumed as surcharge and backfill, is taken as 18 kN/m³, and the safe bearing capacity of the soil is taken as 200 kN/m².

(2) The thickness of the walls is taken from cantilever wall design, which has given the thickness of the walls according to their height. Here, in the problem, for lesser complication in analysis, the thickness of wing walls and the abutment wall is taken the same. So, the thickness of the walls for different heights is as follows:

2.1. For walls of 8 meters in height, the thickness of walls varies from 400 mm at the top to 800 mm at the bottom
2.2. For walls of 10 meters in height, the thickness of walls varies from 500 mm at the top to 1000 mm at the bottom
2.3. For walls of 12 meters in height, the thickness of walls varies from 600 mm at the top to 1200 mm at the bottom

(3) The whole system of abutment with connected wing walls is taken on rigid foundation.

(4) The thickness of the deck slab is taken from an existing bridge, and it is 950 mm at the center gradually reducing to 800 mm at the edges.

(5) The span of the bridge is taken as 11 meters, and it is considered that it has unyielding supports with no bearings.

(6) The loads are considered as per the IRC-6:2016.

2.2. Cases for Analysis. The variations considered in the basic parameters for analysis are as follows:

(1) Wall Height—8 meters, 10 meters, and 12 meters
(2) Wing Wall Length—3 meters, 5 meters, and 7 meters
(3) Width of Abutment Wall—8 meters for 2-lane bridge and 15 meters for 4-lane bridge
(4) Live Loads—70R tracked vehicular load and class A vehicular load

So, as per the variations taken for analysis, there will be total 36 cases.

2.3. Model Characteristics

(i) The modelling and analysis of the problem are done using the STAAD Pro V8i SS6 software.

(ii) The model is made using 4-noded plate element for all the members, i.e., abutment wall and wing walls, and assigned the material property as concrete, as shown in Figure 1.

(iii) The width of the abutment wall is taken as 8 meters and 15 meters for 2-lane and 4-lane models, respectively.

(iv) The plates are finely meshed using the quadrilateral meshing feature of the software. So, to get better accuracy in the results, the mesh size is kept at 0.5 × 0.5 meter.

(v) The thickness of plates is varying from top to bottom in every model and is assigned gradually to every mesh strip from top to bottom, so as to provide the required shape of the walls.

(vi) The support for all the bottom nodes of the walls is assigned as a fixed support, as it is taken in the problem that the base of the walls is rigid.

(vii) A beam of size 100 × 100 mm is modelled over the abutment wall, as shown in Figure 1.

(viii) It is assigned the material property as metakaolin geopolymer concrete, which is created in the software, and provided the required data such as Young’s modulus and Poisson’s ratio from previous researches [12–14], as shown in Figure 2. This is modelled to allow the application of vertical and horizontal loads on the abutment wall.

2.4. Load Calculations

(i) All the loads, except the soil and wind loads, are applied on the beam. The soil and wind loads are applied to the plates directly.

(ii) The load combinations are formed as per IRC-6: 2016, Table 1, Page No.-7.
(iiii) Dead load \( (G) \) is calculated per unit width of the abutment. The calculation is shown as follows—span of bridge = 11 m.
Average thickness of deck slab = \((950 + 800)/2 = 875 \text{ mm}\) = 0.875 m
Width of abutment wall = 8 m (for 2 lane) and 15 m (for 4 lane)
Therefore, \( G = (0.875 \times 11 \times (8 \text{ or } 15) \times 25)/(2 \times (8 \text{ or } 15)) = 120.3125 \text{ kN/m} = 120.5 \text{ kN/m} \) (taken)

(vii) “G” is applied uniformly over the width of the abutment wall, and self-weight of the whole structure is also added.

(viii) Live load \( (Q) \) is calculated for 70R[T] and class A loading by taking the dispersion of load through the depth of the deck slab, i.e., 800 mm at the supporting edge. Also, for the maximum reaction to being generated, the loading vehicle is kept at the edge of the span.
So, \( Q = 277.3 \text{ kN} \) over 1.764 m dispersed width of the driving chain of 70R[T] loading vehicle.
Therefore, \( Q = (277.3/1.764) = 157.2 \text{ kN/m} \) (taken), for 70R[T] loading.
Similarly, for class A vehicular load—\( Q = 260.9 \text{ kN} \) over 1.304 m dispersed width of the wheel of class A loading vehicle.
Therefore, \( Q = (260.9/1.304) = 200.08 \text{ kN/m} \) (taken), for class A loading.

(vi) “Q” is applied over the width of the abutment wall as per IRC-6:2016, Table No.-6A, Page No.-17.

(vii) Vehicle impact load (Qim) is applied as per the following:
IRC-6:2016, Clause 208.3 b) i) 1), Page No.-30, i.e., 10% of \( Q \), for 70R[T] loading
IRC-6:2016, Clause 208.2 i., Page No.-30, i.e., \((4.5/(6+\text{span})) \times Q\), for class A loading
“Qim” is applied in the same manner as “Q”

(viii) Wind load \( (w) \) as per IRC-6:2016, Table No.-12, Page No.-33. It is applied directly on plates in all the three exposed directions.

(ix) Braking load \( (Fb) \) is the longitudinal force, applied over the abutment wall as per the following:
IRC-6:2016, Clause 211.1 Note and Clause 211.2 a), Page No.-42, for 2 lane
IRC-6:2016, Clause 211.1 Note and Clause 211.2 b), Page No.-42, for 4 lane

(x) Bearing friction load \( (Fr) \) is applied as per IRC-6:2016, Clause 211.5.1.2, Page No.-44.

(xi) Earth pressure load \( (Fep) \) consists of soil surcharge and earth pressure loads, and these are also applied directly to the plates.
Soil surcharge load = \( k \times \gamma \times \text{heq} \) (as per IRC-6:2016, Clause 214.1.1.3, Page No.-49) = 0.33 \times 18 \times 1.2 = 7.128 \text{ kN/m}^2
Earth pressure load = \( K_a \times \gamma \times (\text{height of wall}) \), at bottom = 0.33 \times 18 \times 8 = 47.52 \text{ kN/}
\text{m}^2 = 0.33 \times 18 \times 10 = 59.4 \text{ kN/}
\text{m}^2 = 0.33 \times 18 \times 12 = 71.28 \text{ kN/m}^2

3. Results
3.1. Results. All the models were analyzed, and the results are presented in the form of tables in this section. The locations
where the vertical moments (My), horizontal moments (Mx), and torsional moments (Mxy) are taken in the model are shown in Figure 3.

3.2. Comparison of Moments. 3.3. Deflected Shapes of Models. The typical deflected shape of the walls under the provided loading is shown in Figure 4.

4. Discussion

4.1. Variation in Vertical Moments in Abutment Wall
(i) It is evident from Tables 1 and 2 that for 2-lane width the vertical moment (My) in the abutment wall decreases rapidly as the length of the wing walls increases from 3 m to 7 m. It is in the range of 28–40%, 40–57%, and 50–68% for height of walls of 8 m, 10 m, and 12 m, respectively, for both the types of loadings.

(ii) It is observed from Tables 3 and 4 that for 4-lane width the vertical moment (My) in the abutment wall decreases gradually as the length of the wing walls increases from 3 m to 7 m. It is in the range of 7–10%, 14–20%, and 20–30% for height of walls of 8 m, 10 m, and 12 m, respectively, for both the types of loadings.

4.2. Variation in Horizontal Moments in Abutment Wall
(i) It is indisputable from Tables 5 and 6 that for 2-lane width the mid. horizontal moment (Mx(mid)) in the abutment wall increases rapidly as the length of the wing walls increases from 3 m to 7 m. It is in the range of 11–18%, 24–40%, and 38–59% for the

| Table 1: Comparison of My(max) in abutment wall for 2-lane-70R[T] models. |
|-------------------------------------------------|
| Length of wing walls | 3 m | 5 m | 7 m | % Variation in My(max) |
|----------------------|-----|-----|-----|-----------------------|
| Height of walls (m)  |     |     |     |                       |
| 3 m to 5 m          | 217 | 157 | 132 | 27.65                 |
| 3 m to 7 m          | 310 | 185 | 133.5 | 40.32                |
| 3 m to 7 m          | 467.5 | 239.5 | 150 | 48.77                |

| Table 2: Comparison of My(max) in abutment wall for 2-lane-class A models. |
|-------------------------------------------------|
| Length of wing walls | 3 m | 5 m | 7 m | % Variation in My(max) |
|----------------------|-----|-----|-----|-----------------------|
| Height of walls (m)  |     |     |     |                       |
| 3 m to 5 m          | 252 | 183 | 155.5 | 27.38                |
| 3 m to 7 m          | 345.5 | 205 | 149.5 | 40.67                |
| 3 m to 7 m          | 510 | 259.5 | 163.5 | 49.12                |

Figure 3: Location of moments.
Figure 4: Deflected shape of models. (a) Model for 3 m long wing wall. (b) Model for 5 m long wing wall. (c) Model for 8 m long wing wall.

Table 3: Comparison of My(max) in abutment wall for 4-lane-70R[T] models.

| Length of wing walls | 3 m | 5 m | 7 m | % variation in My(max) |
|----------------------|-----|-----|-----|------------------------|
| Height of walls (m)  | 3 m | 5 m | 7 m | 3 m to 5 m | 3 m to 7 m |
| 8                    | 544.5 | 504 | 486.5 | 7.44 | 10.65 |
| 10                   | 806 | 694 | 643 | 13.90 | 20.22 |
| 12                   | 1139.5 | 901 | 793.5 | 20.93 | 30.36 |

Table 4: Comparison of My(max) in abutment wall for 4-lane-class A models.

| Length of wing walls | 3 m | 5 m | 7 m | % variation in My(max) |
|----------------------|-----|-----|-----|------------------------|
| Height of walls (m)  | 3 m | 5 m | 7 m | 3 m to 5 m | 3 m to 7 m |
| 8                    | 726 | 678 | 658 | 6.61 | 9.37 |
| 10                   | 970 | 840 | 783 | 13.40 | 19.28 |
| 12                   | 1291.5 | 1021 | 902.5 | 20.94 | 30.12 |

Table 5: Comparison of Mx(mid) in abutment wall for 2-lane-70R[T] models.

| Length of wing walls | 3 m | 5 m | 7 m | % Variation in Mx(mid) |
|----------------------|-----|-----|-----|------------------------|
| Height of walls (m)  | 3 m | 5 m | 7 m | 3 m to 5 m | 3 m to 7 m |
| 8                    | 65.5 | 58.5 | 54 | 10.69 | 17.56 |
| 10                   | 81.5 | 62 | 49.5 | 23.93 | 39.26 |
| 12                   | 95.5 | 60 | 39.5 | 37.17 | 58.64 |
(ii) It is noticeable from Tables 7 and 8 that for 2-lane width the edge horizontal moment ($M_{x(recipe)}$) in the abutment wall decreases gradually as the length of the wing walls increases from 3 m to 7 m. It is in the range of 39–62%, 53–85%, and 66–106% for the height of walls of 8 m, 10 m, and 12 m, respectively, for both the types of loadings.

(iii) It is visible from Tables 9 and 10 that for 4-lane width the mid. horizontal moment ($M_{x(mid)}$) in the abutment wall increases gradually as the length of the wing walls increases from 3 m to 7 m. It is in the range of 4–9%, 8–11%, and 6–3% for the height of walls of 8 m, 10 m, and 12 m, respectively, for both the types of loadings.

(iv) It is crystal clear from Tables 11 and 12 that for 4-lane width the edge horizontal moment ($M_{x(edge)}$)
### Table 10: Comparison of Mx(mid) in abutment wall for 4-lane-class A models.

| Height of walls (m) | 3 m | 5 m | 7 m | % variation in Mx(mid) |
|--------------------|-----|-----|-----|------------------------|
| 8                  | 85.5| 91.5| 93.5| 7.02                   |
| 10                 | 152.5| 161.5| 163 | 5.90                   |
| 12                 | 225.5| 234 | 231.5| 3.77                   |

### Table 11: Comparison of Mx(edge) in abutment wall for 4-lane-70R[T] models.

| Height of walls (m) | 3 m | 5 m | 7 m | % variation in Mx(edge) |
|--------------------|-----|-----|-----|-------------------------|
| 8                  | 112.5| 160 | 181.5| 42.22                   |
| 10                 | 151.5| 240.5| 283 | 58.75                   |
| 12                 | 189 | 328.5| 401 | 73.81                   |

### Table 12: Comparison of Mx(edge) in abutment wall for 4-lane-class A models.

| Height of walls (m) | 3 m | 5 m | 7 m | % variation in Mx(edge) |
|--------------------|-----|-----|-----|-------------------------|
| 8                  | 142.5| 195.5| 221 | 37.19                   |
| 10                 | 173.5| 270.5| 318.5| 55.91                   |
| 12                 | 208 | 348 | 428 | 67.31                   |

### Table 13: Comparison of My(max) in wing walls for 2-lane-70R[T] models.

| Height of walls (m) | 3 m | 5 m | 7 m | % variation in My(max) |
|--------------------|-----|-----|-----|------------------------|
| 8                  | 84.5| 302 | 455 | 257.40                  |
| 10                 | 126 | 442.5| 715.5| 251.19                  |
| 12                 | 174 | 600.5| 1013.5| 245.11                 |

### Table 14: Comparison of My(max) in wing walls for 2-lane-class A models.

| Height of walls (m) | 3 m | 5 m | 7 m | % variation in My(max) |
|--------------------|-----|-----|-----|------------------------|
| 8                  | 108 | 279.5| 441 | 158.80                  |
| 10                 | 109.5| 424.5| 699 | 287.67                  |
| 12                 | 163.5| 613 | 1000| 274.92                  |
### Table 15: Comparison of $M_x$ (edge) in wing walls for 2-lane-70R[T] models.

| Length of wing walls | Height of walls (m) | 3 m | 5 m | 7 m | % variation in $M_x$ (edge) |
|----------------------|---------------------|-----|-----|-----|-----------------------------|
|                      |                     |     |     |     | 3 m to 5 m | 3 m to 7 m |
| 8                    |                     | 87.5| 119 | 133 | 36.00         | 52.00      |
| 10                   |                     | 116 | 172.5| 200 | 48.71         | 72.41      |
| 12                   |                     | 147 | 237 | 285 | 61.22         | 93.88      |

### Table 16: Comparison of $M_x$ (edge) in wing walls for 2-lane-class A models.

| Length of wing walls | Height of walls (m) | 3 m | 5 m | 7 m | % variation in $M_x$ (edge) |
|----------------------|---------------------|-----|-----|-----|-----------------------------|
|                      |                     |     |     |     | 3 m to 5 m | 3 m to 7 m |
| 8                    |                     | 99.5| 128 | 144.5| 28.64        | 45.23      |
| 10                   |                     | 114 | 174 | 203.5| 52.63        | 78.51      |
| 12                   |                     | 142.5| 235 | 284.5| 64.91        | 99.65      |

### Table 17: Comparison of $M_y$ (max) in wing walls for 4-lane-70R[T] models.

| Length of wing walls | Height of walls (m) | 3 m | 5 m | 7 m | % variation in $M_y$ (max) |
|----------------------|---------------------|-----|-----|-----|-----------------------------|
|                      |                     |     |     |     | 3 m to 5 m | 3 m to 7 m |
| 8                    |                     | 42.5| 237.5| 416 | 458.82        | 878.82     |
| 10                   |                     | 67.5| 307 | 620 | 354.81        | 818.52     |
| 12                   |                     | 91.5| 374.5| 843 | 309.29        | 821.31     |

### Table 18: Comparison of $M_y$ (max) in wing walls for 4-lane-class A models.

| Length of wing walls | Height of walls (m) | 3 m | 5 m | 7 m | % variation in $M_y$ (max) |
|----------------------|---------------------|-----|-----|-----|-----------------------------|
|                      |                     |     |     |     | 3 m to 5 m | 3 m to 7 m |
| 8                    |                     | 71 | 193 | 390 | 171.83        | 449.30     |
| 10                   |                     | 102 | 241 | 573.5| 136.27        | 462.25     |
| 12                   |                     | 126 | 298.5| 782.5| 136.90        | 521.03     |

### Table 19: Comparison of $M_x$ (edge) in wing walls for 4-lane-70R[T] models.

| Length of wing walls | Height of walls (m) | 3 m | 5 m | 7 m | % variation in $M_x$ (edge) |
|----------------------|---------------------|-----|-----|-----|-----------------------------|
|                      |                     |     |     |     | 3 m to 5 m | 3 m to 7 m |
| 8                    |                     | 118 | 164.5| 185.5| 39.41         | 57.20      |
| 10                   |                     | 158 | 245.5| 286.5| 55.38         | 81.33      |
| 12                   |                     | 196.5| 334.5| 405 | 70.23         | 106.11   |
in the abutment wall remains almost constant as the length of the wing walls increases from 3 m to 7 m. It is in the range of 37–62%, 56–87%, and 67–112% for the height of walls of 8 m, 10 m, and 12 m, respectively, for both the types of loadings.

4.3. Variation in Vertical Moments in Wing Walls. It is clearly relevant from the table [9, 10, 15, 16] that "My" is in the range of 250–500% for 2-lane width and 400–800% for 4-lane width, for both the types of loadings (Tables 13–20).

4.4. Variation in Horizontal Moments in Wing Walls. It is observed from the table [11, 17–19] that "Mx(edge)" is in the range of 30–52%, 49–79%, and 62–100% for the height of walls of 8 m, 10 m, and 12 m, respectively, for 2-lane width, and 26–58%, 41–82%, and 65–105% for the height of walls of 8 m, 10 m, and 12 m, respectively, for 4-lane width.

5. Conclusions
The results obtained from the present are thoroughly studied, and from the scope of this work, the following conclusions are drawn:

(i) The connectivity of the abutment and the wing walls induces horizontal moments, which are very critical at the connecting edge. So, the horizontal moments in the walls need to be taken under design considerations.

(ii) As a result of the connection of the wing walls and the abutment wall, the vertical moments in abutment wall decrease and in wing walls it increases with the change in the length of the wing walls.

(iii) The vertical moments in the abutment wall are very much affected by the change in the length of wing walls. Variation in moments is in a range of 28–68% for 2-lane width and 7–30% in the case of 4-lane width.

(iv) The connection between the wing walls and the abutment wall introduces horizontal moments in the abutment wall. Variation in mid-span horizontal moments is in a range of 10–60% in 2-lane width, whereas it is 5–10% in 4-lane width. However, these variations are in a range of 40–100% in horizontal edge moments.

(v) In the wing walls, variation in vertical moments with the change in length of the wing walls is in a range of 250–500% for 2-lane width and 400–800% in 4-lane width.

(vi) The use of the MGPC as the material of both the walls showed satisfactory results [20–23].

Abbreviations
CC: Cement concrete
CO₂: Carbon dioxide
GHGs: Greenhouse gases
MGPC: Metakaolin geopolymer concrete.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
There are no conflicts of interest among the authors.

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