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Non-linear soil-structure interaction analysis of railway bridge subjected to earthquake ground motions considering different types of soil

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Abstract

In this paper, the dynamic behaviour of an existing multi-span railway bridge in Afyon (Turkey) under different earthquake ground motions considering soil-structure interaction (SSI) is investigated. A Two-dimensional (2D) finite element model of the railway bridge-soil system was established and a 2D version of the PLAXIS FEM package has been performed in numerical analysis. Considering the soil property of the bridge site, the analysis was performed for three types of soil; the soils were specified as soft, medium and stiff. Three types of earthquakes including Kocaeli (Turkey, 1999), Kobe (Japan, 1995) and Manjil (Iran, 1990) earthquakes are defined as input motions. According to the result of the dynamic analysis, the dynamic responses of the railway bridge including the horizontal and vertical displacements of the top of the railway bridge (point A), base point of the bridge (point B) and soil level (point C) are calculated by the PLAXIS program and showed as graphic form. The obtained displacement values are different for each kind of earthquake ground motion; hence, it means that the bridge structure and soil have different responses to each kind of earthquake ground motion. The displacements obtained by the Kocaeli earthquake are compared with the results obtained by Kobe and Manjil earthquakes. The analysis with PLAXIS demonstrated that for different conditions delimitation, distribution of travel and the fundamental frequency for each soil type change according to its mechanical properties. The obtained results show that the phenomenon of structural soil interaction must consider in the bridge analysis and also demonstrates that the proximity of the fundamental frequencies of the structure and soil strongly influences on soil-structure interaction.

Keywords Railway Bridge · PLAXIS 2D · Dynamic behaviour · Soil-structure interaction · Finite element method

Introduction

Railway bridges form an important transportation link in the railway network of a country and are fundamental elements of the infrastructure in modern societies. In transportation systems, sometimes it demands that the railway bridges are to be constructed across the seismic regions. Due to railway bridge importance, functionality loss of these types of bridges is not an acceptable performance criterion after a seismic event. Therefore, maintaining the safety of the railway bridge in seismic areas is of great importance for post-earthquake relief operations. The failure of the railway bridge foundation and substructure in an earthquake is one of the most common causes of damage to the structure.

The earthquake resistance of railway bridges located in seismically active regions such as Turkey is very important. Determining the soil properties accurately and taking them into account during dynamic analysis provide an important contribution for understanding the behaviour of bridge structures under earthquake conditions. During an earthquake, due to the different responses of the soil and bridge, the bridge pier affects the behaviour of the soil and the soil affects the behaviour of the bridge pier. Bridges subjected to earthquake effect move with the soil and the soil changes the dynamic behaviour of the bridge structure such as mode shape and period. Because of the importance of the soil-structure interaction

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(SSI), the earthquake regulations are included on the agenda for SSI analysis in Turkey (TEC 2007). The building code of Turkey has been revised and the new TBEC(2018) is a comprehensive revision of the TEC 2007. The new earthquake building code became legally effective in 2019.

In the past, many railway bridges have failed or were extensively damaged due to earthquakes. Seismic damage to bridges with simply supported girders was commonly caused by foundation failures due to loss of bearing capacity of the foundation soils and ground deformations. Failure of a bridge during a strong earthquake event might cause an obstruction to the necessary rescue and rehabilitation activities; it is very important to predict the behaviour of a bridge structure subjected to potential strong motions. Therefore, the safety of the railway bridges in a seismic region is of great importance particularly for post-earthquake relief operations.

Research on the dynamic response of bridges, especially to seismic actions, has reached a great interest because of the amounts of bridge failures which have happened in recent years due to earthquakes like Loma Prieta (USA, 1989), Northridge (USA, 1994) and Kobe (Japan, 1995) earthquakes. These earthquakes have demonstrated that near-field ground motions can potentially damage and severely affect structures such as bridges. These earthquakes alarmed the researchers and field engineers which started looking toward sufficient dynamic analyses and design methods to minimize the seismic risk for the protection of bridges from severe earthquake attacks.

Among many other aspects, soil-structure interaction (SSI) is an important aspect which must be considered in the dynamic modelling of the railway bridge structures. The seismic assessment of multi-span railway bridges requires consideration of dynamic SSI impacts on the seismic response of such bridges. Consideration of SSI effects is very important for defining the seismic response of bridges and lets engineers and field researchers design more seismically resilient bridges (Baheddi and Youb 2015).

There had been several studies in the past for the dynamic behaviour (especially to seismic actions) of train-bridge coupling systems. The dynamic behaviour of train-bridge systems is under the influence of seismic ground motions carried out by Wu and Yang (2002). Miyamoto et. al. (1997) presented the dynamic analysis responses of the Shinkansen train-bridge systems subjected to seismic ground motions. Xia et al. (2006) and Du et al. (2011) studied the dynamic responses of train-bridge systems under influence of ground motions considering seismic wave effects.

In recent years, many researchers have studied the effect of SSI on the seismically resilient designed bridges. Spyrakos (1990; Spyrakos 1992) by using linear-elastic models have demonstrated the extremely important role of SSI on non-isolated bridges during seismic excitations and have showed that SSI largely affects the seismic responses of such structures and increased damping. Ciampoli and Pinto (1995) investigated the conventionally designed bridge considering the inelastic piers model which was built on shallow foundation types. According to Eurocode, seven accelerograms for far field type of excitations and intermediate stiffness soils consisted in the seismic input. Mylonakis and Gazetas (2000) considered acceleration time-histories recorded on soft soil type by using a simplified bridge system model. Results showed that the increased damping and period lengthening due to soil-structure interaction effects have a negative and detrimental influence on the imposed seismic demands. A finite element (FE) study on the seismic response of the I-880 viaduct in Oakland, CA, is presented by Jeremic et. al (2004). were as the same conclusions as Mylonakis and Gazetas (2000). According to the obtained results, it concluded that SSI can have detrimental and beneficial impacts on the response of the bridge structure considering the ground motion characteristics (Fig. 1).

Mylonakis and Gazetas (2000) presented a case history in Kobe, Japan, where the Hanshin Expressway failed catastrophically during the 1995 Kobe earthquake. Obtained results showed that the soil-interaction effects were not considered during the design process and seismic analyses. Crouse et al. (1987), Somani (1984) and Spyrakos (1990; Spyrakos 1992) analytical studies have showed the significant role of SSI on non-isolated bridges during seismic excitations. Jangid and Tongaonkar (2003) studied the effects of SSI on isolated deck bridges. According to the results, consideration of the soil-structure interaction in the analytical analysis will affect the reduction in design costs and enhancement of safety. Zhang and Gu (2020) studied the seismic response of a curved bridge considering soil-structure interactions based on a separated foundation model. It is concluded that when considering SSI, the spatial variation of ground motion should be fully considered to avoid underestimating the structural response. Sextos et al. (2017) studied the effects of multi-angle input on the seismic responses of curved beam bridges based on the refined finite element model. Ramadan et al. (2020) investigated the influence of non-synchronized motion due to the difference in the ground motion arrival time at different bridge supports on the seismic performance of continuous box girder bridges with considering soil-structure interaction. Ozcelik and Sarp (2017) focused on seismic soil-structure interaction of existing buildings in the Burdur settlement area built near the active Fethiye-Burdur Fault Zone (FBFZ) in order to highlight the highly risky, potentially risky, and lowly risky buildings for guiding decisions on retrofitting or renewal these buildings (Fig. 2).

In the solution of soil-structure interaction problems, it is required to carefully model the unbounded nature of the underlying media. For solving this problem, many numerical methods such as transmitting or absorbing boundaries have been developed. Two main approaches for analyzing are the

Fig. 1 Nishinomiya-ko Bridge collapse in the 1995 Kobe earthquake

substructure method and direct method (Bab et al. 1996). Developments made by Wolf and Song (1996) concluded that employing the direct method with a restricted zone of the soil may capture the fundamental aspects of the non-linear nature of the problem which is relevant to soft soil conditions. The secondary soil non-linearity may increase or decrease the base forces of structures depending on structure type, properties of the soil and frequency content of the input ground motions (Halabian and Hesham El Naggar 2002).

Scope and objective

The objective of this research is to analyze the dynamic behaviour of an existing railway bridge in Afyon (Turkey), subjected to different earthquake ground motions considering soil-structure interaction. The analysis was performed for three types of soil (soft, medium and stiff). Kocaeli (Turkey, 1999), Kobe (Japan, 1995) and Manjil (Iran, 1990) earthquakes are defined as input motions for dynamic load. A

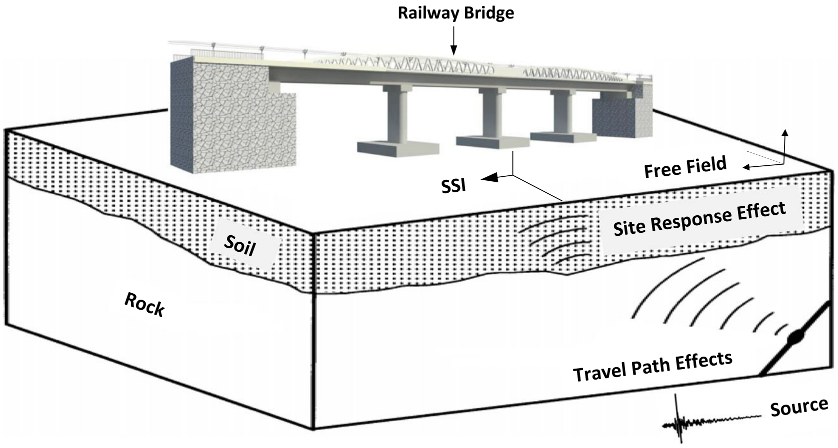


Fig. 2 Schematic showing the context of SSI in an engineering assessment of seismic loading for railway bridge system

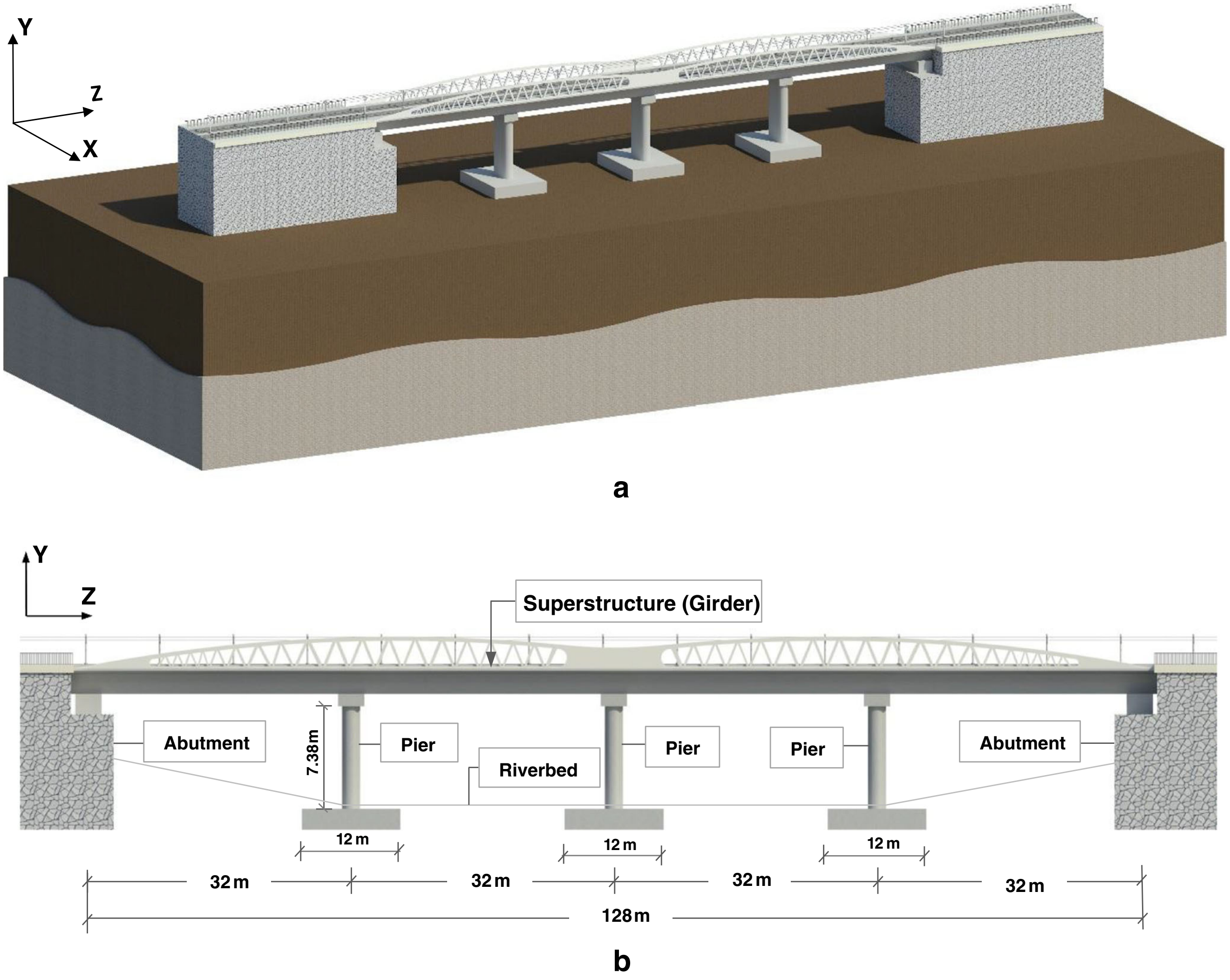


Fig. 3 (a) 3D and (b) 2D views of the railway bridge

comparative study of the displacements for these three types of soils and earthquakes has been performed. According to the results of the dynamic analysis, the relative displacement graphs for the top point of the bridge (point A), base point of the bridge (point B) and free-field (Point C) were prepared and showed in a graphic form. It is expected that the findings of the present study will guide to a better understanding of the dynamic behaviour of railway bridge under seismic loadings considering soil-structure interaction.

Description of the case study

The railway bridge system studied is a multi-span plate girder bridge as shown in Fig. 3. The proposed railway bridge is located in Afyon (Turkey), subjected to a typical seismicity. Some standard measures were taken into consideration for analyses. The bridge is a 128-m-long and 4-span structure which contains rigid abutments and RC piers. The bridge is supported on three elliptical reinforced concrete columns 7.38 m deep. The superstructure consists of a main girder of 3.25 m deep and 12 m wide. The soil types that are surrounding the railway bridge pier are considered as stiff, medium and soft. The seismic response of the railway bridge system is investigated for the three types of earthquakes. Manjil (Iran, 1990), Kobe (Japan, 1995) and Kocaeli (Turkey, 1999) earthquakes are defined as input motions in seismic analyses. The concrete class of the proposed railway bridge is C30.

Finite element modeling

The dynamic behaviour of a multi-span railway bridge considering soil-structure interaction (SSI) is studied under different earthquake ground motions. As the purpose of this study, the example of the Afyon Railway Bridge was used to set up the numerical model by taking into account absorbing boundary conditions. Finite element method (FEM) analytical

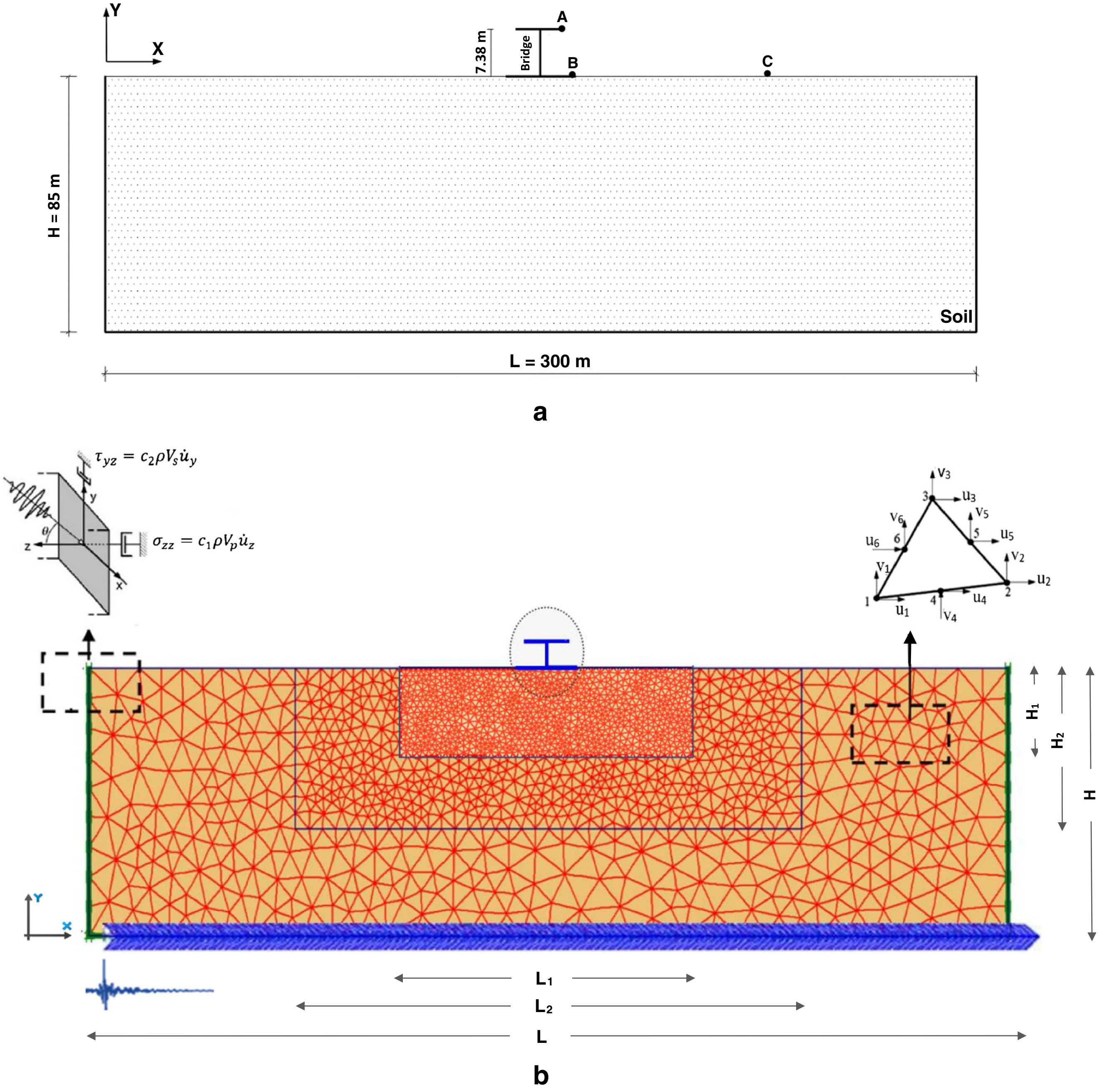


Fig. 4. Soil-structure model. (a) General form of soil-structure model. (b) Plaxis 2D finite element mesh

models were developed for numerical analysis. A two-dimensional view of the finite element (FE) mesh is shown in Fig. 4. The dynamic behaviour of the bridge pier-soil system is observed and different analyses were performed in terms of comparative results. The comparative results are presented and showed in graphic form. In this study, a 2D finite element (FE) model under plane-strain condition considering the undrained elastoplastic Mohr-Coulomb model is applied for seismic analysis. For this purpose, the soil-structure model was defined using the PLAXIS 2D and finite element method (Brinkgreve et al. 2002). For determining the FE model dimensions, many analyses were employed in the past and it is suggested that these boundary areas must be as far as at least 8–10 times of the superstructure base width (Rosset and Kausel 1976). In the present study, in addition to the existing information, two-dimensional (2D) plane strain analyses of soil were employed to find the sufficient soil dimensions for soil-structure analyses. Discretization of the FE model of the soil area has been made by taking into account the absorbing boundary conditions. Firstly, the effect of wave propagation on the horizontal expansion of the soil model was investigated by keeping the height of the soil model constant ($H = 60$ m).

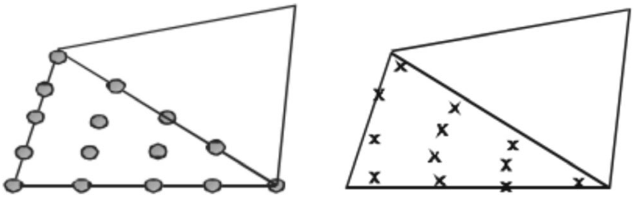


Fig. 5 Stress point position in soil elements (Brinkgreve 1998)

According to the time-displacement relationship results obtained from the points where the wave propagation is controlled, it is concluded that L = 300 m is sufficient. After determining the horizontal expansion of the FE model of the soil area (L = 300 m), the effect of the wave propagation on the height of the soil model was also investigated. According to the time-displacement relationships taken from the points where the wave propagation is controlled, it is concluded that it is sufficient to choose H = 85m and Δh = 4m. According to analysis results, the finite element model dimensions of the soil component were chosen as 300 m by 85 m. The mesh of the subzones (hereby: H_1 = 20 m, L_1 = 80 m; Δh_1 = 1 m, H_2 = 52 m, L_2 = 190 m; Δh_2 = 2 m and the remaining subzone area; Δh = 4m) are used in the modeling.

The soil model and mesh geometry are both considerable parameters in this study. In order to simulate the response of soils under dynamic loading, the advanced constitutive material properties can be used for a detailed modeling of the dynamic strain-stress behaviour of soils which carry on high non-linearity under large amplitude forced vibrations such as seismic loading (Celebi and Kirtel 2013). In the present study, for two-dimensional analysis of the bridge-soil system, 15-node triangular elements which provide accurate stresses and strain calculation are chosen and shown in Fig. 5.

The behaviour of the soil considered in this study is simulated according to the undrained elastoplastic Mohr-Coulomb model considering plane-strain conditions. The Mohr-Coulomb model is generally used for granular materials such as soil. The stress-strain relationship is considered as elasto-perfectly plastic (Fig. 6).

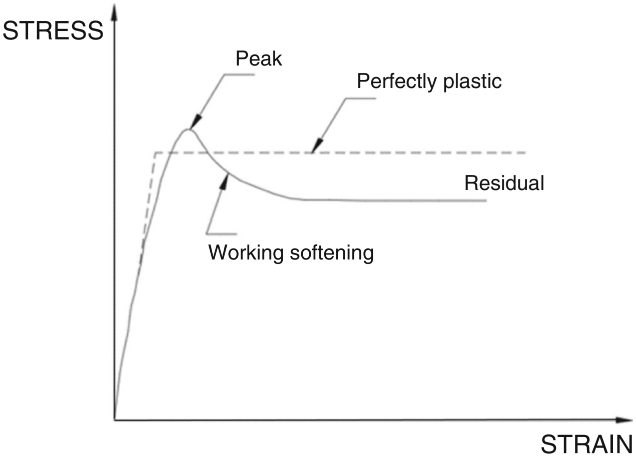


Fig. 6 Elasto-plastic assumption of the Mohr-Coulomb model (Pantelidis 2019)

Seismic analysis of the railway bridge

The arrangement of the analyses is based on a simplified model of a multi-span railway bridge which is located in Afyon, Turkey. As the purpose of this study, the example of the Afyon Railway Bridge is used to set up the numerical model by taking into account absorbing boundary conditions. Dynamic behaviour of the railway bridge specially seismic actions and time history analyses of the soil-structure models were achieved. The seismic response of railway bridge is studied for different types of earthquakes with different properties taken from the PEER NGA database. Kobe (Japan, 1995), Kocaeli (Turkey, 1999) and Manjil (Iran, 1990) earthquakes are defined as input motions (Fig. 7). There are two main important factors in the selection of the relevant earthquake records. One of them is the peak ground acceleration (PGA) value in order to see the effect of the magnitude of the earthquake on the soil-structure system and the other one is frequency content to observe the structure-soil-earthquake interaction in different soil conditions. The natural fundamental frequency of the bridge pier used in the dynamic analyses was 3.7 Hz. Seismic waves with different characteristics have a great influence on the dynamic response of structures. Three different earthquake ground motions were used to see the effects of earthquakes with a fundamental frequency far and close to the structure frequency and also to observe how different soil conditions change these effects. The properties of strong motion parameters for selected earthquakes are different and given in Table 1.

By inputting the earthquake accelerations as input motions to the system, the dynamic responses of the bridge including the horizontal and vertical displacements for different points were obtained by PLAXIS 2D FEM software. While selecting the observation points, measurement points were defined on the soil surface (C) and base point of the structure (B) to obtain the results and see the kinematic interaction which is a part of the soil-structure interaction. Furthermore, the "A" measurement point is defined in order to observe the behaviour of the soil-structure as a whole system under the effect of earthquake ground motions. Obtained results by the Kocaeli earthquake are compared with the results obtained by the Manjil and Kobe earthquakes (Figs. 8 and 9).

Considering the soil property of the bridge site, in this part of the study, a seismic analysis was performed for one type of soil which is selected as soft. The properties of the soil are given in Table 2.

Table 1 Properties of the earthquake ground motions

Earthquake	Date	Magnitude	PGA (g)	Resonance frequency (Hz)
Kobe	16-01-1995	6.9	0.50	2.07
Kocaeli	17-08-1999	7.4	0.35	0.29
Manjil	20-06-1990	7.4	0.51	2.92

A suitable value for the strength reduction factor in the interface (R_{inter}) was chosen in order to model the roughness of the interaction. This parameter is related to the soil strength to the interface strength which is represented by the following equation:

$$\tan(\varphi)_{\text{interface}} = R_{\text{inter}} \cdot \tan(\varphi)_{\text{soil}}, c_{\text{inter}} = R_{\text{inter}} \cdot c_{\text{soil}}$$

Where c and φ are the cohesion (adhesion) and friction angle of the interface which is used in the material model of the interface material. For real soil-structure interaction, the interface is weaker and more flexible than surrounding soil which means that the value of R_{inter} should be less than 1.0. In the absence of detailed information, this value is assumed to be of the order of 2/3 (Brinkgreve and Vermeer 1998). According to the soil properties, the value of R_{inter} for this analysis was chosen 0.67.

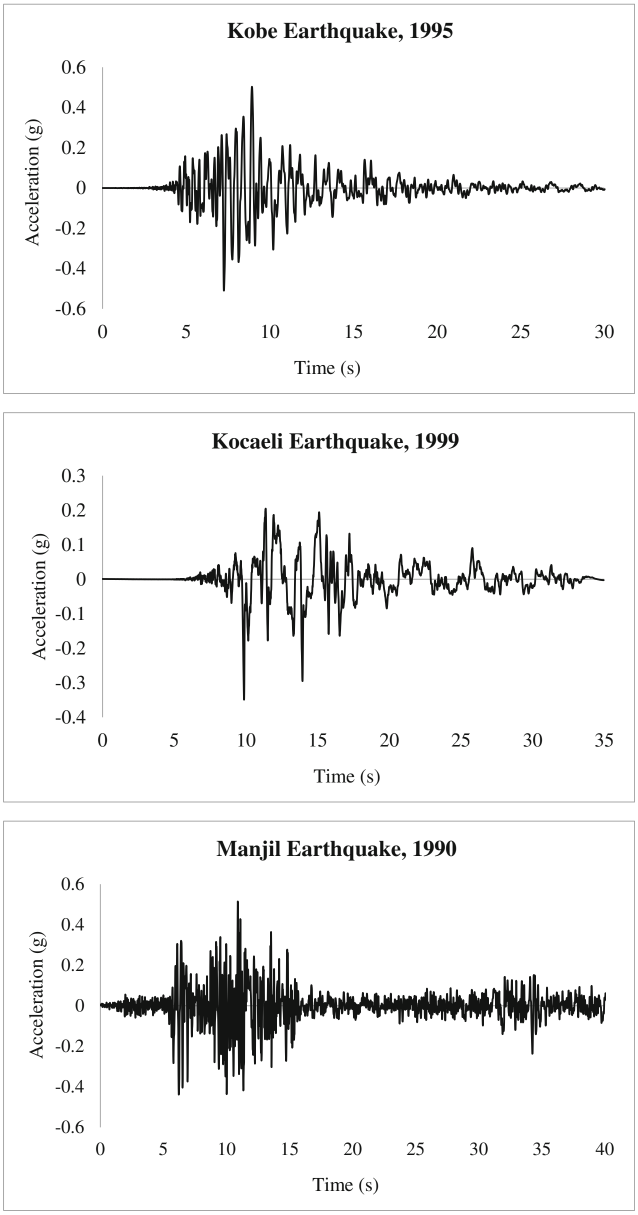


Fig. 7 Acceleration records of Kobe, Kocaeli and Manjil earthquakes

In this part of the study, the dynamic behaviour of the bridge pier-soil system is carried out for different soil conditions with different stiffnesses. According to the results, the dynamic responses (horizontal and vertical displacements) of the bridge for the top point of the bridge (point A) for different types of soils are obtained comparatively and showed in graphic forms. Kocaeli (Turkey, 1999) earthquake is defined as input motion in the seismic analysis (Fig. 6b). Considering the soil property of the railway bridge site, the analysis was performed for three types of soils. In order to create the substructure soil models, railway bridge surrounding soil was selected as soft, medium and stiff. The properties of the soils are given in Table 2.

Considering the Kocaeli earthquake acceleration as input motion, the behaviour of the bridge-soil under this earthquake was investigated (Fig. 10). The horizontal and vertical displacements of the top of the railway bridge (point A) were calculated by the PLAXIS 2D FEM package for each type of soil and the relative graphs for the selected point were prepared (Fig. 11).

Results and conclusions

The purpose of this investigation was to study the dynamic behaviour of a multi-span railway bridge system under seismic actions considering soil-structure interaction (SSI). Finite element method (FEM) analytical models were developed for numerical analysis and the soil-structure interaction effects under ground motion are directly carried out. The objective of this study was to develop an understanding of the seismic response of a soil-bridge system for different types of soils under the influence of different earthquakes. In this study,

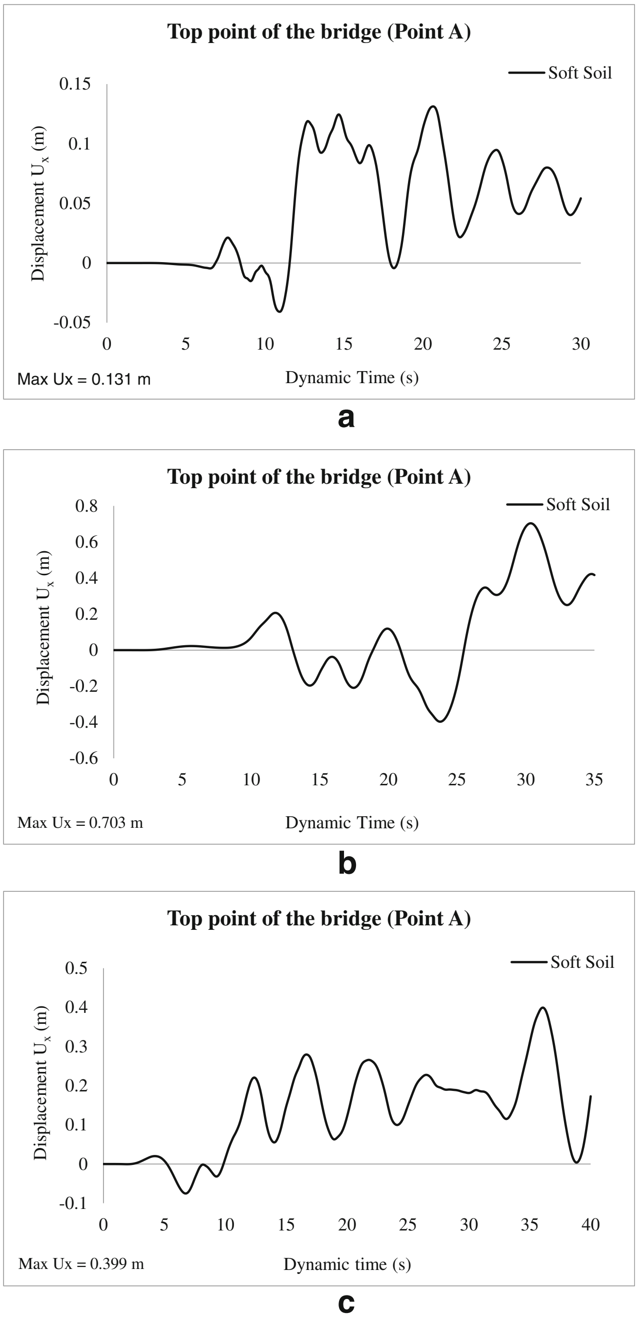


Fig. 8 Time-history of the horizontal displacement under the influence of different earthquakes. (a) Kobe earthquake, 1995. (b) Kocaeli earthquake, 1999. (c) Manjil Earthquake, 1990

three types of earthquake motions were selected in order to measure the influence of ground motion as a dynamic effect. The Kocaeli (Turkey, 1999), Kobe (Japan, 1995) and Manjil (Iran, 1990) earthquakes were used as inputting motion. To modify the dynamic behavior of the bridge pier-soil system to seismic actions, analysis is carried out for different soil conditions with different stiffnesses. Three types of soil were considered for analyses and defined as soft, medium and stiff.

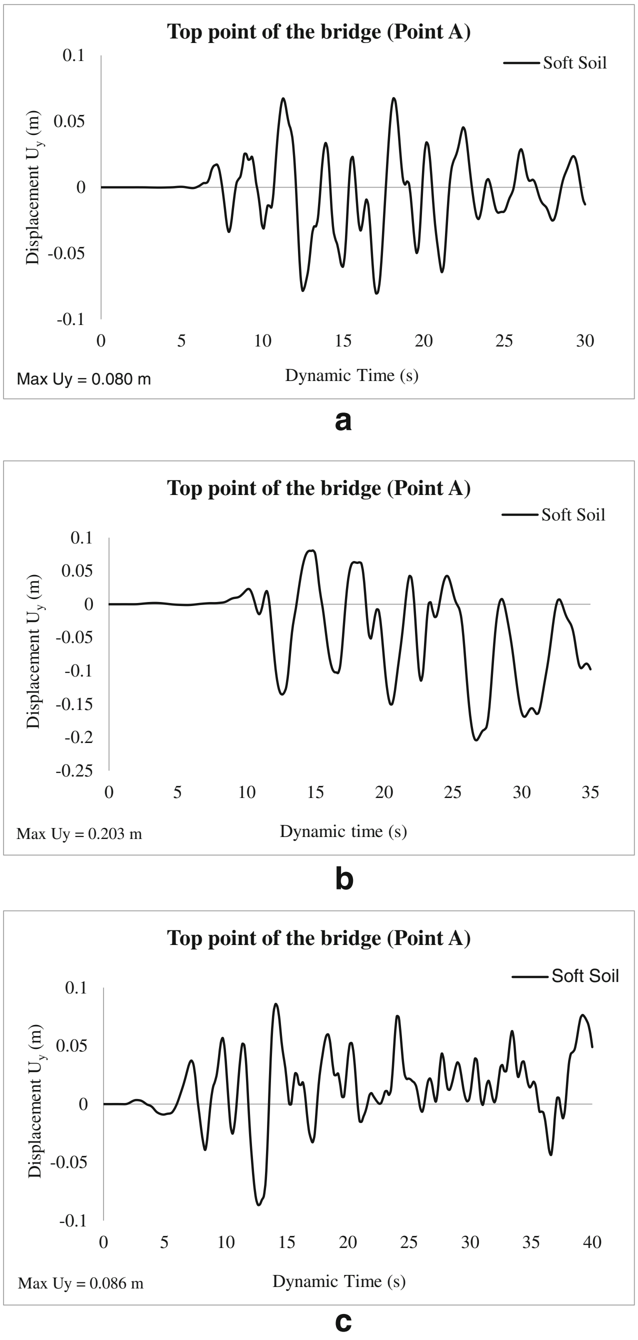


Fig. 9 Time-history of the vertical displacement under the influence of different earthquakes. (a) Kobe earthquake, 1995. (b) Kocaeli earthquake, 1999. (c) Manjil Earthquake, 1990

Figures 11 and 12 illustrate that the maximum horizontal displacements for soft soil, medium soil and stiff soil under the influence of the Kocaeli earthquake are respectively 0.703 m, 0.884 m and 0.419 m. As a result, the maximum horizontal displacement of the top of the bridge (point A) for medium soil was respectively 20% and 53% bigger than soft and stiff soils. The maximum vertical displacements for soft soil, medium soil and stiff soil are respectively 0.203 m, 0.128 m and

Table 2 Properties of the soil for undrained Mohr-Coulomb model (Dave and Tim Law 2006)

Parameter	Symbol	Unit	Soil type		
			Soft	Medium	Stiff
Total unit weight	γ	kN/m^3	16.68	18.88	19.62
Young's modulus	E	kN//m^2	15000	32500	75000
Shear modulus	G	kN//m^2	5434.78	11950	27780
Poisson's ratio	ν	-	0.38	0.36	0.35
Compression wave velocity	V_p	m/s	128.40	168.4	245.2
Shear wave velocity	V_s	m/s	56.51	78.75	117.8
Cohesion	c	kN//m^2	25	50	100
Friction angle	φ	o	35	35	35
Dilatancy angle	ψ	o	0	0	0
Interface strength reduction factor	R_{inter}	-	0.67	0.67	0.67

0.091m. It was found that the maximum vertical displacement of the top of the bridge for soft soil was respectively 37% and 55% bigger than medium and stiff soils. Furthermore, the maximum horizontal and vertical displacements for the fixed base (rigid base system) under the influence of the Kocaeli earthquake are 0.026 m and 0.005 m respectively. According to the results, the maximum horizontal displacement of the top of the bridge for the fixed-base system was 80% higher than maximum vertical displacement.

The results of the analyses from Figs. 8 and 9 show that the maximum horizontal displacements under the influence of the Manjil and Kobe earthquakes for soft soil are respectively 0.399 m and 0.131m. Examining the obtained results, it was found that the maximum horizontal displacement of the top of the bridge under the Kocaeli earthquake was respectively 43% and 81% bigger than the Manjil and Kobe earthquakes. The obtained results of maximum vertical displacements under the influence of the Manjil and Kobe earthquakes for soft soil are respectively 0.086 m and 0.080 m. It was found that the maximum vertical displacement of the top of the bridge under the Kocaeli earthquake was respectively 58% and 60% bigger than the Manjil and Kobe earthquakes.

Figure 13 shows that, the maximum horizontal displacements of the top of the railway bridge (point A), base point of the bridge (point B) and soil level (point C) under the influence of the Kocaeli earthquake for soft soil are respectively 0.703 m, 0.470 m and 0.344 m. According to the results, the maximum horizontal displacement of point A was respectively 33% and 51% bigger than point B and point C. On the other hand, the maximum vertical displacements of the selected points (A, B and C) under the influence of the Kocaeli earthquake for soft soil are respectively 0.203 m, 0.276 m and

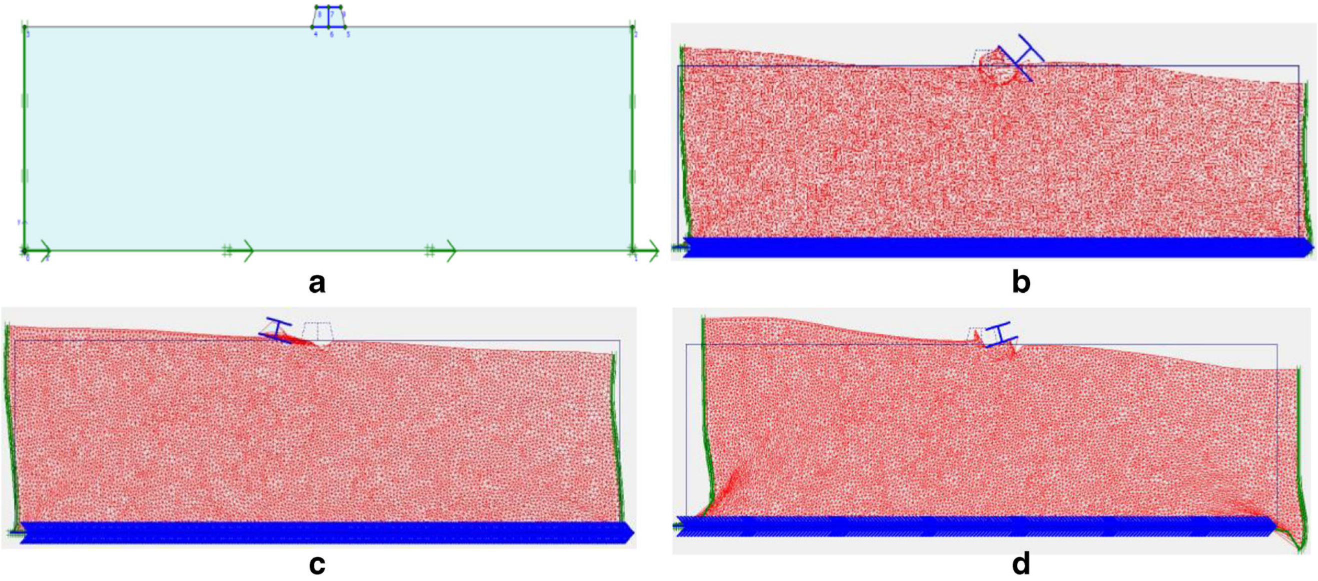
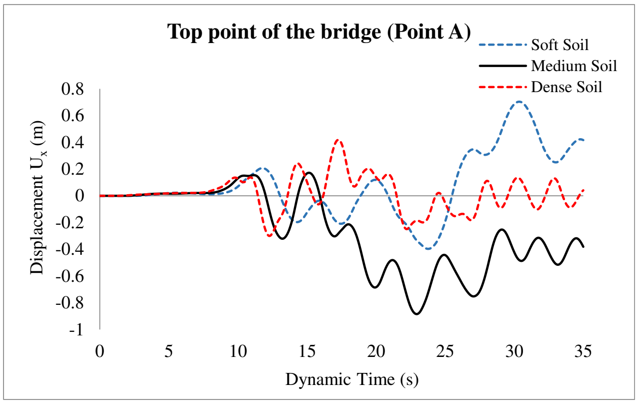
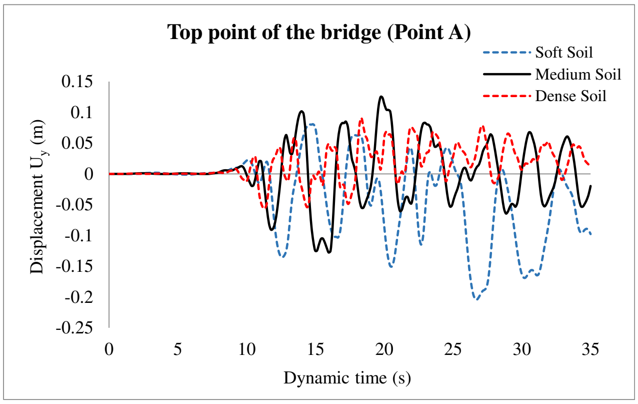


Fig. 10 Deformed shape of the soil-structure system under the influence of Kocaeli earthquake ground motion (PLAXIS 2D). (a) General form of soil-structure model. (b) Soft soil. (c) Medium soil. (d) Stiff soil

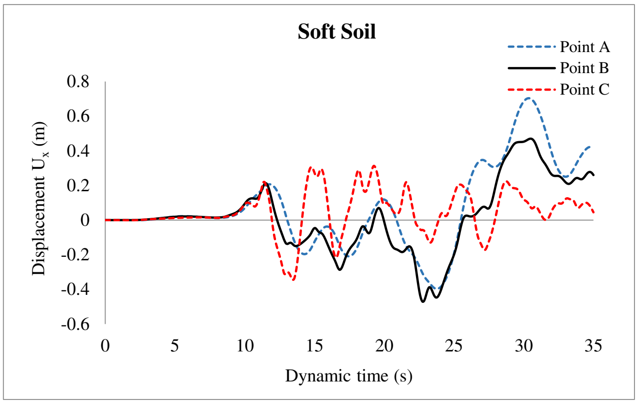


Max Ux for soft soil: 0.703 m, Max Ux for Medium Soil: 0.884 m, Max Ux for Stiff Soil: 0.419 m

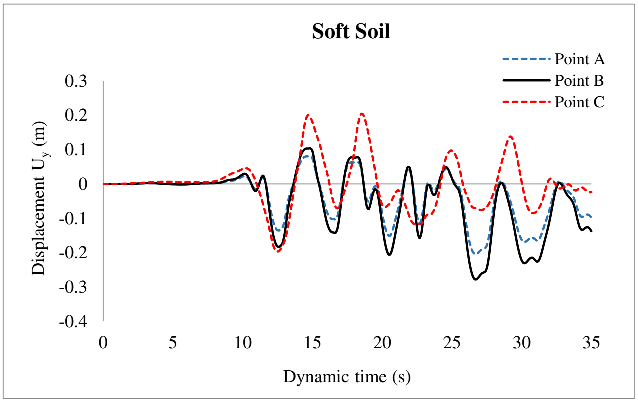


Max Uy for soft soil: 0.203 m, Max Uy for Medium Soil: 0.128 m, Max Uy for Stiff Soil: 0.091m

Fig. 11 Behaviour of the bridge-soil system for different soil conditions under the influence of Kocaeli earthquake



Max. Disp. for Point A: 0.703 m, Max. Disp. for Point B: 0.470 m, Max. Disp. for Point C: 0.344 m



Max. Disp. for Point A: 0.203 m, Max. Disp. for Point B: 0.276 m, Max. Disp. for Point C: 0.202 m

Fig. 13 Behaviour of the bridge-soil system under the influence of the Kocaeli earthquake

0.202 m. It was found that the maximum horizontal displacement of point B was respectively 26% and 27% bigger than point A and point C.

The analysis with PLAXIS 2D demonstrated that for different conditions delimitation, distribution of travel and the fundamental frequency for each soil type change according to its mechanical properties and it has been observed that the mechanical properties of the soil and also the frequency content of the seismic load largely affect the dynamic behaviour of the proposed bridge pier and the maximum displacements differ when considering soil-structure interaction. The obtained results show that it is necessary to consider the phenomenon of soil-structure interaction in the bridge analysis and also demonstrates that the proximity of the fundamental frequencies of the structure and soil strongly influences soil-structure interaction. From the obtained results, it is concluded that to analyse or design structures to resist strong earthquakes, it is necessary to have an understanding for selecting earthquake ground motion records for performing time-history analyses or designing and evaluating existing structures. The important characteristics of the ground motions like magnitude, peak ground acceleration and frequency content should be considered in the selection procedure.

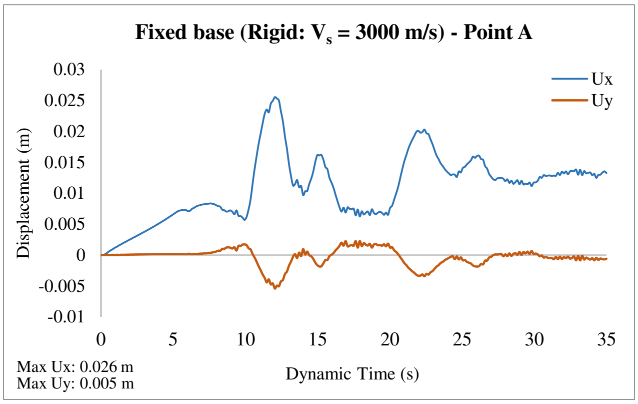


Fig. 12 Behaviour of the bridge-soil system for fixed base (rigid base) under the influence of Kocaeli earthquake

Declarations

Conflict of interest The authors declare that they have no competing interests.

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