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Numerical Analysis for Multi-Support Excitation of a Long Bridge with Tall Piers

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Abstract

The study is related to the assessment of seismic performance of long multi-span railway bridge with through type open web superstructure and located in the highest seismic zone of India. Piers are tall with heights varying from 60 to 140 m. In a long bridge, spatial variation in the input seismic excitation should be considered and the effect of such excitation at different pier foundation level on the seismic performance of the overall bridge should be assessed. A detailed finite element model with soil-structure interaction is considered. Asynchronous ground motions are modelled using conditional simulation by considering the coherency losses and a time delay of arrival with change in phase as well as amplitude of the earthquake signals from origin to the spatial points of interest along the bridge. Multi-support excitation of the bridge is performed by converting the acceleration time history to displacement time history. The responses at different pier locations for the synchronous and asynchronous motion are evaluated and the requirement of asynchronous input in multi-support excitation for long bridge with tall piers are observed to be significant for assessment of safety of running vehicle.

Keywords: long bridge, tall piers, seismic performance, conditional simulation, asynchronous motion, multi-support excitation

1 Introduction

Long bridges may have multiple supports and the abutments at two ends as well as intermediate piers are quite likely to be at significant distance apart. During seismic excitation, the expectation of the same earthquake motion at every support point is thus unlikely to be accurate as during its propagation, the earthquake motion undergoes reflection, refraction and losses its coherent nature resulting in a whole different motion when measured at different points for the same earthquake event. The spectral properties of ground motion get altered because of (a) wave passage effects which is due to the time shifts in the arrival of the seismic waves at the supports (Adanur et al.[1]) (b) the incoherence effect which is due to extended source effect in which different frequencies in the relative geometry of the source and site produce different time shift (Konakli and Kiureghian [2]) (c) the local soil effect which causes scattering (reflection, refraction etc) of waves by inhomogeneity along the travel path. The asynchronous ground motions were started being analyzed after the installation of dense instrument arrays since 1979 with El Centro differential arrays. Before this, the spatial variation of the motions was attributed to the wave propagation effect only (Bogdanoff et al.[3]). Numerous researchers have done work on spatial variation of seismic ground motion and its application on long span structures. In general, the spatial variations of seismic ground motions are evaluated from data recorded at dense instrument arrays. Zerva and Zervas [4] studied the estimation of coherency from the recorded data and discussed on its interpretation. Some empirical and semi-empirical coherency models based on the recorded data, their validity as well as limitations and the effect of coherency on the seismic response of extended structures were studied. Lavarato et al.[5] studied the nonsynchronous seismic ground motion generated at different foundation point of a long span bridge. Basu et al.[6] developed a framework which accounts for both phase variability and amplitude variability of spatially varying ground motion. For the purpose of assessment, a definition of target spectrum based on the direction of arrival was explored. The effect of choice of coherency model on the simulated spatially varying ground motion was investigated. Seismic response analysis of structures subject to multi-support excitation has been carried out by various methods like modal analysis (Berrah [7]), modified response spectrum method (Kiureghian and Neuenhofer [8]), Monte Carlo simulation (Mirzabozorg et al.[9]), random vibration analysis (Zhang et al.[10]) etc. Balamonoca et al.[11] used deterministic approach using proper orthogonal decomposition vector (POD) or proper orthogonal mode to analyse rsponse of the structure subjected to multisupport excitation. Experimental and numerical studies show that the relative displacement of the bridges tends to increase causing pounding when subjected to spatially varying earthquakes (Li et al.[12]). It is understood from the literature study that the asynchronous motion will cause enhanced relative motion in pier top in multi support long span bridge compared to synchronous motion. In railway bridge, this effect causes relative displacement of the continuous rail on which trains are moving. In the present study, development of asynchronous motion and its effect on long span bridge with multi support arrangement has been presented. In railway bridge, the continuous track alignment undergoes lateral movement during seismic excitation. The train speed depends on the track curvature in addition to the other factors. The relative effect of track curvature between synchronous and asynchronous ground movement has been studied for a long railway bridge with tall piers and located in the highest seismic zone of India.

2 Finite Element Modelling of the considered Bridge

The bridge under consideration is a railway bridge with open web girder superstructure. The bridge is located in Manipur, India which has the highest seismicity in the country. The total length of the considered bridge is 703 m, which comprises of eight simply supported spans. It has two 69 m span with through type truss girder, five numbers of 103.5 m span with through type truss girder and a plate girder span of 28.5 m. The bridge consists of seven intermediate annular piers of height ranging from 60 metres to 141 metres. The tall Piers resting on Pile foundations are flexible and are to be modelled appropriately to represent their actual behaviour. The bridge is supported on a group of piles with a diameter of 1.5 meters and length varying between 22 meters to 30 meters at the respective locations (Figure 1). Members of the superstructure with different sectional geometries are modelled in section designer. Beam elements are used to model the piers, piles, while plate elements are used to model the pile cap. The superstructure is also modelled using beam elements, wherein appropriate releases are made to ensure only axial degrees of freedom to members of the truss and rotations degrees of freedom are released for stringers and cross girders to ensure shear transfer only. The through-type truss girder and plate girder spans are simply supported and boundary conditions are imposed with help of body constraints in SAP 2000 Nonlinear. The near-field soil is modelled using Beam on Winkler Foundation, where soil elements are modelled as discrete non-linear springs as specified in API 2008 [13]. The soil resistance in the lateral and axial direction of the pile are summarised as *P-y* curve to represent the relationship between the lateral resistance of soil and pile displacement, *t-z* curve to represent the relationship between shaft skin frictional force and relative movement of the pile with respect to the soil, *Q-z* curve to represent the mobilized tip bearing capacity and settlement. The detailed finite element model of the considered bridge along with soil-pile system is shown in Figure 2.

3 Multi-support excitation using the displacement input method

Multi-support excitation in SAP 2000 Nonlinear is performed by converting acceleration time history to displacement time history, while the time step is reduced to $\frac{1}{10}\,th$ of acceleration time history. The *P-y* spring is positioned along with two orthogonal directions on the horizontal plane and is connected to the pile at discrete points over its length. The converted displacement time history and applied as joint/ground displacement at each fixed end of the two-jointed *P-y* spring (Figure 3). The structural response that is obtained from displacement-based input is the total displacement response, whereas for acceleration-based input, the response that is obtained is the relative displacement response. The equations of motions that are solved by SAP 2000 for performing multi-support excitation are

$$\begin{bmatrix} M_{ss} & M_{sb} \\ M_{sb} & M_{bb} \end{bmatrix} \begin{pmatrix} \ddot{u}_s \\ \ddot{u}_b \end{pmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{sb} & C_{bb} \end{bmatrix} \begin{pmatrix} \dot{u}_s \\ \dot{u}_b \end{pmatrix} + \begin{bmatrix} k_{ss} & k_{sb} \\ k_{sb} & k_{bb} \end{bmatrix} \begin{pmatrix} u_s \\ u_b \end{pmatrix} = \begin{Bmatrix} 0 \\ R_b \end{Bmatrix} \quad (1)$$

where $\ddot{u}_s$, $\dot{u}_s$, u_s are the vectors representing the motion of the superstructure in the absolute coordinate system; $\ddot{u}_b$, $\dot{u}_b$, u_b are the vectors representing ground motion in the absolute coordinates; M_{ii}, C_{ii}, k_{ii} are the mass, damping and stiffness matrices. The meaning of subscripts like *ss, bb* and *sb* are the degrees of freedom of superstructure, base and their coupled term. R_b is the lateral reaction at the nodes of the foundation. Considering the expanded form of first row of Equation 1, we get

$$M_{ss}\ddot{u}_s + C_{ss}\dot{u}_s + k_{ss}u_s = -(M_{sb}\ddot{u}_b + C_{sb}\dot{u}_b + k_{sb}u_b) \quad (2)$$

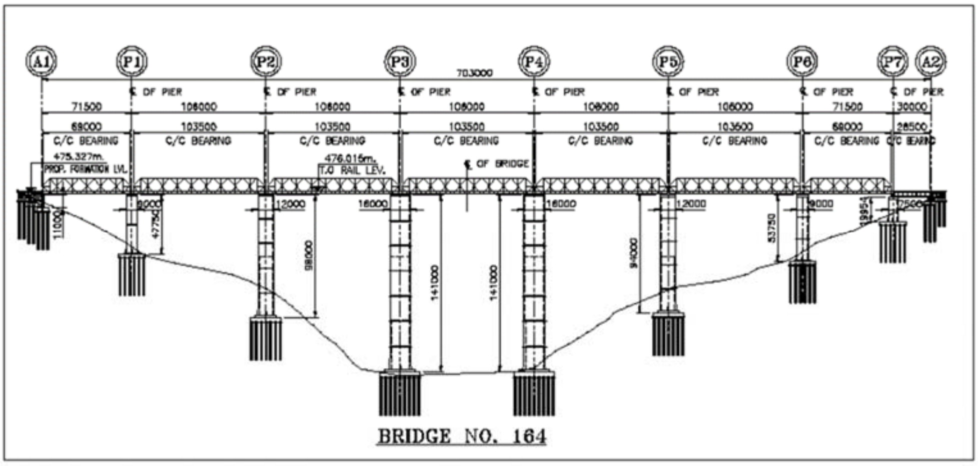


Figure 1 Tall long railway bridge in Manipur

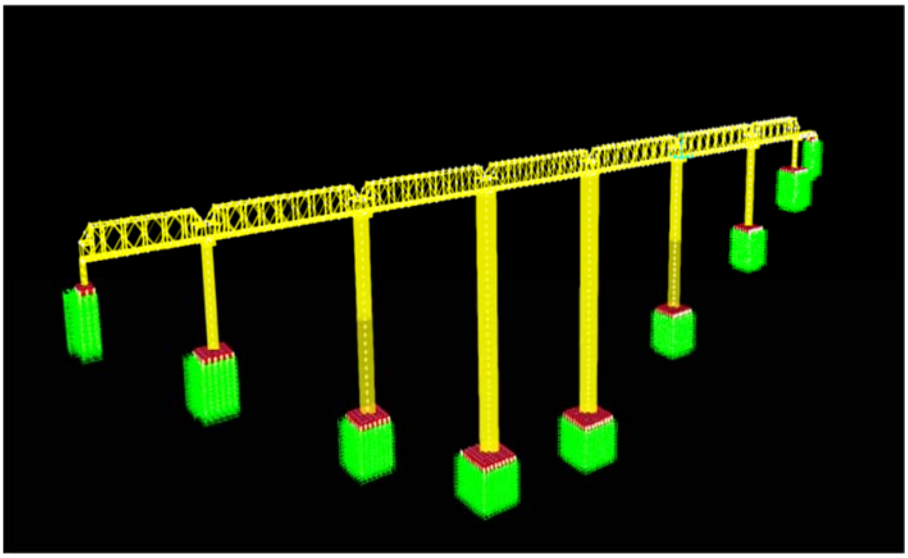


Figure 2 Finite Element model of the bridge with Near-field soil springs

In case of the lumped mass model, all non-diagonal terms are zero, thus M_{sb} is equal to zero. The damping term $-C_{sb}\dot{u}_b$ can be neglected (Computers and Structures [14]). So, Equation 2 can be written as

$$M_{ss}\ddot{u}_s + C_{ss}\dot{u}_s + k_{ss}u_s = -k_{sb}u_b \quad (3)$$

where u_b is the vector of ground motion in terms of displacements; $-k_{sb}u_b$ is the force experienced by the superstructure for the ground motion in the absolute coordinates. Equation 3 is the displacement-based input model for the analysis of structure under ground motion.

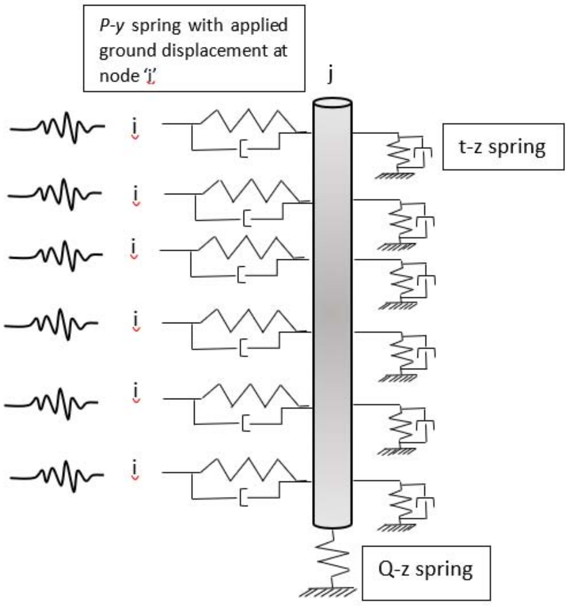


Figure 3 Schematic diagram of Pile with input ground displacement at 'i^{th} ' node

4 Seismic analysis of the long span bridge for synchronous and asynchronous input motion

In the present study, two earthquake records with different peak accelerations, frequency contents and durations have been selected as input motion for the time-history analysis of the considered bridge. These recorded earthquakes are Koyna (1967): Comp – Longitudinal and El Centro (1940): Comp – 180. These input earthquake motions have been converted to spectrum compatible with respect to design spectrum for DBE (5% damped) as presented in IS: 1893 [15]. These spectrum compatible time histories are used as synchronous input motion. The conditional simulation of earthquakes that vary spatially using the procedure that has been developed by Fenton et al.[16] is adopted in this study and is used as asynchronous input motion.

4.1 Comparison of responses at Pier top

As the earthquake wave reaches Pier-P1, there is a reduction in the amplitude of the absolute displacement as compared to A1. This is expected since there is a reduction in the amplitude and shift in phase as the wave travels from one Pier to another. However, due to the continuity of the bridge, the relative displacement is higher in case of asynchronous and wave passage effect due to the delay in arrival time at different piers as shown in Figure 4(a) and (b). This trend of decrease in the total displacement response is followed to the subsequent piers and the increase in relative displacement is seen in Figure 4(c) and (d). The displacement time histories at the pier and abutment top are further used to specifically show the peak values of displacement for both the cases of Koyna and El Centro ground motion Figure 5 (a) and (b).

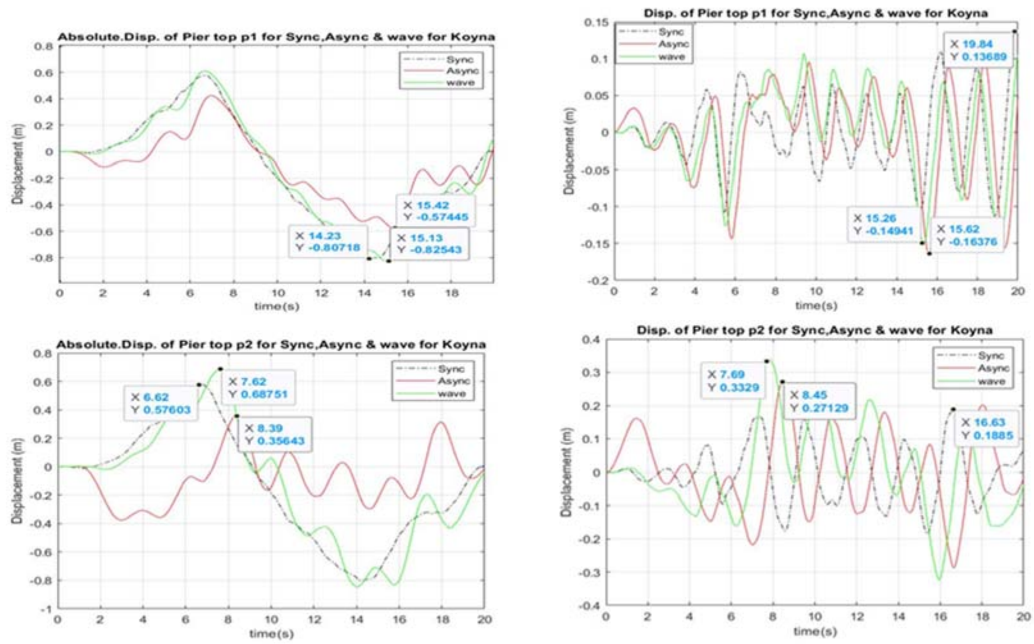
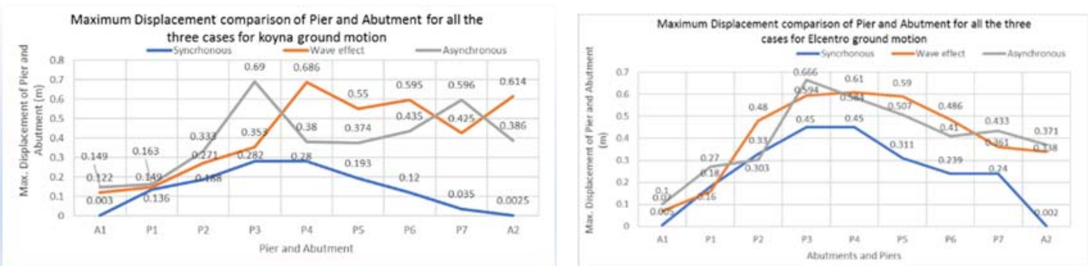


Figure 4 Relative displacement response of different piers under Koyna input

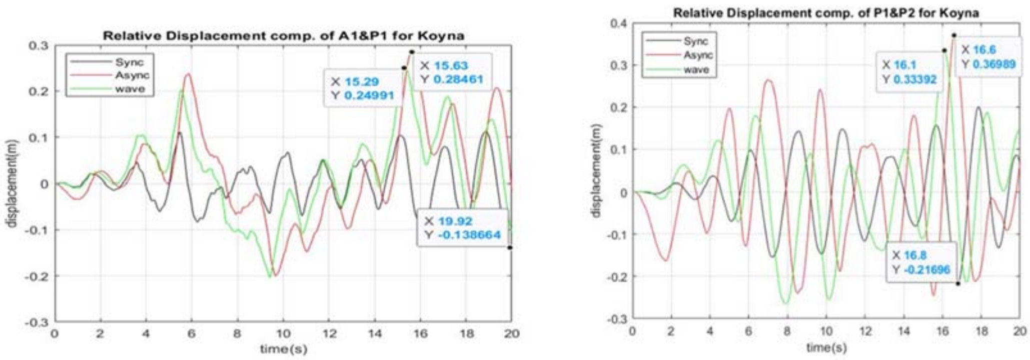


(a) With Koyna input motion (b) With El-Centro input motion

Figure 5 Maximum absolute displacement values for two different input motion

4.2 The relative displacement of adjacent piers

The bridge under consideration have different length of piers as well as abutments and thus introduces geometric irregularity. The piers which are adjacent to each other and have the same natural frequency may vibrate in phase without introducing any relative displacement between them. In the present case, both Pier-3 and Pier-4 are of 141 metres height with 103 metres span between them and are observed to move in the same phase for synchronous input case. Considering the wave passage effect or asynchronous motion, the wave hit these piers at different arrival times and there is a significant relative displacement between those two piers which cannot be observed in the synchronous motion-based analysis. This larger relative displacement may result in unseating of girders from supporting bearings. The relative displacement responses of the adjacent piers with different geometric configurations are shown in Figure 6 (a-b). The peak values of the relative displacements of different girders are specifically shown in Figure 7. It is seen that girders supported on the identical piers show larger relative displacement in the asynchronous and wave passage compared to synchronous case.



(a) Between A1 and P1 (b) Between P1 and P2

Figure 6 Relative displacements between two consecutive supports

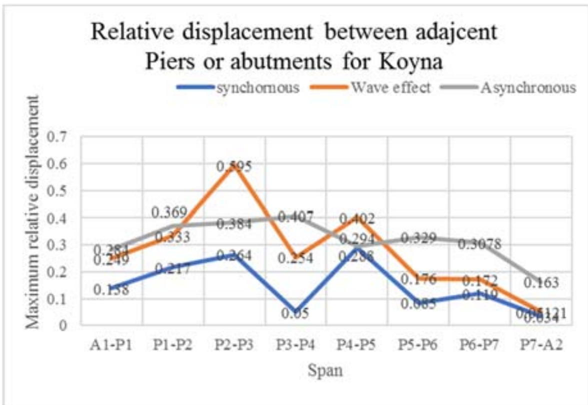
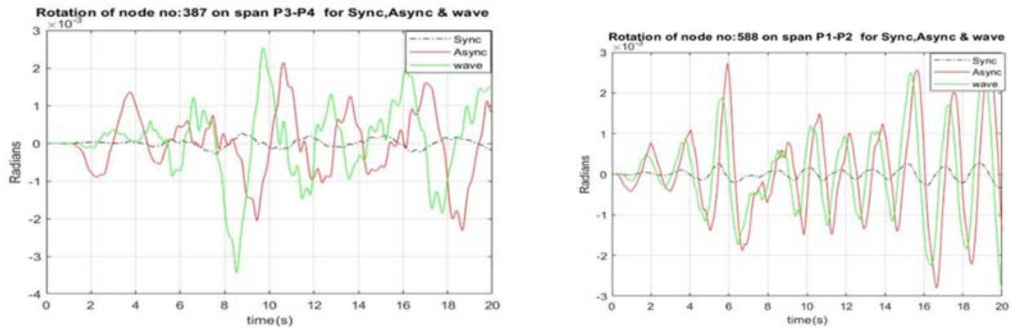


Figure 7 Relative displacements of different spans of the bridge

4.3 Other significant observations

The input motion with wave passage effect and coherency losses can introduce significant variation in responses of some degree of freedom, which are otherwise observed to have negligible values under synchronous motion as input. A few superstructure nodes such as node number 387 on span P3-P4 and node number 588 on span P1-P2 are considered for the study, which are rotational degree of freedom i.e, torsion for the considered span. Figure 8 (a-b) clearly indicate that the torsion at those nodes are significantly higher for asynchronous and motion with wave passage effect than the similar values corresponding to synchronous motion case. Similar observations were also made by Balamonica et al.[11] that the torsional degree of freedom is underestimated in analysis with synchronous input and may cause significant torsional stresses in the superstructure.



(a) At node 387 on span P3-P4 (b) At node 588 on span P1-P2

Figure 8 Torsional rotation under El-Centro ground motion

4.4 Effect on track curvature

The curvature of the deflected track under transverse seismic ground movement has been studied for El-Centro EQ and Koyna EQ, for both synchronous and asynchronous motion. In Figure 9 (a-b), the curvature of the deflected track has been plotted along the length of the bridge at different time instances when the individual pier top deflection is maximum. Two such deflected track alignment corresponding to synchronous and asynchronous transverse ground movement considering El-Centro and Koyna EQ has been plotted and shown in Figure 10 (a-b) at time instance when the deflection at top of pier P3 is maximum. All the deflections are absolute and the considered points have been joined by spline to get the deflected shape of the track. The boundary condition to form the spline is, the angle of rotation of the track at the two abutment ends are zero as the track beyond the abutments may be considered as aligned along the bridge axis. The curvature of the deflected shape of the track has been calculated along the length of the bridge from the spline coordinates. Similar curvature of the deflected shape of the track has been calculated for other time instances when the other pier top deflections are maximum and all these curvature plots have been superimposed in Figure 9(a) for El-Centro EQ and in Figure 9(b) for Koyna EQ. The safe velocity of the train during EQ varies with the curvature of the track. More is the curvature less will be the safe velocity. From Figure 9 (a) it is clear that the track curvatures are less in the case of asynchronous ground motion compared to synchronous ground motion considering El-Centro EQ. Whereas in Figure 9(b), considering Koyna EQ the trend is reversed. This shows that track curvature for asynchronous ground motion may be higher or lower compared to the synchronous ground motion for different EQ time histories.

5 Conclusions and Contributions

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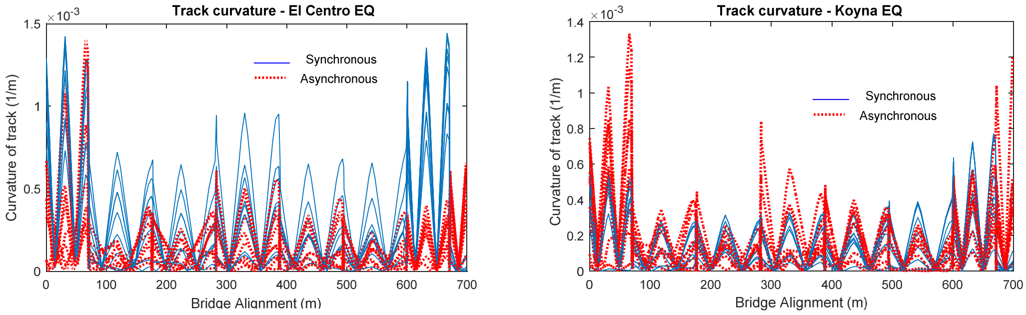
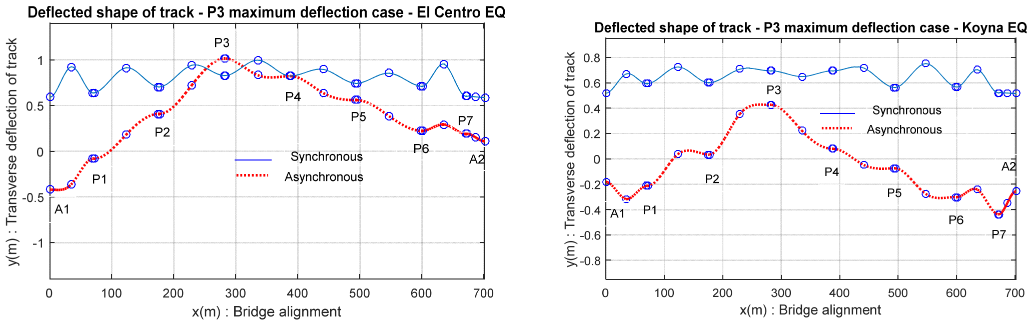
A long-span bridge with through type truss girder is considered for the detailed seismic analysis. Finite element model of the bridge is made along with SSI using 1D nonlinear uncoupled springs. The bridge model is analysed using synchronous and asynchronous ground motions and the responses of the bridge are studied. The displacement responses of the Pier and abutments are observed along with the relative displacement of adjacent piers.



(a) Under El-Centro excitation (b) Under Koyna excitation

Figure 9 Track curvature for synchronous and asynchronous ground motion



(a) Under El-Centro excitation (b) Under Koyna excitation

Figure 10 Deflected shape of track for synchronous and asynchronous transverse ground motion considering Koyna EQ at the time instance when P3 pier top undergoes maximum deflection

The important conclusions are as follows:

- Increase in the displacement demand in piers and abutments are observed for the analysis with asynchronous input as compared to synchronous input based analysis.
- Coherency losses in input motion may result in unseating of the superstructure due to larger relative displacement of adjacent piers.
- Active rotational degree of freedom that may lead to higher torsion in the superstructure, which is not found insignificant in the synchronous motion based analysis.
- Effect of curvature in track due to synchronous motion and asynchronous motion is case sensitive and depends on the characteristics of ground motion itself.

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