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COMPARISON OF MODAL BEHAVIOUR OF INTEGRAL ABUTMENT BRIDGE WITH AND WITHOUT SOIL STRUCTURE INTERACTION

Sreya Dhar[1]**, Kaustubh Dasgupta**[2]

[1, 2] Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

Integral abutment bridges (IAB) have gained popularity over past few years. The main advantage of IAB over conventional bridges is the absence of any bearing at the deck-abutment junction which leads to reduced possibility of unseating of bridge deck during strong earthquake shaking. The seismic response of bridges with integral abutments depends significantly on the abutment-soil interaction in the longitudinal direction and soil-pile interaction in the transverse direction. In the present study, the modal behaviour of IAB is investigated with and without the presence of Soil Structure Interaction (SSI). The soil flexibility for soil-pile and abutment-backfill interactions is represented by springs. This leads to significant increase in the overall flexibility of the bridge system as compared to the model with all the Degrees Of Freedom (DOFs) restrained at the bottom of pier. Due to higher longitudinal stiffness contributed by both the deck and the abutments, the SSI bridge model shows complete longitudinal mode of vibration in higher mode. By removing the abutments and end spans of the deck, the first longitudinal mode of vibration occurs in one of the lower modes. Hence, numbers of spans in the bridge play an important role in the modal behavior of the bridge. The importance of SSI in modal analysis highlights its need for inclusion in the seismic design of IABs.

Keywords: *Integral Abutment Bridge, Soil-Structure Interaction, Modal Analysis.*

1 Introduction

Soil-structure interaction is an important aspect in the investigations of structural behaviour for carrying out performance based earthquake engineering studies. Particularly, in the case of bridges, SSI along with multi-support excitations during earthquake shaking play an important role in the seismic behaviour of a bridge. In urban areas, IABs are now becoming very popular due to minimal maintenance costs over their service periods. In typical bridges, the joints and bearings repair and maintenance affect the life cycle cost of the bridge and overall economy [1, 2]. One of the most common problems of traditional bridge construction in seismic zone is unseating of the superstructure from the support bearings. This problem is eliminated in integral abutment construction as there are no support bearings [3]. Past studies on integral abutment bridges have accounted for the stresses in different components arising from creep, shrinkage and temperature effects [4]. The length of the integral bridge mainly depends on the pile capacity, soil type and abutment movement due to intensity of temperature and seismic load and other factors [5]. Backfill soil properties influence the IAB behavior significantly [4, 6]. The contribution of bridge abutments in the natural vibration behaviour of IAB was also observed to be significant [7].

The present study mainly focuses on the natural behavior of IAB with and without considering the effect of SSI. The effect of the abutment on the modal behavior of the structure have also been investigated.

2 Description of Model

2.1 Bridge Model

In the present study, the previously studied Humboldt Bay Middle Channel Bridge [8, 9] has been considered with certain modified characteristics. The modelling of the bridge is carried out using the computer program SAP2000 V16.0.0 [10] (Fig. 1). The bridge is 330m long, 10m wide and 12m in height. The bridge superstructure is integrally connected to the abutments at the two ends. The height, width and the thickness of the abutments are 12m, 10m and 1.2m respectively. The superstructure consists of concrete deck slab which is resting on four precast prestressed concrete symmetric I-shaped girders. The cross-sectional area and the second moments of the areas are taken as $0.73m^2$, $0.49m^4$(major axis) and $0.0094m^4$(minor axis) respectively. The deck slab is 165 mm thick and it is rigidly connected with girders by rigid links. The superstructure is resting on piers which is connected to deck by pier caps. The length and cross-sectional area of pier cap are 10m and $4m^2$ respectively. The height and cross-sectional area of each pier are 12m and 3.4 m^2 respectively. Each pier is supported on pile foundation with each pile group having five precast driven piles. Pile foundations are

[1] Ph. D Student, sreya.dhar@gmail.com
[2] Assistant Professor, kd@iitg.ernet.in

assumed to extend up to 5.2m depth from ground level. The superstructure, pier and piles are discretized using 2-noded frame elements with 6 Degrees of Freedom (DOFs), namely (a) three translational and (b) three rotational DOFs at each node. Each individual deck span is discretized into 10 elements. Abutments and pile caps have been modelled by linear elastic 4-noded shell elements. Abutment piles have been modeled same as pier piles, with 1m nominal spacing. The modulus of elasticity and unit weight of concrete are taken as 28 GPa and 24 kN/m^3 respectively.

2.2 Foundation and Abutment Backfill

Springs have been used to model the flexibility of the backfill soil behind the abutments and the cohesive soil surrounding the piles (Fig. 1). For each spring, force-displacement curves have been used as per API-RP2 [11]. Piles are friction type or floating piles and have been incorporated with skin friction and lateral load resisting capacity due to surrounding soil. Both the soil lateral stiffness and initial skin friction increase with the depth of the piles. The springs are also assigned to account for both the aspects. Each soil spring is modelled using 1-noded link element in the program SAP2000 (Fig. 2(a)). At each pile tip, the end bearing resistance has been modelled by 2-noded link element in SAP2000 (Fig. 2(b))). As the piles are of only 5.2m of depth, it is considered to be short piles. Soil mass has not been considered for the present study while modelling soil-structure interaction of the IAB.

Each abutment has been designed against the passive earth pressure during seismic excitation or temperature increment, since the active earth pressure is considered to be negligible [12]. Abutment backfill behavior has been modelled considering dense sand properties [8]. The lateral passive pressure exerted by the backfill soil, tends to increase with the depth of abutment backwall. Abutment-backfill interaction has been modelled as per BA 42/96 [13] curves for end screen abutments of IAB. These properties have been assigned to the 2-noded link elements (Fig. 2(c)). As linear elastic behavior is required for the modal analysis, the initial stiffness has been considered for the soil spring elements from their nonlinear force-deformation curves (Fig. 3). For soil-pile interaction, initial lateral stiffness and skin friction are shown in Table 1. The initial lateral stiffness for abutment-backfill interaction is shown in Table 2. Only near field soil-pile interaction has been considered.

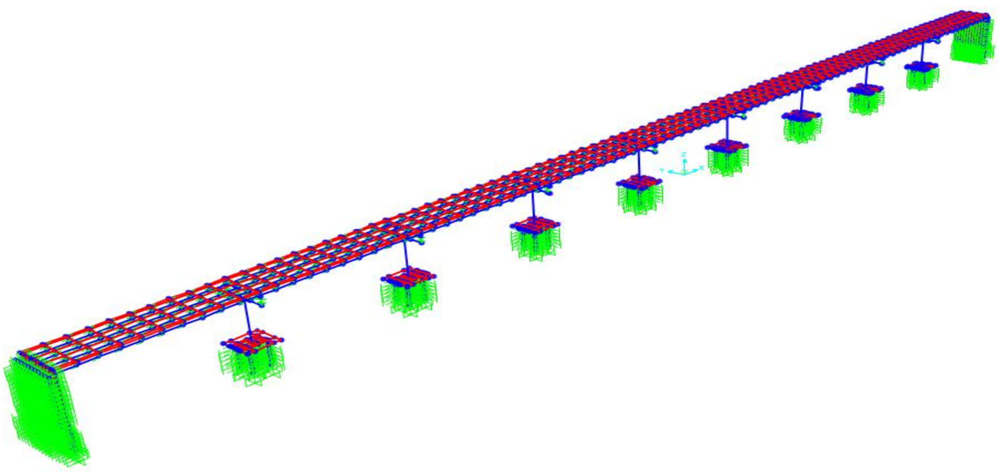


Figure. 1 Modified Humboldt Bay Middle Channel Bridge with soil-structure interaction modelled in SAP2000.

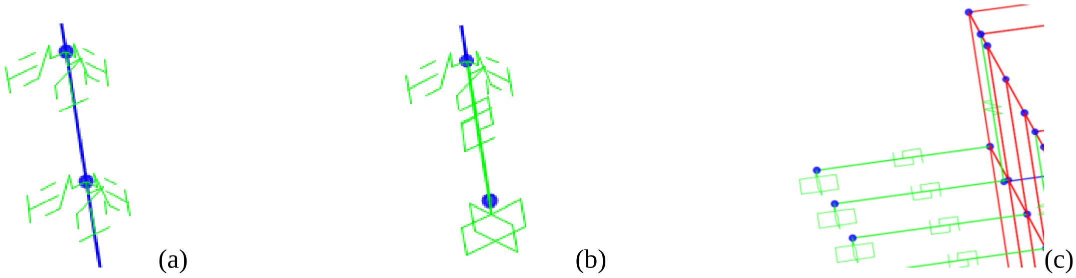


Figure. 2 (a) 1-noded horizontal and vertical link elements at different depth of piles, (b) 2-noded link element at the tip of each pile and (c) 2-noded link elements for modelling abutment-backfill interaction.

Table. 1 Soil initial lateral stiffness and skin friction on pile at different depths

Depth, m	Lateral stiffness, kN/m	Skin friction, kN/m^2
1.0	250	2,497
2.0	250	3,248
3.0	250	3,973
4.0	748	4,587
5.2	748	5,228

Table. 2 Initial lateral stiffness for abutment-backfill interaction at different depths of abutment

Depth, m	Initial lateral Stiffness (K), kN/m
1	6,042
2	12,083
3	18,125
4	24,166
5	30,208
6	32,429
7	42,291
8	48,332
9	54,374
10	60,415
11	66,456
12	72,498

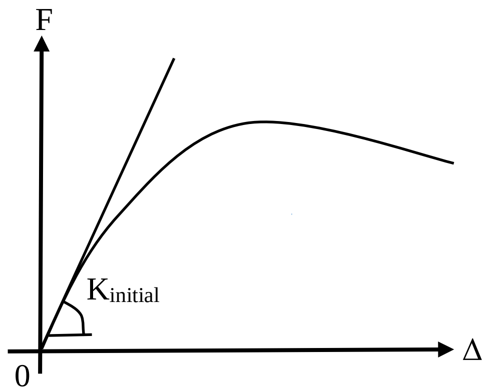


Figure. 3 Initial stiffness ($K_{initial}$) from the generic force – displacement curve of soil spring

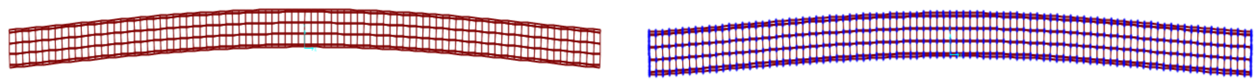
Modal analysis of the bridge model has been carried out without the presence of piles, pile cap and soil and by considering the bottom nodes of pier as fully restrained. This model will be henceforth called as fixed base model. The same analysis has been carried out for the other model considering the soil-pile and backfill-abutment interactions. Modal analysis is carried out with initial zero stress condition in soil which implies absence of any other preceding static/dynamic analysis. Further, modal behavior of IAB is also studied by removing end spans and abutments.

Hence, four cases have been considered to compare the modal behavior of the bridge which are (a) only bridge model, (b) complete SSI model, (c) Case(i), where both the endspans with abutments have been removed from bridge and (d) Case(ii), further endspans have been removed.

3 Comparison of modal analysis results

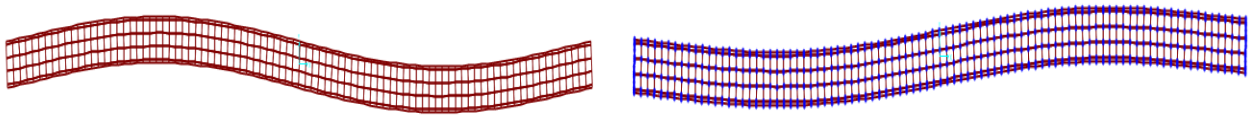
For both the SSI model and the fixed base model, the natural periods and the mode shapes of the first 12 modes of vibration have been compared. The mode shapes of vibration for the first 3 modes are shown in Figs. 4 to 6. The first modes are along the transverse direction of the bridge for both the models. Due to soil-pile interaction and increased flexibility, the entire piercap-pier-pilecap-pile group system deforms along the height of the bridge. This results in less relative transverse deformation of the deck with respect to the bottom of pier in the corresponding mode shapes. However, in case of fixed base model, the variation of transverse deformation is steeper due to the large relative transverse deformations of deck with respect to the restrained bottom node of pier. For both the models, the 2nd modes involve twisting of the bridge deck.

In the 3rd and the 4th modes, the deck deforms in a wave-shaped profile in the vertical direction for both the models. For both the models, the contribution of longitudinal stiffness by the deck and the two abutments remains the same. However, in SSI model, the flexibility is increased due to the presence of pilecap-pilegroup-soil system below each pier. Further, the abutments of SSI model become relatively stiffer due to the presence of abutment-backfill interaction springs. The observation of the first longitudinal mode of vibration of the bridge depends on the relative influence of the combined longitudinal bridge stiffness (for the mentioned components) and the bridge stiffness along the transverse direction. Due to large difference between the two stiffness, the first longitudinal mode of vibration occurs in the 11th mode for the bridge model with SSI (Fig. 7). As compared with the bridge with SSI model, the difference between the transverse bridge stiffness and the longitudinal bridge stiffness is lesser for the fixed base bridge model. This leads to the occurrence of the first longitudinal mode of vibration in 7th mode for the fixed base bridge model. For 2-span integral bridge in underlying clayey soils, longitudinal modes of vibration were also observed in early modes in Ref. [6]. It is observed that the range of natural periods for the bridge model with SSI is higher than the entire range for the fixed base bridge model for the first 12 modes of natural vibration (Table 3). For higher modes, the natural periods are closely spaced for both the models. The presently studied bridge is expected to show significantly large response under earthquake ground motions with dominant period in the range of 0.8-2.1 sec. However, the analysis of fixed base model shows an entirely different (lower) range for dominant periods of ground motions. Thus, using fixed base bridge model for estimation of design forces may lead to unsafe design. Considering more realistic behaviour, SSI needs to be considered in performance based bridge engineering studies.



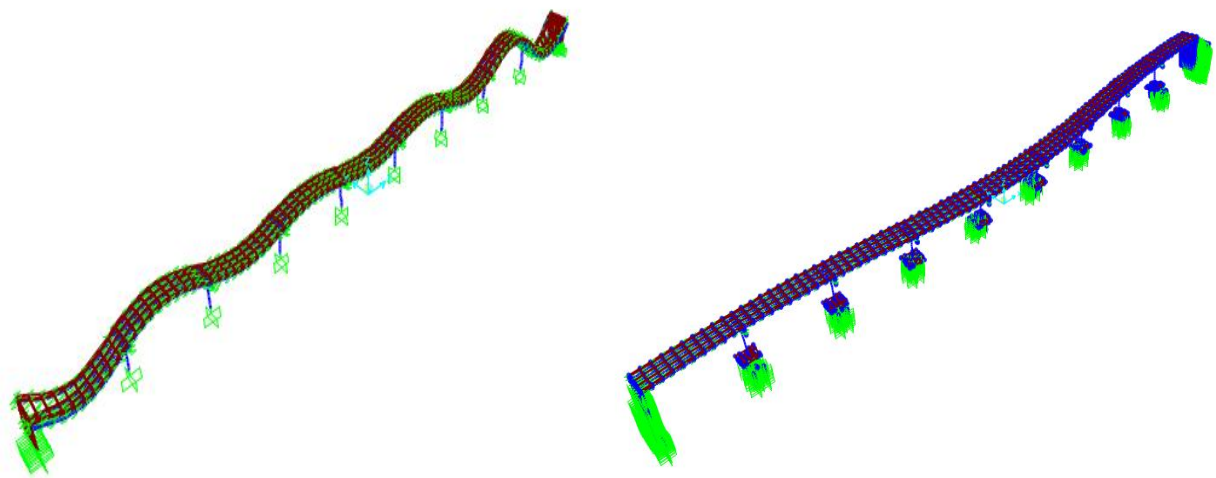
(a) (b)

Figure. 4 Plan views of first mode shape of vibration for (a) fixed base bridge model and (b) bridge with SSI model



(a) (b)

Figure. 5 Plan views of second mode shape of vibration for (a) fixed base bridge model and (b) bridge with SSI model



(a) (b)

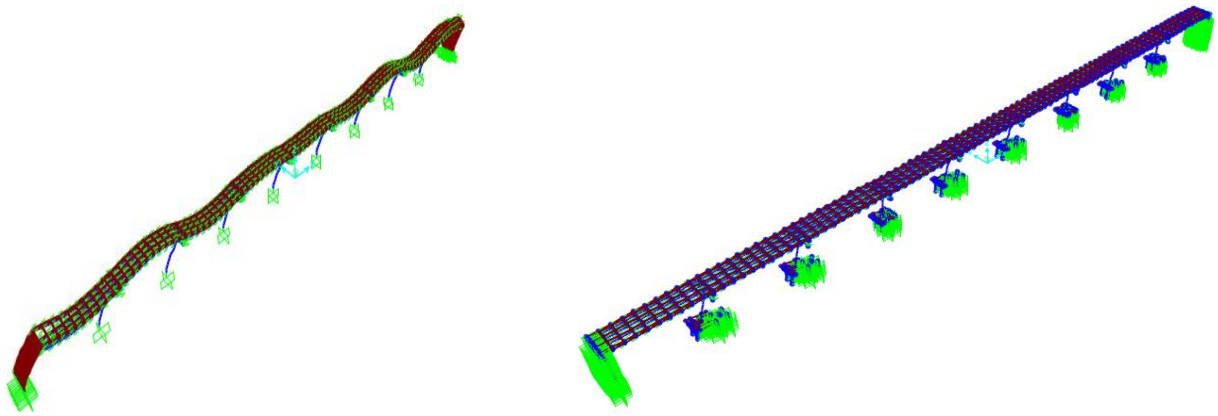
Figure. **6** Plan views of third mode shape of vibration for (a) fixed base bridge model and (b) bridge with SSI model.

Table. 3 Comparison of natural periods for fixed base and SSI models

Mode no.	Time Period, s			
	(a)Bridge Model	(b)Full SSI Model	(c)Case (i)	(d)Case (ii)
1	0.697	2.136	2.216	2.190
2	0.651	1.654	2.070	2.020
3	0.549	1.282	1.897	1.864
4	0.547	1.066	1.651	1.274
5	0.540	0.912	1.060	0.900
6	0.494	0.865	0.891	0.860
7	0.493	0.852	0.858	0.840
8	0.464	0.840	0.849	0.774
9	0.457	0.833	0.838	0.764
10	0.452	0.815	0.777	0.761
11	0.434	0.802	0.767	0.760
12	0.410	0.776	0.762	0.747

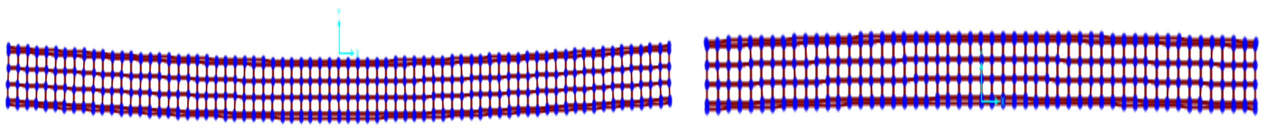
4 Removal of End Spans in Bridge with SSI Model

Bridge abutments contribute more to the bridge stiffness along the transverse direction than the longitudinal direction due to their large length. In the present study, the contribution of abutments to the bridge stiffness is investigated by first removing the end spans of bridge and the abutments (Case (i)). The increase in flexibility is observed for the first 9 modes (Table 3) of the new bridge with increase in the natural periods. The bridge natural vibrations occur in transverse, torsional and longitudinal modes of vibration for the first three modes respectively. Next, the two end spans of the reduced bridge were further removed (Case (ii)). However, the bridge response showed increase in stiffness for all the modes of vibration (Table 3). This is due to the reduction in the ratio of mass/stiffness for the entire bridge on removal of the spans. The nature of mode shapes of vibration for Case (ii) remains the same as in Case (i) (Fig. 8). Hence, the abutments and the number of spans of a bridge contribute to the relative magnitudes of transverse and longitudinal stiffness, and hence play an important role in the modal behaviour of the bridge.



(a) (b)

Figure. **7** Longitudinal mode of vibration for (a) fixed base bridge model and (b) bridge with SSI model.



(a) (b)

Figure. **8** Transverse mode of vibration for (a) Case (i) and (b) Case (ii) models.

5 Summary

The present study is intended to compare the modal behaviour of an integral abutment bridge for two conditions, namely (a) absence of SSI and (b) presence of SSI. In the presence of pilecap-pilegroup-system and abutment-backfill interaction, the natural vibration characteristics of the bridge are quite different from those obtained through the conventional modelling approach, i.e., by restraining the bottom nodes of the piers. The contribution of abutments and the number of spans of the bridge have also been illustrated.

For both the cases, stiffness of the bridge along the transverse direction was lower as compared to the bridge stiffness along the longitudinal direction. This resulted in occurrence of transverse vibration configurations in the lower modes. Also, the components contributing to the SSI response of bridge influence the occurrence of longitudinal mode of vibration in the lower or the higher modes. The removal of abutments and the end spans bring changes to the mass/stiffness ratio of the overall bridge. This leads to some modes becoming stiffer and a few modes becoming more flexible.

The present study is carried out on the modified model of a real bridge for which extensive studies had been carried out in the past [8,9]). To have more generalized conclusions, further studies need to be carried out on different bridge configurations with parametric variations. For longer bridges with more number of spans, heterogeneity of underlying soil becomes an important issue.

References

[1] Mistry, V., Integral abutment and jointless bridges. In *The 2005-FHWA Conference, Integral Abutment and Jointless Bridges (IAJB 2005)*, Baltimore, Maryland, USA, March 16-18, pp. 3-11, 2005.

[2] Yannotti, A.P., Alampalli, S. and White, H.L., New york state department of transportation’s experience with integral abutment bridges. In *The 2005-FHWA Conference, Integral Abutment and Jointless Bridges (IAJB 2005)*, Baltimore, Maryland, USA, March 16-18, pp. 41-49, 2005.

[3] Wasserman, E. and Walker, J., Integral abutments for steel bridges. Technical report, Tennessee Department of Transportation, American Iron and Steel Institute, 1996.

[4] Kumari, P., Seismic Analysis of Integral Abutment Bridges, *M.Tech Thesis*, Dept. of Civ. Eng., IIT Guwahati, 2013.

[5] Greimann, L. F., Yang, P. S., Edmunds, S. K., and Worlde-Tinsae, A. M., Design of piles for integral abutment bridges, Final report, IOWA department of Transportation, ISUERI-Ames 84228, 1984.

[6] Farahani, R. V., Zhao, Q. and Burdette, E. G., Seismic Analysis of Integral Abutment Bridge in Tennessee including Soil–Structure Interaction, *Journal of the Transportation Research Board*, 2201, pp. 70-79, 2010.

[7] Goel, R. K., Earthquake Characteristics of Bridges with Integral Abutments, *Jr. of Struct. Eng.*, ASCE, Vol. 123(11), pp. 1435-1443, 1997.

[8] Zhang, Y., Conte, J.P., Yang, Z., Elgamal, A., Bielak, J. and Acero, G., Two dimensional nonlinear earthquake response analysis of a bridge-foundation ground system, *Earthquake Spectra*, Vol. 24(2), pp. 343-386, 2008.

[9] Elgamal, A., Yan, L., Yang, Z. and Conte, J.P., Three- Dimensional Seismic Response of Humboldt Bay Bridge-Foundation-Ground System, *Jr. of Struct. Eng.*, ASCE, Vol. 134(7): pp. 1165- 1176, 2008.

[10] CSI, Integrated Software for Structural Analysis and Design SAP2000 Version 16.0.0, Computers and Structures Inc. Berkeley, USA, 2013.

[11] American Petroleum Institute (API RP2A-WSD: 2000), Recommended practice for planning, designing and constructing fixed offshore platforms-working stress design, Washington, D.C, 2000.

[12] Clough, G. M. and Duncan, J. M., Foundation engineering handbook: Edited by H.Y. Fang, Indian Edition, CBS publishers, New Delhi, India, 1991.

[13] BA 42/96 Highway Agency, Design Manual for Integral Bridges: Design Manual for Road and Bridges, Vol. 1, The Stationery office, London, 1993.