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Full Length Research Paper

The comparison of soil-pile interaction and fixed base support for integral prestressed concrete box-girder bridge

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This paper is to investigate the effect of soil-pile interaction for integral prestressed concrete box-girder bridge under low intensity earthquake. The soil-pile interaction was compared to fixed base support to see its effect. In this case study, one integral prestressed concrete box-girder bridge in Selangor, Malaysia had been chosen, that is, Kampung Sawah Bridge. To produce the low seismic loading, the ground response analysis had been conducted to produce three synthetic acceleration time histories loading. For soil-pile interaction, the p-y curves were determined by using LPILE program. The seismic analyses conducted were vibration analysis and nonlinear time history analysis. Free vibration analysis presented the periods and mode shapes of the structure while nonlinear time history analyses presented the maximum displacement at the top of pier and middle of deck and pier and deck forces response. It can be concluded that the soil-pile interaction support gives the longer period compared to fixed base support which almost differ about more than five times higher for the first mode. The displacement soil-pile interaction is higher compared to fixed base support; the increasing of displacement is more at transverse direction event for deck and pier. The all forces response from soil-pile interaction support is higher compared to fixed base support, except the axial force response of pier.

Key words: Nonlinear time history, integral concrete box-girder bridge, soil-pile interaction, fixed base.

INTRODUCTION

Integral prestressed concrete box-girder bridge has become best choices due to its ability to construct bridges with long span; reducing of maintenance cost problem and aesthetic value. However, the performance of this type of bridge under earthquake loading is very important to study due to the deck continuity and monolithic system for deck and pier.

Normally, during the analysis, the bridge engineer often assumed the bridge support as the fixed base support. The fixed base model is simpler, but it neglects the soil effects and could lead to overly conservative bridge designs for short bridges (Chen, 1996; Karbakhsh et al., 2011a). The assumption of rigid supports at abutments and piers should not be made based on ground simplicity and ease of calculation (IStructEng, 1989). For the seismic analysis, soil-pile interaction effects are accounted due to the soil flexibility contribution which is more than 20% of the total displacement at the top of the pier (British Standard Institution, 2005b). Therefore, the effect of soil-pile interaction support (SPIS) and fixed base support (FBS) for integral prestressed concrete box-girder bridge was investigated. In this study, Kampung Sawah Bridge in Selangor Malaysia had been chosen.

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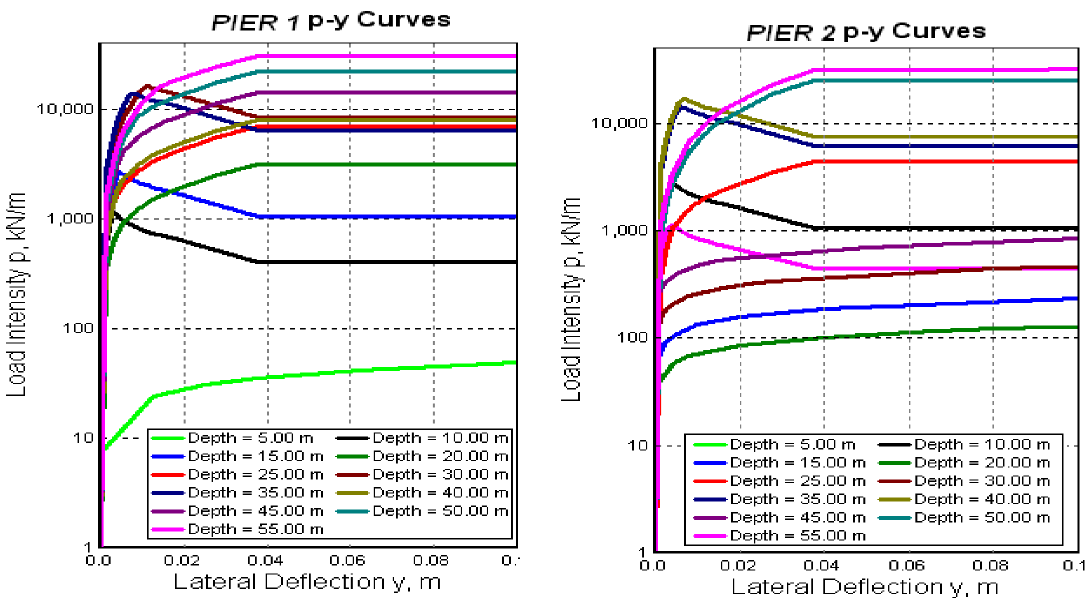

Figure 1. Various depth of soil stiffness curve for piers of Kampung Sawah Bridge.

For soil-pile interaction, the p-y curves will be determined by using LPILE program (LPILE V5.0, 2007). The behaviour of a pile under lateral loading creates soil reaction which is a function of the lateral deflection of a pile. The foundation stiffness is a major element in the seismic analysis of the bridge structure, provided there is interplay between superstructure and substructure responses of the bridge. The foundation stiffness can be modelled by a set of springs that represent the stiffness of the foundations (Karbakhsh et al., 2011b). The bridge structure and substructure, including soil-pile interaction will be modelled by using SAP 2000 Finite Element software (SAP 2000, 2009).

The seismic analyses conducted were vibration analysis and non-linear time history analysis. Free vibration analysis presented the periods and mode shapes of the structure while non-linear time history analyses considered the displacement and response forces on the deck and piers (Hashamdar et al., 2011).

Based on Yashinsky and Ostrom (2000), vertical accelerations are addressed separately from the horizontal bridge analysis. A vertical load analysis is not required for bridge site with peak rock accelerations less than 0.5 g, because the vertical ground motion is assumed to attenuate rapidly as the distance between the site and the fault increases. In this study, only lateral accelerations are considered since the maximum acceleration at the surface is about 0.0555 g.

MATERIAL PROPERTIES AND ANALYSIS

Soil-pile interaction

The foundation stiffness is a function of the properties of the substructure and surrounding soil (soil-structure interaction) in addition to the level of loading from the superstructure. It is important in this study to determine the nonlinear and dynamic properties of the soil to obtain the accurate soil stiffness for seismic analysis.

Based on Boulanger et al. (1999), soil-pile interaction can be an important consideration in evaluating the seismic response of pile-supported structures, particularly in soft clay or liquefying sand. Methods of analyzing seismic soil-pile-structure interaction have included 2D and 3D modeling of the pile and soil continuum using finite element, or finite difference methods, dynamic beam on a nonlinear Winkler foundation (that is," dynamic *p-y*") methods and simplified two-step methods that uncouple the superstructure and foundation portions of the analysis.

The p-y method is a method of analyzing the ability of deep foundations to resist loads applied in the lateral direction. This method uses the finite element method. The p-y graphs are graphs which relate the force applied to soil to the lateral deflection of the soil. In essence, non-linear springs are attached to the foundation in place of the soil. The springs can be represented by the following equation

$$P = ky \qquad (1)$$

where k is the non-linear spring stiffness defined by the p-y curve, y is the deflection of the spring, and p is the force applied to the spring.

The p-y curves model of the Bridge location can be seen in Figure 1.

Site response analysis

Soil data were collected from existing soil investigation (SI) of the bridge. The shear wave velocity (Vs) were obtained by converting the N-SPT value from Standard Penetration Test to shear wave velocity using empirical formula proposed by Ohta and Goto (1978), Imai and Tonouchi (1982) and by averaging those two formulas. Based on the analysis, the Vs-30 of BH2 (located at pier 1) and BH3 (located at pier 2) are 135 and 145 m/s. Generally, the site can be classified as soft

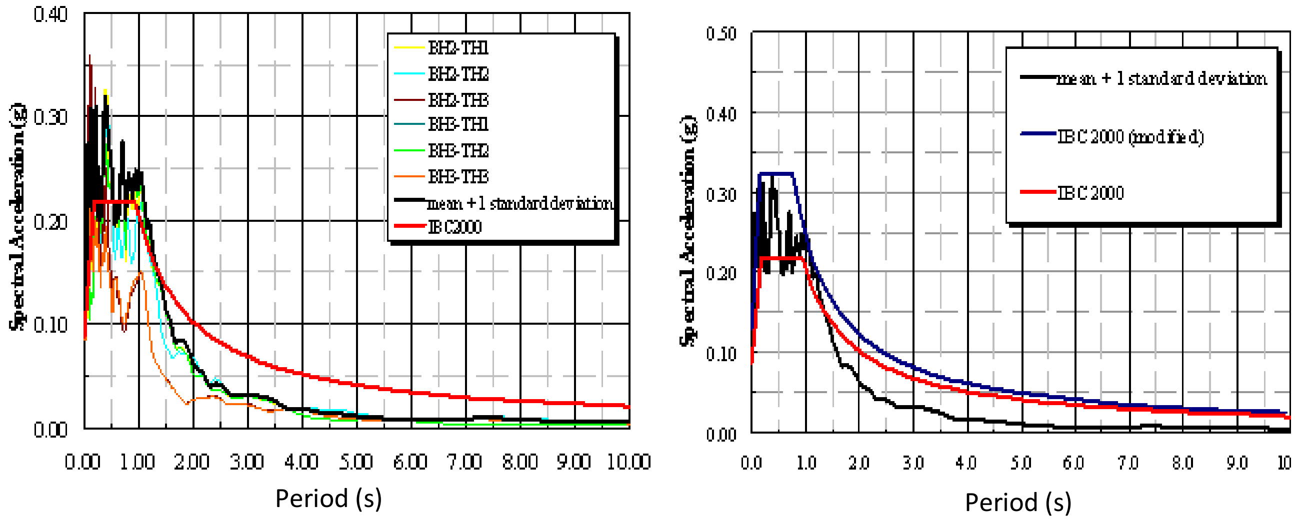

Figure 2. Response spectra and recommended design response spectra at the bridge location (TR = 500, Soil type Se).

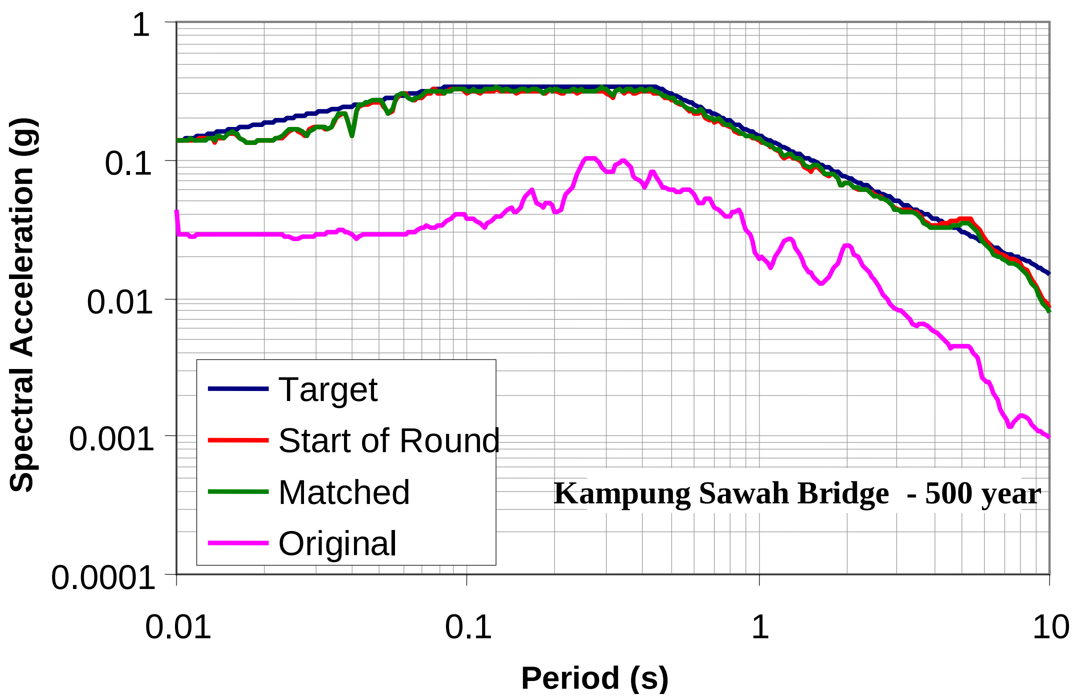

Figure 3. Spectral matching analysis for producing earthquake time history loading.

soil or site class E (Se) in accordance with Uniform Building Code, UBC (1997). Based on seismic hazard assessment study for west Malaysia (Adnan et al., 2009), the bridge location peak ground acceleration (PGA) at the bedrock for 500-year return period of earthquake is 0.0555 g. The predominant periods of the spectra generally occur in the range of 0.1 to 0.9 s. The design acceleration response spectra curves can be drawn based on equations in the IBC 2000 code of practice (International Code Council, 2000) (Figure 2). By conducting spectral matching analysis (Figure 3), three synthetic time histories at the surface are shown in Figure 4.

Finite element modelling

AASHTO LRFD Bridge Design Specification (AASHTO LRFD, 2005) and Eurocode 8 Part 1 (British Standard Institution, 2005a) have stated that the elastic seismic force effects on each of the principal axes of a component resulting from analyses in the two perpendicular directions are combined to form two load cases. In this study, 100% of the absolute value of the force effects in one of the perpendicular directions combined with 30% of the absolute value of the force effects in the second perpendicular direction is taken into account.

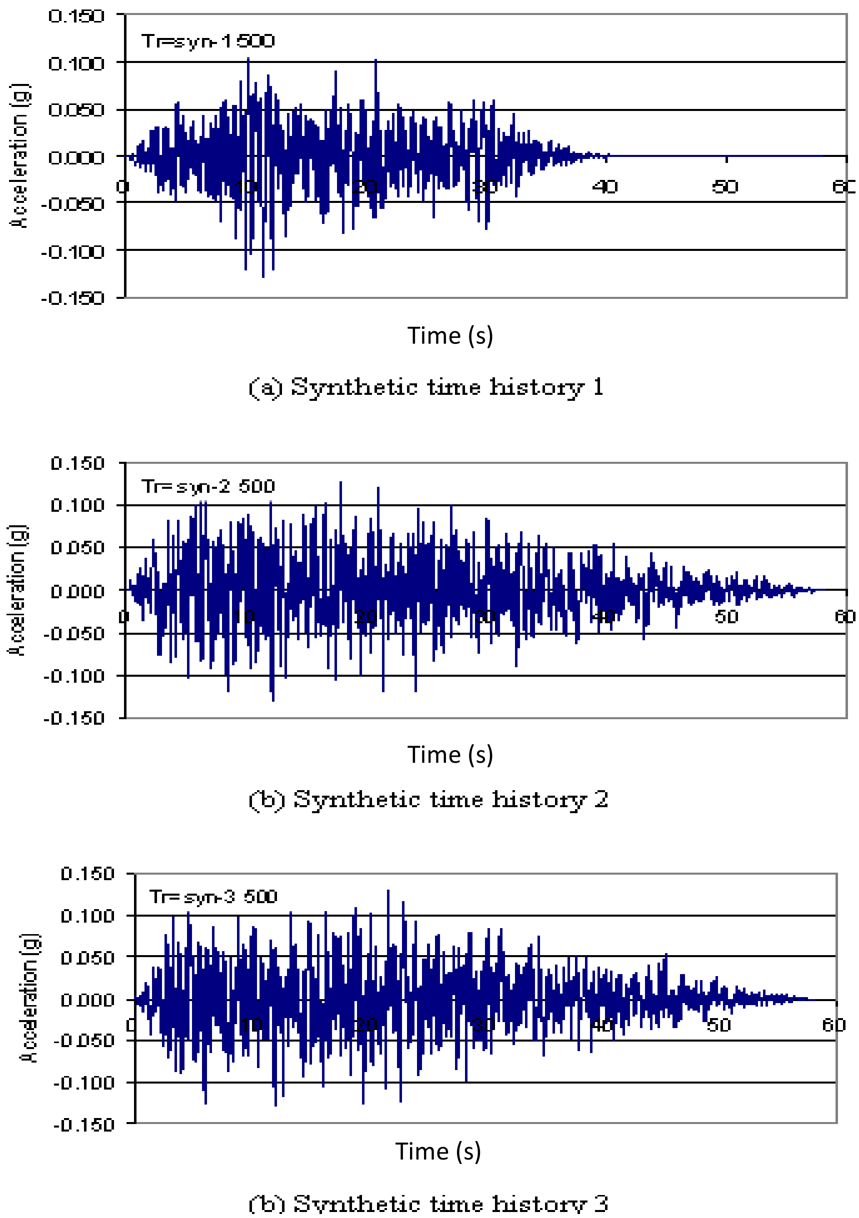

Figure 4. Time history at surface for 500 years return period.

The analyses implemented in this research are free vibration and time history analyses. Figure 5 shows all of the bridge components that were taken into account in finite element modelling. The reference nodes at the middle of deck and top of pier were selected for displacement monitoring. The displacement monitoring of the bridge can be seen in Figure 6. Node 217 is the top of pier and node 2636 is the middle of span.

RESULTS AND DISCUSSION

Free vibration analysis

The free vibration analysis considers ten modes of bridge finite element model. Table 1 shows the comparison between soil-pile interaction support and fixed based support for the first 10 mode shapes. The soil-pile interaction support gives the longer period of 5 times compared to fixed base support for the first mode. Figure 7 shows the mode shapes for both types of bridges.

Nonlinear time history analysis

The combination of 100% of earthquake force from x-direction and 30% of earthquake force from y-direction (100%X+30%Y) for bridge displacement responses with

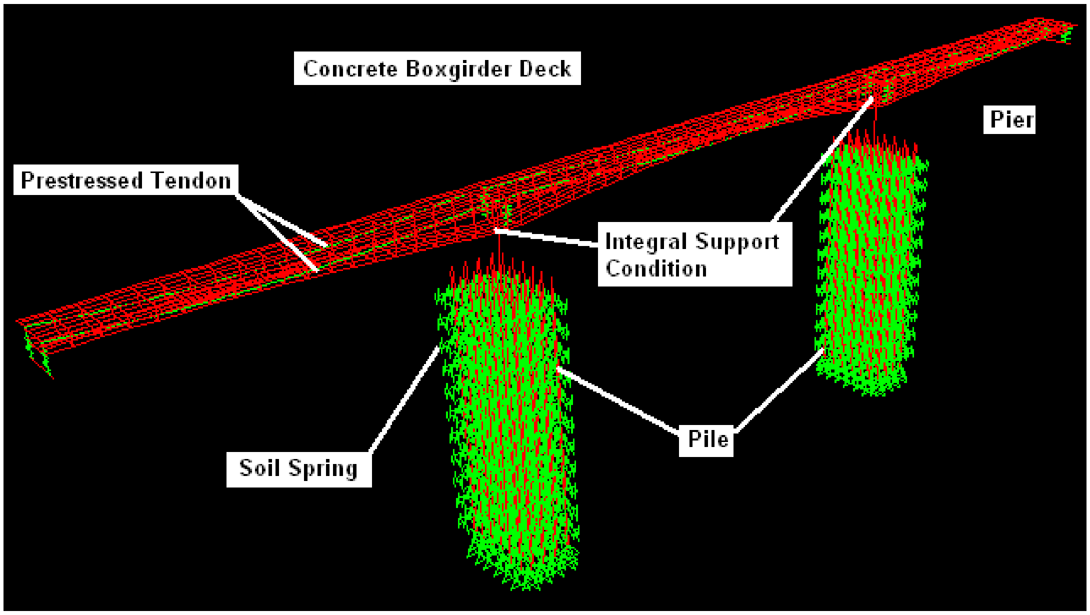

Figure 5. Finite element modelling of Kampung Sawah Bridge.

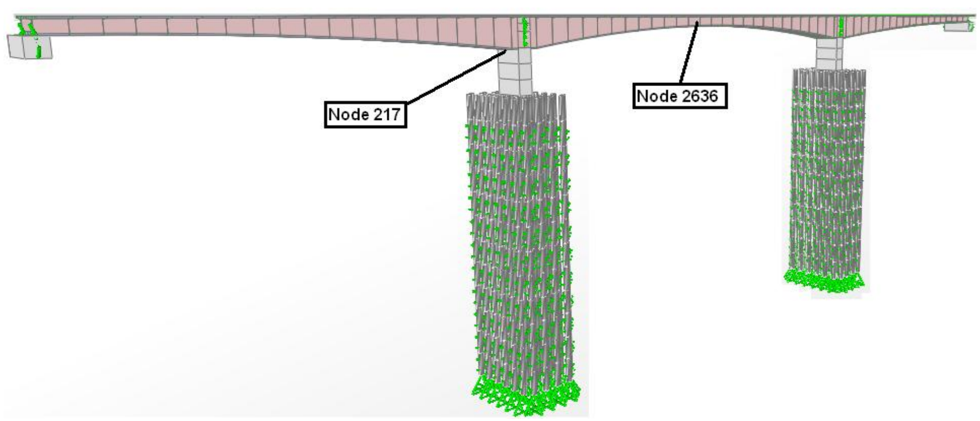

Figure 6. The node reference location for displacement monitoring of the Bridge.

Table 1. Dynamic characteristics of the bridge.

No. of mode shape	Period (s)	
	Soil –pile interaction	Fixed base support
1	3.47013	0.68339
2	3.04016	0.64320
3	1.72289	0.52127
4	0.68368	0.49408
5	0.63760	0.33936
6	0.54754	0.33372
7	0.49745	0.32251
8	0.45038	0.24034
9	0.43610	0.21250
10	0.42278	0.20198

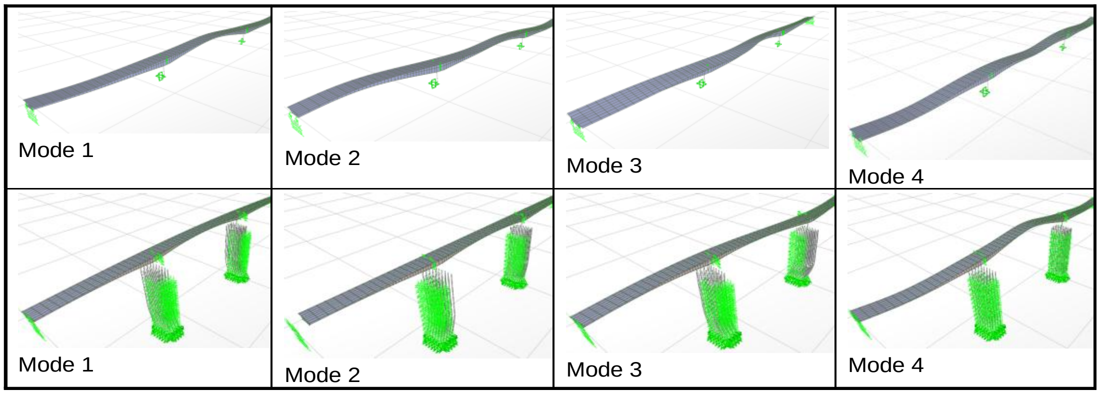

Figure 7. Mode shapes for fixed base and soil-pile interaction support of the bridge.

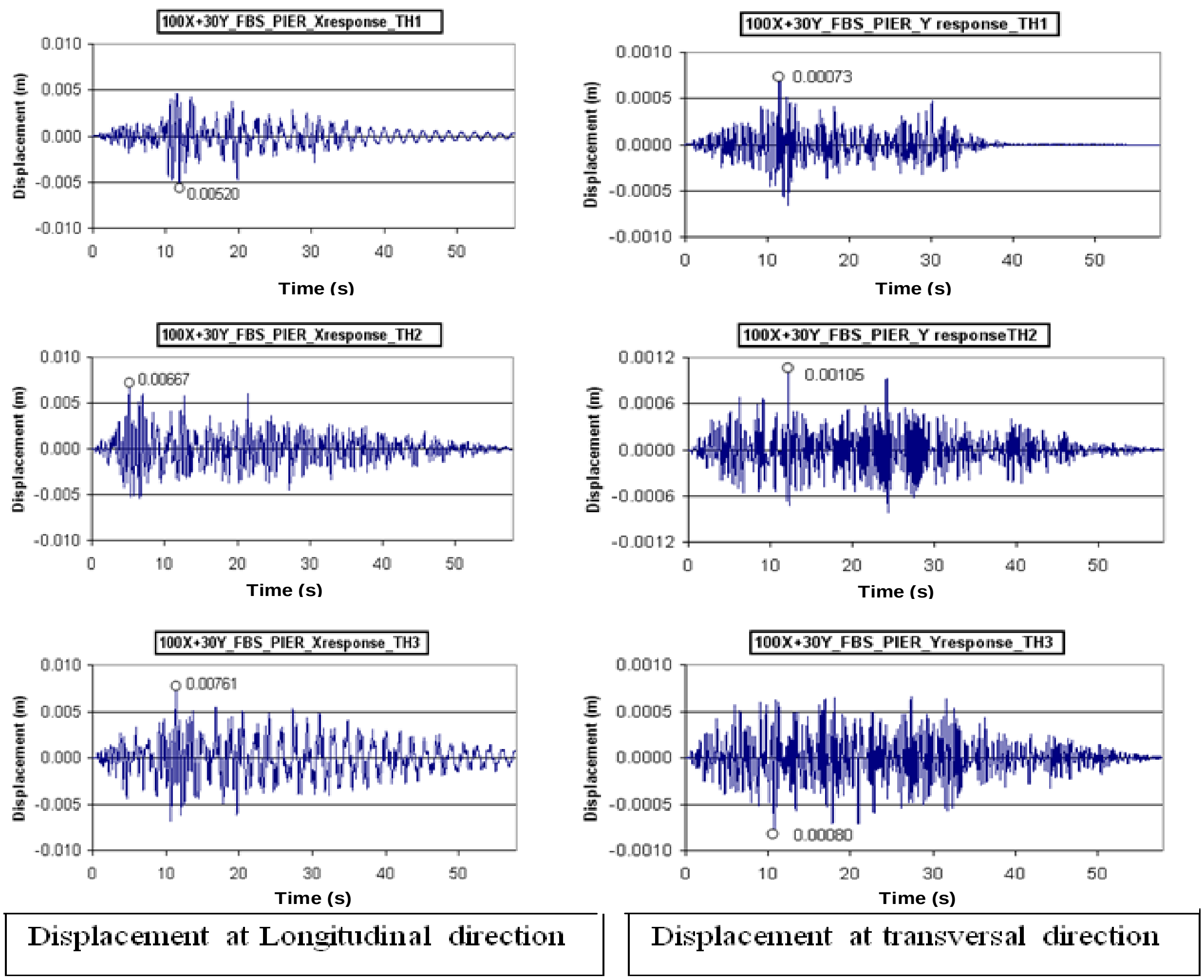

Figure 8. Longitudinal and transversal displacement response for top of pier under TH1, TH2, and TH3 loading (Fixed base support with 100%X+30%Y earthquake direction).

fixed base support can be seen in Figures 8 and 9; Figures 10 and 11 show the displacement responses of soil-pile interaction support. Table 2 shows the maximum value of displacement response for SPIS and FBS Bridge.

The combination of 30% of earthquake force from x-direction and 100% of earthquake force from y-direction (30%X+100%Y) with fixed based support can be seen in Figures 12 and 13. Figure 14 and 15 shows the soil-pile

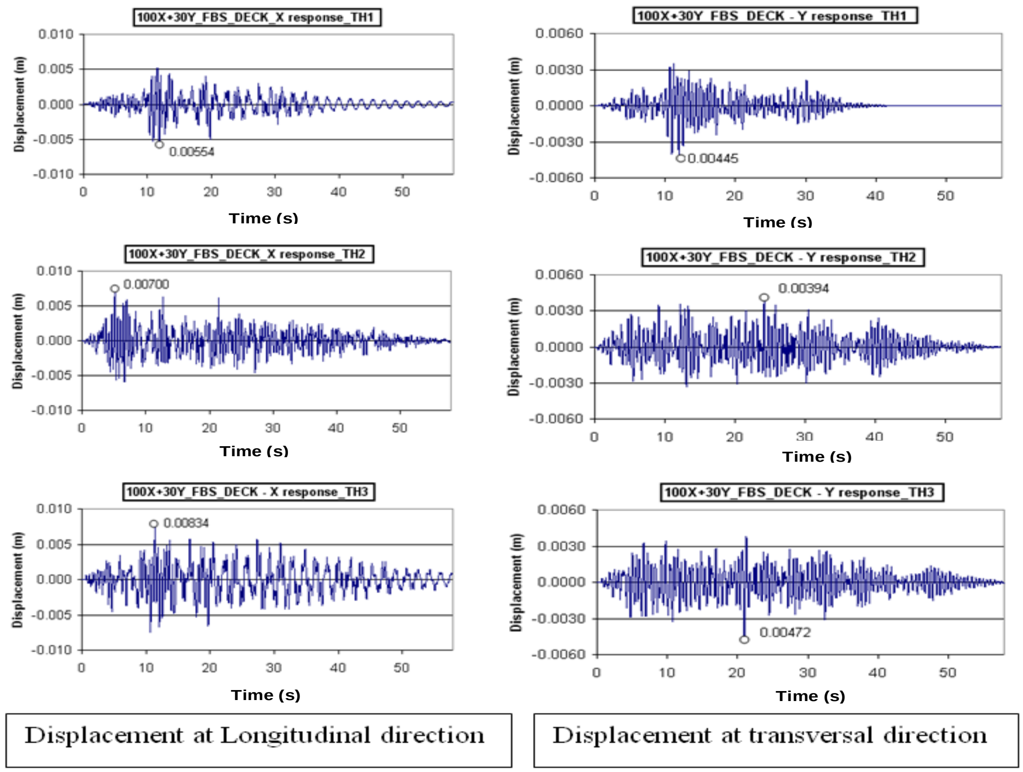

Figure 9. Longitudinal and transversal displacement response for middle of deck under TH1, TH2, and TH3 loading (Fixed base support with 100%X+30%Y earthquake direction).

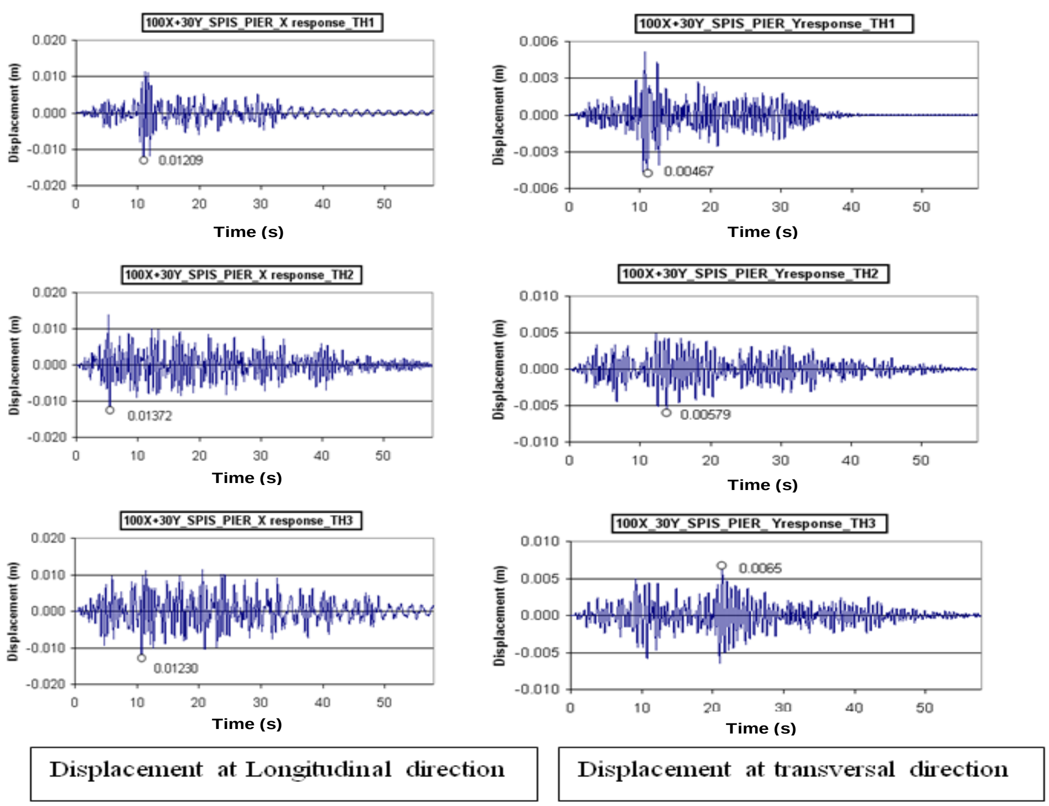

Figure 10. Longitudinal and transversal displacement response for top of pier under TH1, TH2, and TH3 loading (Soil-pile interaction with 100%X+30%Y earthquake direction).

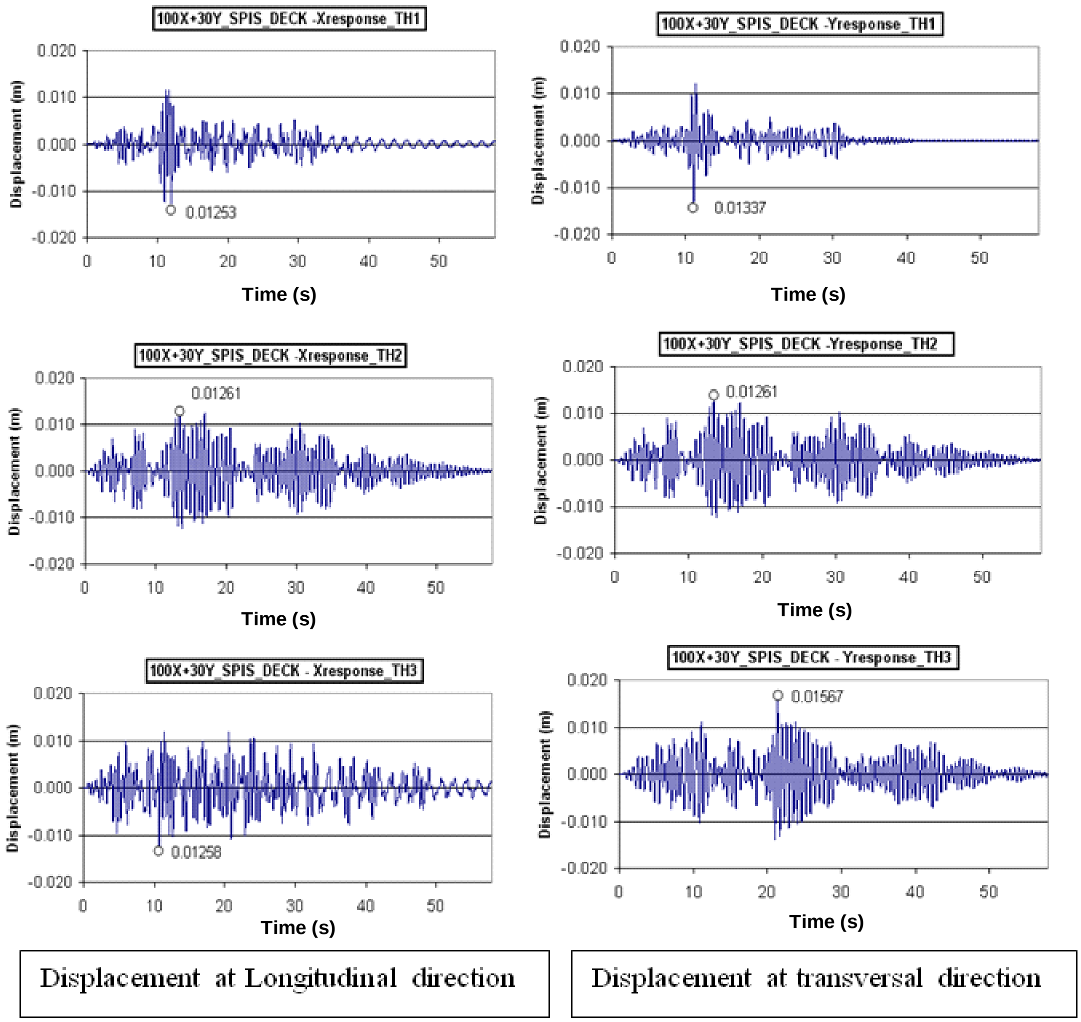

Figure 11. Longitudinal and transversal displacement response for middle of deck under TH1, TH2, and TH3 loading (Soil-pile interaction with 100%X+30%Y earthquake direction).

Table 2. Structure displacement for 100%X+30%Y earthquake direction combination.

Combination earthquake loading direction	Joint node	Max displacement (m)		Description
		X- direction	Y- direction	
SPIS	217	0.01372	0.00650	Top of pier
	2270	0.01261	0.01567	Middle of span
FBS	217	0.00761	0.00105	Top of pier
	2270	0.00834	0.00472	Middle of span

SPIS, Soil pile interaction support; FBS, fixed base support.

interaction support under the same combination of earthquake direction. Table 3 shows the maximum value for displacement response at 30%X + 100%Y earthquake direction.

Table 4 shows that the soil-pile interaction support gives higher displacement compared to fixed base support for structural responses. For 100%X+30%Y earthquake direction, the top of piers response shows the transversal maximum displacement of SPIS is five times higher compared to FBS, while longitudinal displacement is more

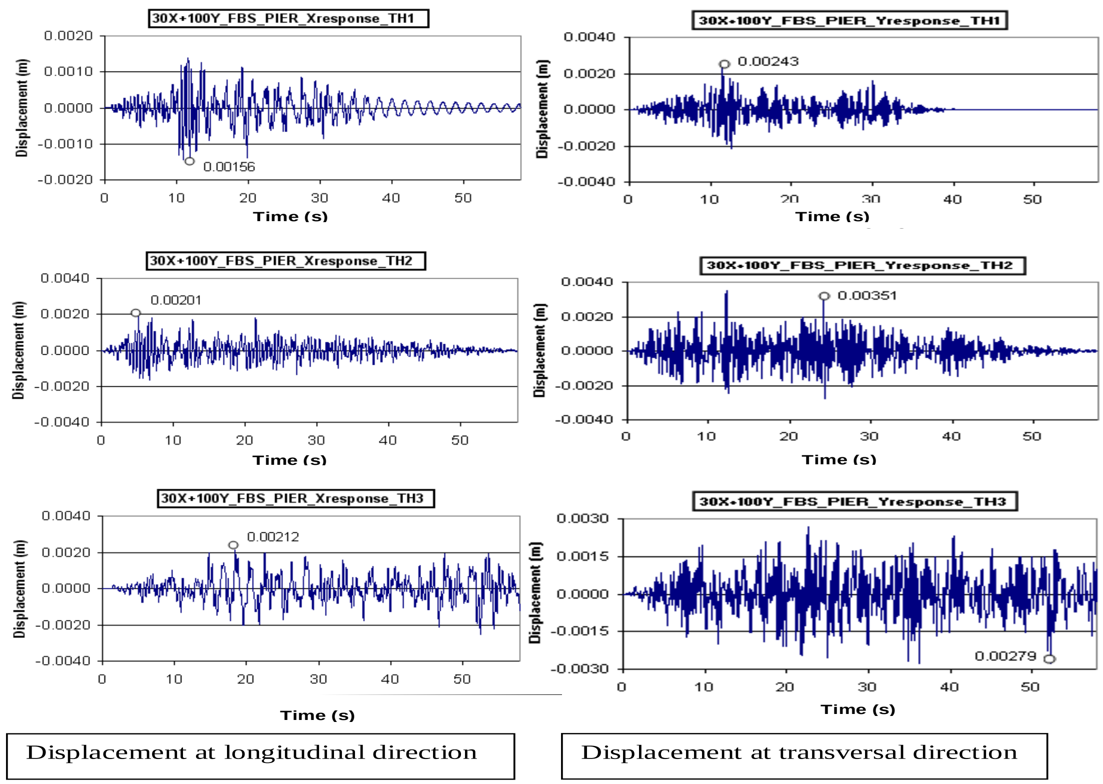

Figure 12. Longitudinal and transversal displacement response for top of pier under TH1, TH2, and TH3 loading (Fixed base support with 30%X+100%Y earthquake direction).

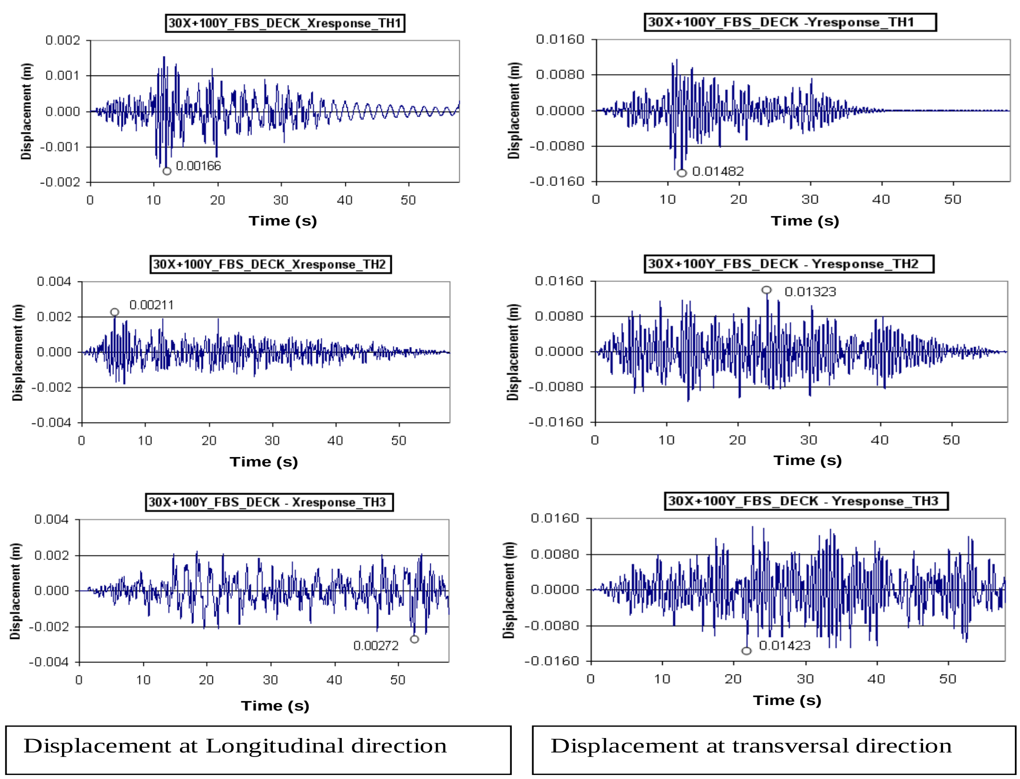

Figure 13. Longitudinal and transversal displacement response for middle of deck under TH1, TH2, and TH3 loading (Fixed base support with 30%X+100%Y earthquake direction).

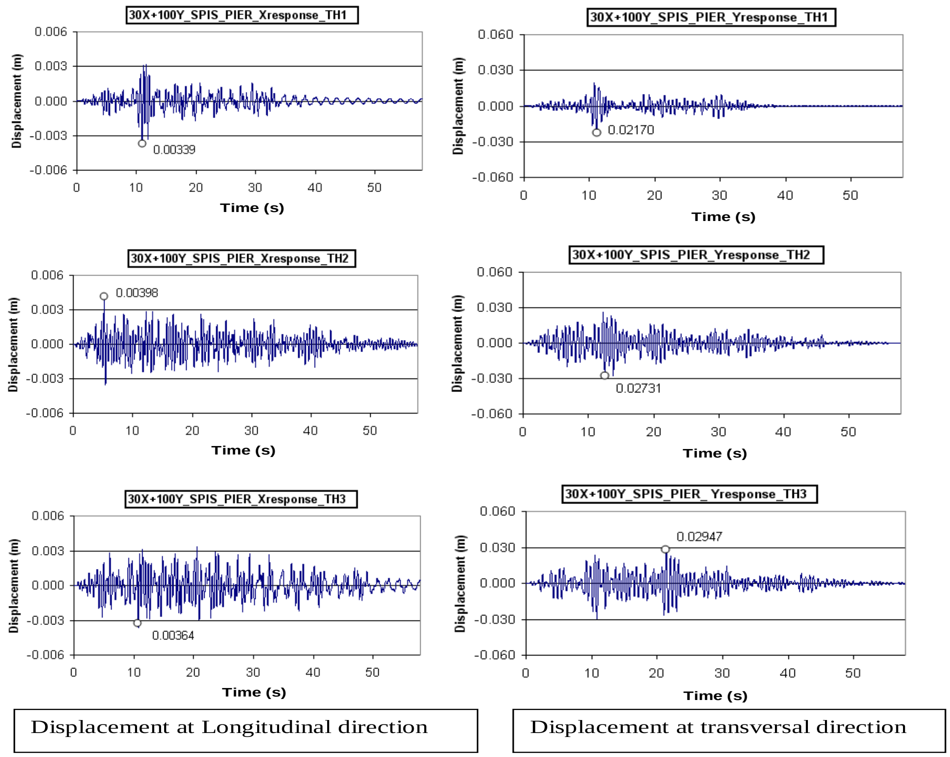

Figure 14. Longitudinal and transversal displacement response for top of pier under TH1, TH2, and TH3 loading (Soil-pile interaction with 30%X+100%Y earthquake direction).

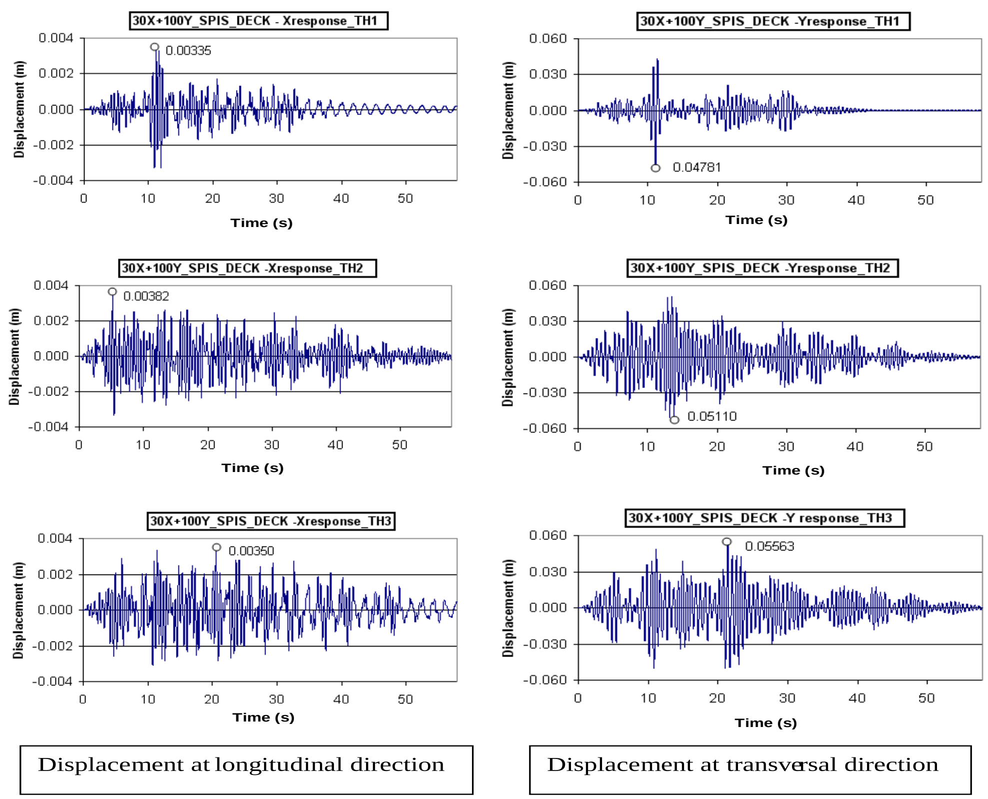

Figure 15. Longitudinal and transversal displacement response for middle of deck under TH1, TH2, and TH3 loading (Soil-pile interaction with 30%X+100%Y earthquake direction).

Table 3. Structure displacement for 30%X+100%Y earthquake direction combination.

Combination earthquake loading direction	Joint node	Max displacement (m)		Description
		X- direction	Y- direction	
SPIS	217	0.00398	0.02947	Top of pier
	2270	0.00382	0.05563	Middle of span
FBS	217	0.00212	0.00351	Top of pier
	2270	0.00272	0.01482	Middle of span

SPIS, soil pile interaction support; FBS, fixed base support.

Table 4. Structure displacement: soil-pile interaction support versus fixed base support.

Earthquake direction	SPIS	FBS	Difference (%)	Node displacement direction	Description
100%X+30%Y	0.01372	0.00761	80.29	217-x	Top pier
	0.00650	0.00105	519.05	217-y	
	0.01261	0.00834	51.20	2270-x	Middle span
	0.01567	0.00472	231.99	2270-y	
30%X+100%Y	0.00398	0.00212	87.74	217-x	Top pier
	0.02947	0.00351	739.60	217-y	
	0.00382	0.00272	40.44	2270-x	Middle span
	0.05563	0.01482	275.37	2270-y	

SPIS, soil pile interaction support; FBS, fixed base support.

than 0.8 times. For 30%X+100%Y earthquake direction, the top of piers response shows the transversal maximum displacement of SPIS is seven times higher compared to FBS, while longitudinal displacement is more than 0.87 times.

It is the same for middle span maximum displacement responses. For 100%X+30%Y earthquake direction, the middle of span response shows the transversal maximum displacement of SPIS is twice higher compared to FBS, while longitudinal displacement is more than 0.5 times. For 30%X+100%Y earthquake direction, the middle of span response shows the transversal maximum displacement of SPIS almost three times higher compared to FBS, while longitudinal displacement is more than 0.4 times.

This seismic analysis approved the Eurocode 8 part2 statement which says that the soil-pile interaction effects are accounted due to the soil flexibility contribution that is more than 20% of the total displacement at the top of the pier.

The analysis results are higher compared to the study that had been done by Chang and Robertson (2003). This is because, only continuous bridge (non-integral) was considered in his study. Based on Chang and Robertson (2003), for continuous bridge, transverse pier displacement for models with soil springs were up to 21% larger than model without soil springs.

Time history analysis of bridge model was performed by using the earthquake ground motion input at the surface (Figure 4). Based on the analysis result (Figures16 to 19), soil-pile interaction support bridge produced the maximum axial, shear force and bending moment for longitudinal and transversal direction for pier and deck. However, for pier response, the axial force of fixed base support bridge gives higher response compared to soil-pile interaction support bridge.

Conclusions

In this study, a detailed step by step soil spring, bridge modelling and seismic analysis procedure of integral prestressed concrete box-girder bridge was presented clearly. As a conclusion, soil-pile interaction support should be considered in seismic analysis due to the following statements:

i. Soil-pile interaction support gives longer period of structure compared to fixed base support;
ii. The displacement of soil-pile interaction is higher compared to fixed base support. The increasing of displacement happens more at transversal direction event for deck and pier;

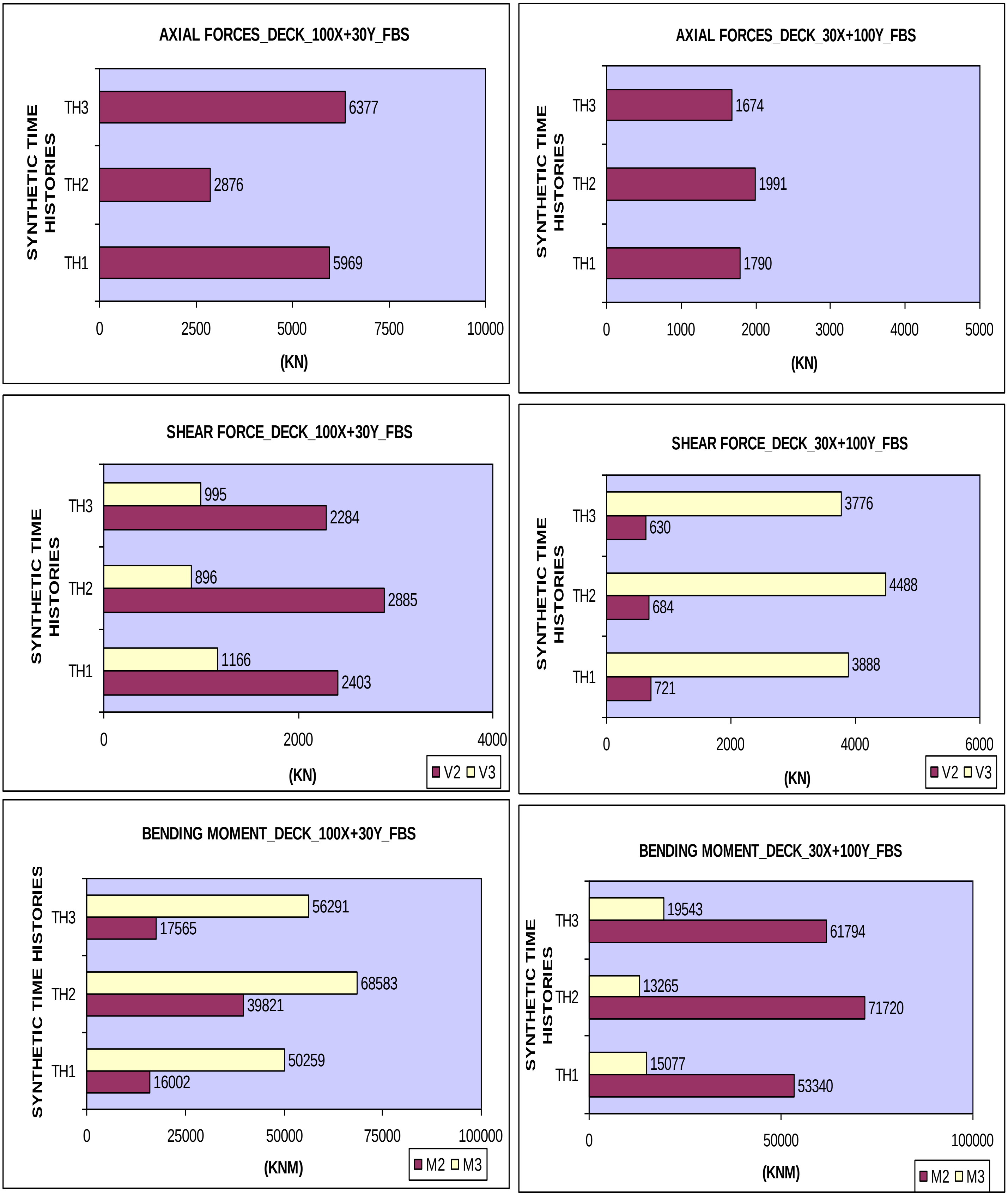

Figure 16. Deck response for fixed base supports under both earthquake direction.

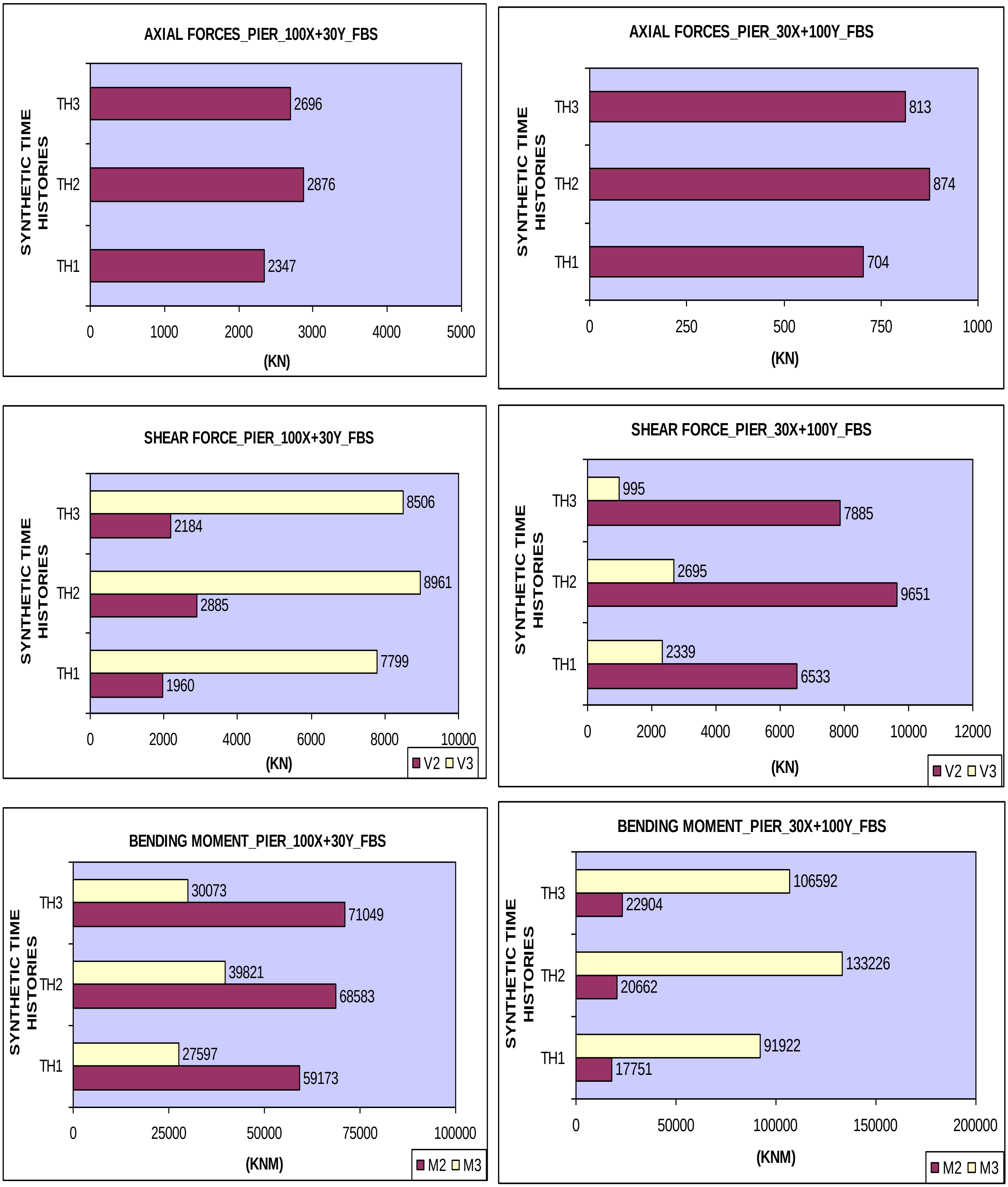

Figure 17. Pier response for fixed base supports under earthquake direction.

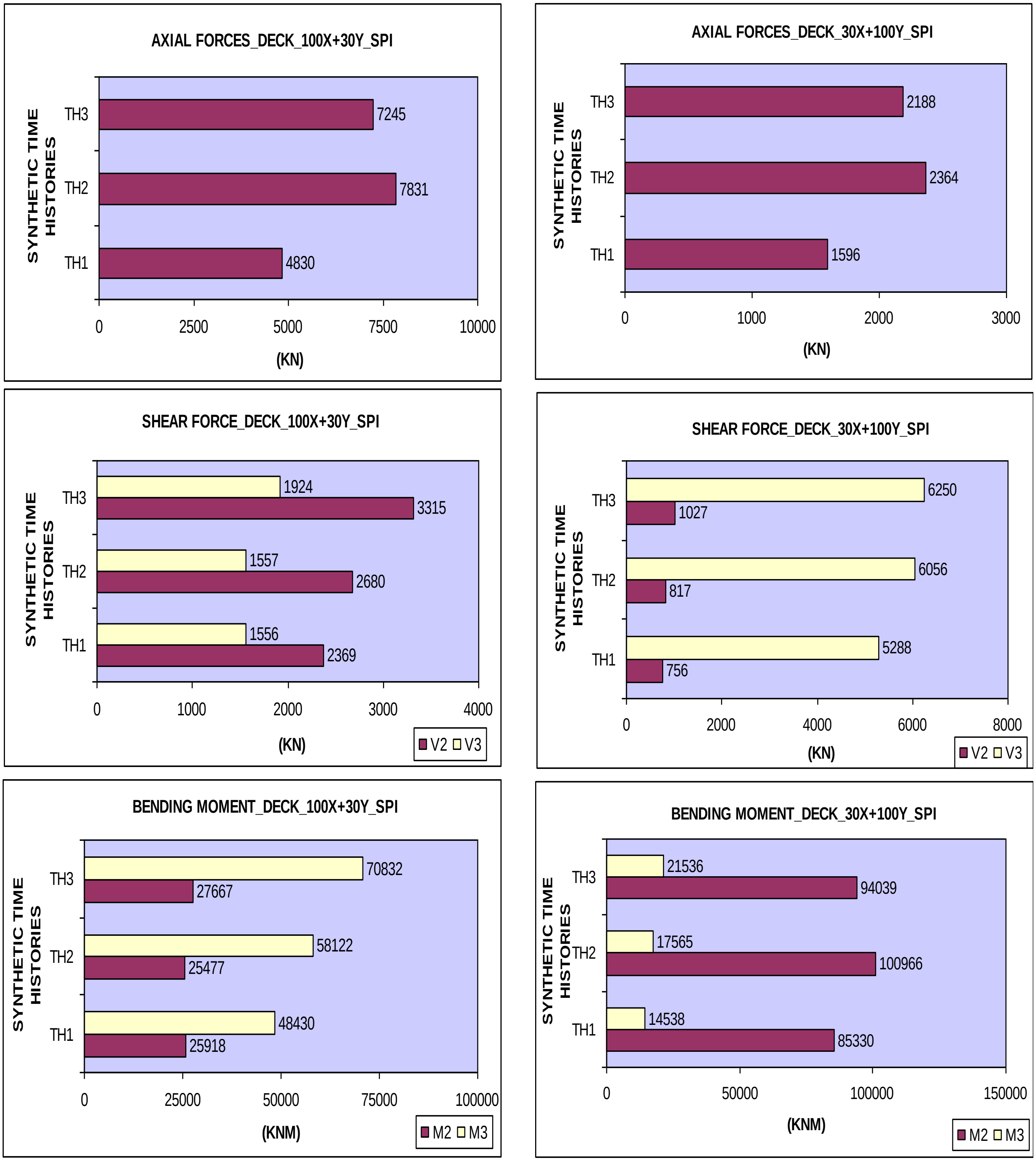

Figure 18. Deck response for soil-pile interaction support under both mix earthquake direction.

iii. All forces response from soil-pile interaction support is higher compared to fixed base support, except the axial force response of pier.

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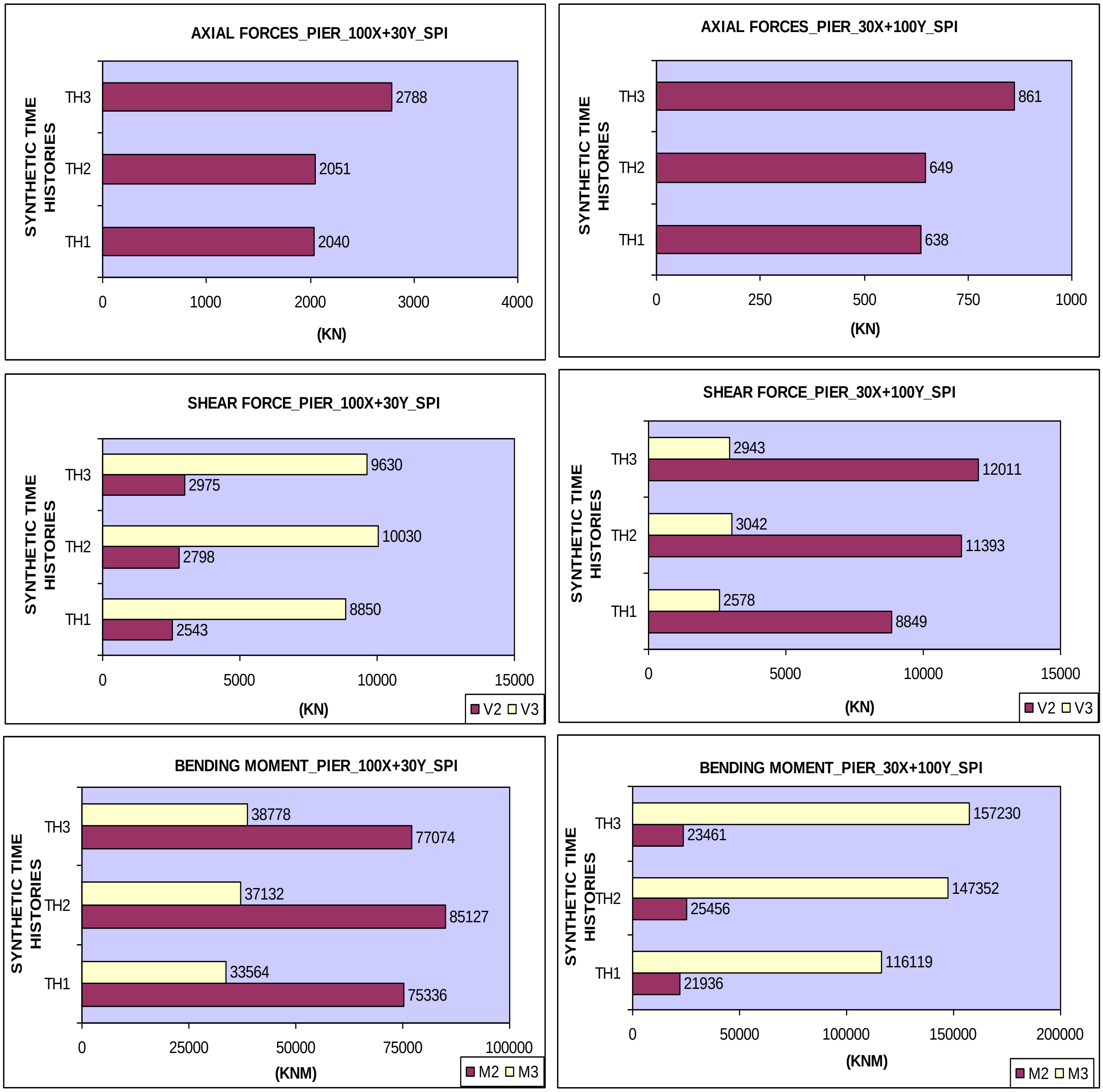

Figure 19. Pier response for soil-pile interaction support under both mix earthquake direction.

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