

# Model tests and FE-modelling of dynamic soil-structure interaction

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**Abstract.** The forces applied to a structure from the soil ground during an earthquake and the dynamic response of a structure are problems that are not well understood. In recent years, seismic design technology aided by numerical simulation is under active development. Successful improvement of the accuracy and reliability of numerically simulated results relies on a clear understanding of the seismic force transmission mechanism between the soil and a structure associated with mechanical properties of soil.

In this study, laboratory shaking tests were conducted using the unique apparatus designed to have a structure move only by its inertial force and the lateral earth pressure that comes from surrounding sandy soils. The earth pressure at the structure surface and the relative displacement between the soil and the structure were measured in the experiments under various conditions.

A new Finite Element interface model for sandy soil-structure dynamic interaction is proposed from the experimental results. Estimated seismic responses of a bridge pier calculated by the proposed interface model, conventional linear elastic model and tension cut-off model are compared.

Keywords: Soil-structure dynamic interaction, laboratory shaking test, finite element method, earthquake

## 1. Introduction

The basic concept of seismic designs and technologies is to ensure that structures resist the largest earthquake on record without collapse (e.g. [1,2]). The forces applied to a structure from the soil ground during an earthquake and the dynamic response of a structure against seismic motions are problems that are not well understood and highly structured. Safety factors are widely used in the design to compensate the uncertainty associated with these problems. In recent years, seismic design technology aided by numerical analyses is under active development (e.g. [3,4]). The improvement of the accuracy and reliability of numerical simulations can not be achieved without a clear understanding of the seismic force transmission mechanism between the soil and a structure.

In a seismic force transmission mechanism problem, the main concerns are the earth pressure applied at the interface of the structure and the soil, the displacement of the structure and the deformation of the soil. A soil-spring is the most commonly used numerical model to apply seismic forces and traction to a structure and to impose displacement boundary conditions (e.g. [1,2]). However, the soil-spring stiffness is generally determined without regard to the stress-strain behaviour of the soil, which depends on its stress history and its properties such as water content, bulk density and grain size distribution.

The authors have provided that model test results of a nonlinear relationship between the applied earth pressure and the relative displacement of an underground structure, and indicated that an elasto-viscoplastic model with Mohr-Coulomb yield criteria is adequate for simulations of the relationship (e.g. [5,6]).

In this study, a new finite element modelled the dynamic earth pressure-displacement behaviour of an interface

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between the soil and the structure is proposed from laboratory shaking tests results. Two dimensional finite element analyses of dynamic response of a bridge pier during earthquake are carried out in which the proposed interface element is used to estimate the soil-foundation dynamic interaction. The simulated results are compared with those of a numerical model using the conventional linear elastic and tension cut-off interface models.

## 2. Model shaking tests

### 2.1. Outline of laboratory shaking test

Laboratory shaking tests were carried out to investigate a dynamic interaction between a soil and a structure. A schematic diagram of the laboratory shaking test apparatus is shown in Fig. 1 [5]. The shaking of the tank was allowed in only one horizontal direction as shown in Fig. 1.

Inside of the shaking tank, a hollow rectangular structure model made of steel with 40 cm width, 30 cm depth and 80 cm height was placed in the centre of the tank. At the both sides of the structure model, rectangular parallelepiped soil grounds of 40 cm width, 30 cm depth and 40 or 60 cm height were made as shown in Fig. 1. The mass of the structure model was set to 50, 75, 100 or 150 kg. On the interface between the bottom of the structure model and the tank, steel ball bearings were installed to cut off the lateral force transmitted through the interface as shown in Fig. 1 [6]. The soil grounds were made by tamping to fill the gaps between the structure model and the tank. When the tank is shaking, therefore, only the lateral forces coming from the soil grounds act upon the structure model except for bearing vertical support forces.

The earth force applying to the structure model was measured by pressure transducers installed on the structure model as shown in Fig. 1. The relative displacement between the structure model and the tank was measured by a laser distance sensor attached to the tank. The details of the soil parameters used in the tests are shown in Table 1 (about soil parameters, see [7] for example).

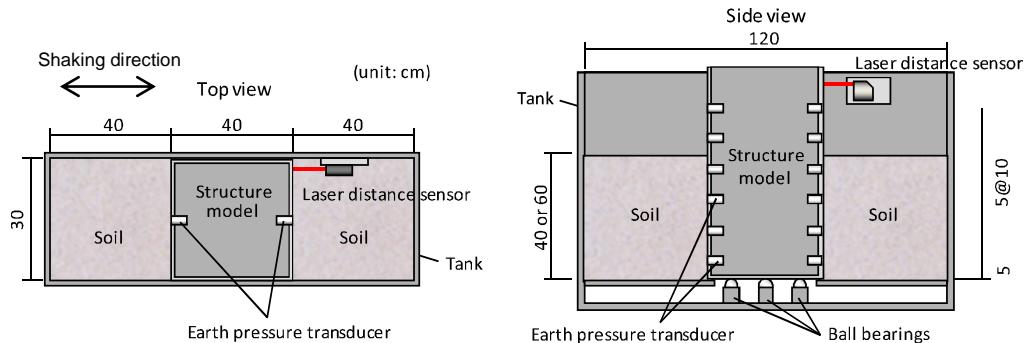


Fig. 1. Shaking tank details [5].

Table 1  
Soil test results

Density (g/cm <sup>3</sup> )	2.658
Clay	12.29
Element composition (%)	
Silt	7.50
Fine sand	77.02
Medium sand	3.19
Uniformity coefficient $U_c$	56.70
Curvature coefficient $U'_c$	28.40
Mean grain size $D_{50}$ (mm)	0.16
Optimum water content $w_{opt}$ (%)	10.64
Maximum dry density $\rho_{max}$ (g/cm <sup>3</sup> )	1.804

2  
3      Table 2  
Shaking test parameters

Soil property	Initial mass density $\rho_0$ (g/cm <sup>3</sup> )	1.91
	Initial void ratio $e_0$	0.54
	Water content $w$ (%)	10.6
	Soil depth (cm)	40
Structure property	Mass (kg)	120
Sinusoidal shaking waveform	Frequency (Hz)	4
	Displacement amplitude (mm)	10
	Maximum acceleration (gal)	632

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5      **2.2. Laboratory shaking test results**

6      Experimental earth pressure-relative displacement relations on the structure wall were measured at the depth of  
7      5 cm lower from the soil surface and further every 10 cm. Elastic modulus of soil  $E$  was calculated by assuming  
8      one-dimensional compression from the gradient of the earth pressure-relative displacement relation curve under  
9      compressive loading  $K$  (Eq. 1).

10     
$$E = KW \quad (1)$$

11    where  $W$  is a compression span that is 40 cm in this experiment. Gradient  $K$  is calculated as follows:

12     
$$K = (p_{\max} - p_{\min}) / (\delta_{\max} - \delta_{\min}) \quad (2)$$

13    where  $p_{\max}$  and  $p_{\min}$  are the maximum and the minimum earth pressure,  $\delta_{\max}$  and  $\delta_{\min}$  are the maximum and the  
14    minimum relative displacement after the curve has fully developed and reached a stationary state (see Fig. 2).15    Elastic modulus of the soil at the depth of 5 cm upper from the bottom of the tank  $E_{bottom}$  is approximated by the  
16    void ratio of soil  $e$  as following equation, which was obtained by least square fitting from the results of 31 shaking  
17    tests as shown in Fig. 3.

18     
$$E_{bottom} = 18700 \exp(-11.3 e) \quad (3)$$

19    Elastic modulus of soil  $E$  also varies according to the soil depth. Figure 4 shows the variation of normalised  
20    elastic modulus  $E$  with respect to  $E_{bottom}$ . The static lateral earth pressure increases with increasing soil depth  
21    (e.g. [7]). This property was also observed in the dynamic lateral earth pressure measured in our experiments, which  
22    is implied in the distribution of the fraction  $E/E_{bottom}$  shown in Fig. 4. We discuss here only the experimental results  
23    of the deepest earth pressure observation point, because in shallow soil, the magnitude of the dynamic lateral earth  
24    pressure is relatively small and furthermore soil particles can easily change its position under low vertical pressure,  
25    and that makes difficult to observe the earth pressure accurately. Relation between the soil depth  $d$  (cm) and the  
26    fraction  $E/E_{bottom}$  is simply modelled by following equations to determine the elastic modulus distribution in depth.

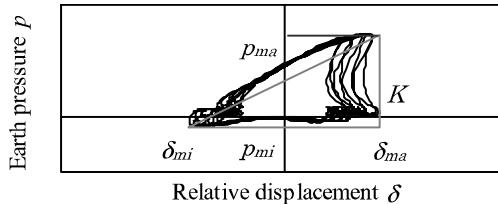
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$$E/E_{bottom} = \begin{cases} 0.2 & (d < 20) \\ 0.2 + 4(d - 20)/75 & (d \geq 20) \end{cases} \quad (4)$$

28      **3. Interface stress-strain relation modelling**29    From a study of the results of the experiment described in the previous section, a new model for soil that repre-  
30    sents the normal stress-strain relations perpendicular to the wall of the structure is proposed here. The stress-strain  
31    diagram shown in Fig. 5a shows the features of the proposed model. In this model, normal elastic modulus  $E_n$  is a  
32    function of normal strain increment  $d\varepsilon_n$ . When  $d\varepsilon_n$  is positive (compressive increment here),  $E_n$  equals to the elastic

33 modulus of the soil  $E$  (paths OA and CD), and when  $d\varepsilon_n$  is negative (tensile increment here),  $E_n$  equals to zero and  
 34 the normal stress  $\sigma_n$  immediately turns to zero (paths ABC and DEO).

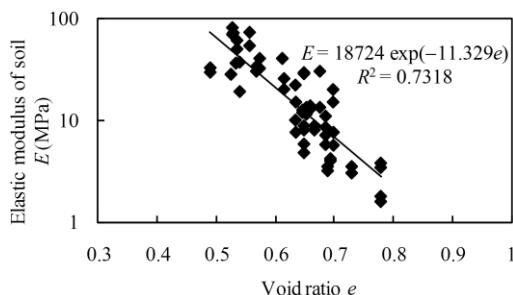
35 There is a clear difference in modelling of the unloading path between the proposed model and a tension cut-off  
 36 model (Fig. 5b). In the unloading paths, the normal elastic modulus  $E_n$  of the proposed model is always set to zero,  
 37 while that of the tension cut-off model keeps the initial elastic modulus  $E$  until the normal strain  $\varepsilon_n$  decreases to zero  
 38 (paths ABC in Fig. 5b).

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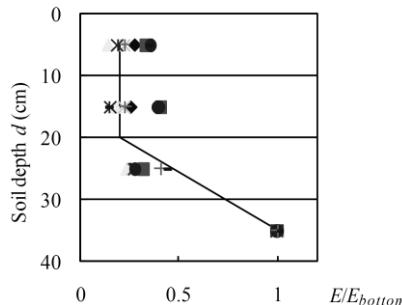
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Fig. 2. Typical example of gradient  $K$  calculation.

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Fig. 3. Experimental elastic modulus-void ratio relations of soil at the depth of 5 cm upper from the tank bottom.

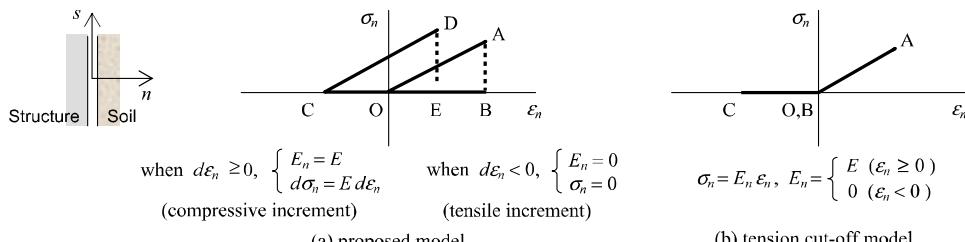


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Fig. 4. Normalised elastic modulus of soil at different soil depth.

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Fig. 5. Stress-strain models for interface element.

## 49      4. Numerical simulation results

50 A case of the model shaking test is simulated by direct time integration method. Finite Element model for the  
 51 simulation is shown in Fig. 6. The soil and the structure model were modelled by 8-nodes plane strain elements [8],  
 52 and the interface between soil elements and structure elements was modelled by 6-nodes quadrilateral anisotropic  
 53 elements [9]. Sinusoidal displacement boundary condition was applied to nodes highlighted by circles in Fig. 6.

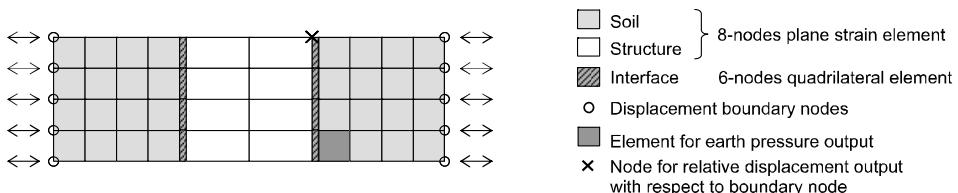


Fig. 6. Finite Element model for simulation.

Three different models of the normal stress-strain relations perpendicular to the wall of the structure, or local  $\xi$ -direction of an interface element were examined. Figure 8a shows the normal stress-strain relation of the proposed model in the previous section. Figure 7b shows the linear elastic model in which the normal stress  $\sigma_\xi$  is always calculated as the product of the elastic modulus  $E$  and the normal strain  $\varepsilon_\xi$ . Figure 8c shows the tension cut-off model in which also  $\sigma_\xi$  is proportional to  $\varepsilon_\xi$ , but the proportionality factor changes from  $E$  to zero when  $\varepsilon_\xi$  is negative.

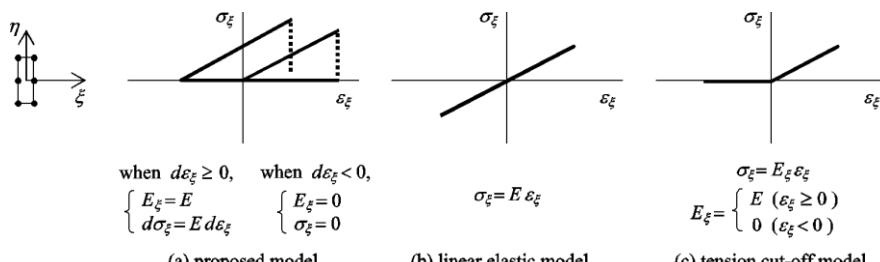


Fig. 7. Stress-strain models for interface element.

Material parameters used in the simulation are shown in Table 3. Elastic moduli of soil and interface were calculated from Eqs (3) and (4) using the initial void ratio  $e_0$  shown in Table 2. Mass proportional damping coefficient of Rayleigh damping  $\alpha$  was introduced to avoid excess oscillation, which is remarkable when the linear elastic model or the tension cut-off model are used. The damping factor  $\alpha = 3.3$  is calculated assuming that the first and the third modal damping factors of the system  $h_1$  and  $h_3$  are both 0.01. These two modes are predominant in horizontal oscillation, and those natural frequencies are  $f_1 = 40.5$  Hz and  $f_3 = 78.7$  Hz respectively.

Figure 8 shows experimental and numerically simulated earth pressure-relative displacement relations. Three types of interface stress-strain model, including the proposed model, the linear elastic model and the tension cut-off model, were used in the simulations. The proposed model gives a good approximation to the experimental hysteresis curve (Fig. 8a). Figures 9 and 10 show the time histories of relative displacement and earth pressure at 35 cm depth respectively. As shown in Fig. 9, all the models can give good approximations to the maximum value of the relative displacement, but the time histories estimated by the linear elastic and the tension cut-off interface models seem to be dominated by higher frequency components than the experimental result.

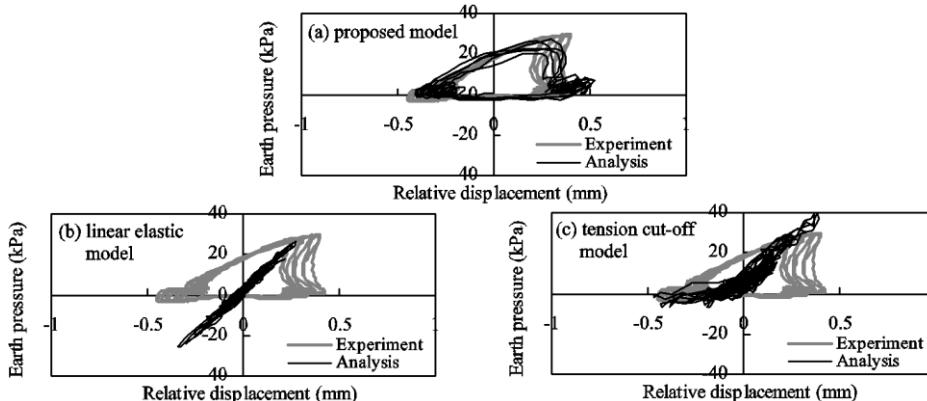
The time histories of the experimental and the numerically estimated earth pressure are compared in Fig. 10. It indicates that the result estimated by the proposed model shows good agreement with the experimental result. Figure 10b indicates that the linear elastic interface model estimates that noticeable negative stress (tensile stress here) can be applied to the structure, which was observed at a low level in the experiments.

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Table 3  
Material parameters for numerical analyses

Parameter		Soil	Interface	Structure
Elastic modulus $E$ (MPa)	depth = 5 cm	8.37	2.1E+5	
	depth = 15 cm	8.37		
	depth = 25 cm	19.53		
	depth = 35 cm	41.86		
Poisson's ratio $\nu$		0.31	—	0.3
Mass density $\rho$ (g/cm <sup>3</sup> )		1.91	—	2.5

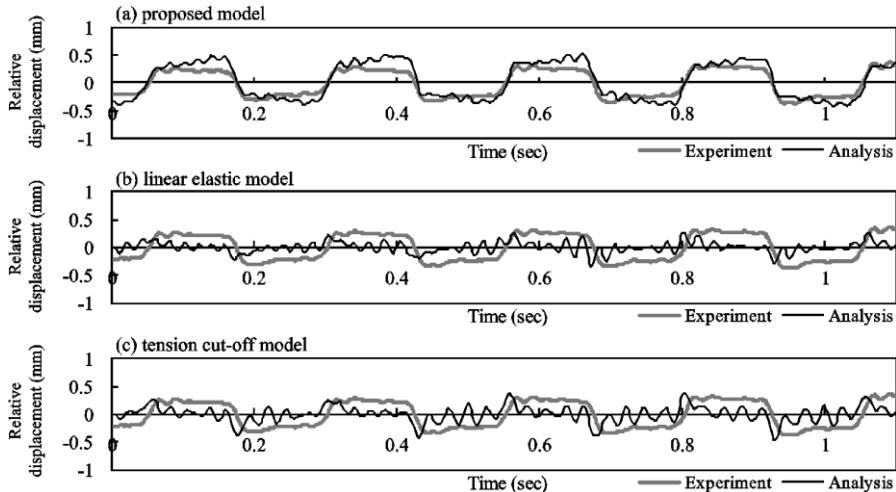
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Fig. 8. Comparison of experimental and analytical earth pressure-relative displacement relations at 35 cm depth.



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Fig. 9. Comparison of experimental and analytical relative displacement time histories.

## 90 5. Application to dynamic response analysis of pier

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In order to examine the influence of interface stress-strain modelling to numerical simulations, the dynamic response in the bridge transverse direction of a simple pier of a simply supported girder bridge shown in Fig. 11 to a seismic motion is calculated using the proposed, the linear elastic and the tension cut-off interface models. In bridge seismic design, the stresses and deformations of the bridge members are checked in two orthogonal directions,

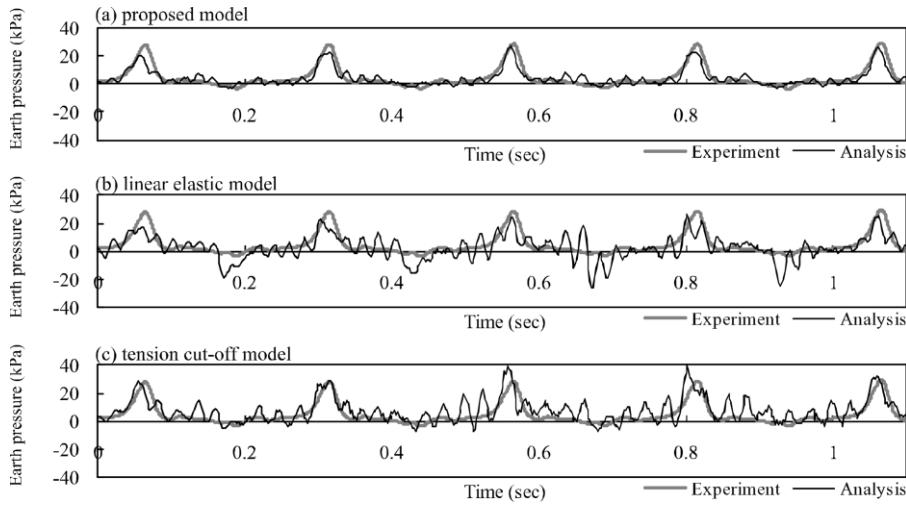


Fig. 10. Comparison of experimental and analytical earth pressure time histories at 35 cm depth.

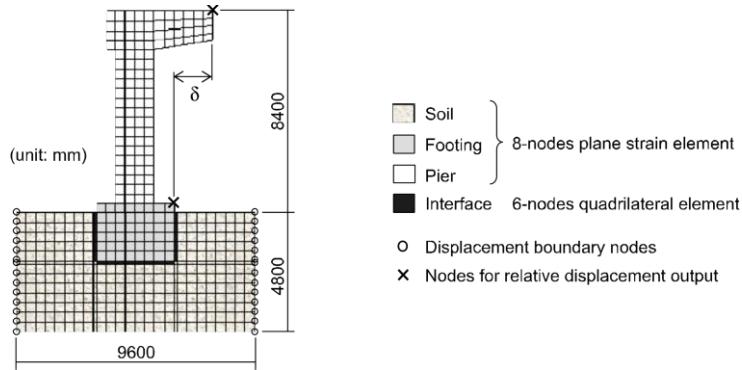
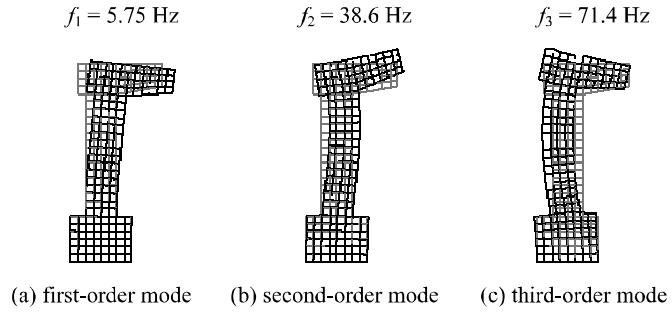


Fig. 11. Simple pier model for dynamic response analysis.

95 except when a bridge pier is located on the edge of an embankment where the earth pressure varies largely with  
 96 direction, which are generally bridge transverse and longitudinal axes (e.g. [1,2]). It is supposed that the pier os-  
 97 cillation can be calculated independently of other parts of the bridge because movable bearings are installed on the  
 98 top of the pier. The first three eigenmodes and its natural frequencies of the bridge pier and the entire system (pier  
 99 and soil) are shown in Figs 12 and 13, respectively. The existence of soft soil makes the natural frequency of the  
 100 entire system lower compared to that of the pier itself.

101 Figure 14 shows the Itajima Bridge longitudinal acceleration record observed at 1968 Hyuganada Earthquake  
 102 used as input waveform. The maximum acceleration is 363 gals (1 gal = 1 cm/sec) and the predominant frequencies  
 103 are around 0.8 and 0.5 Hz.

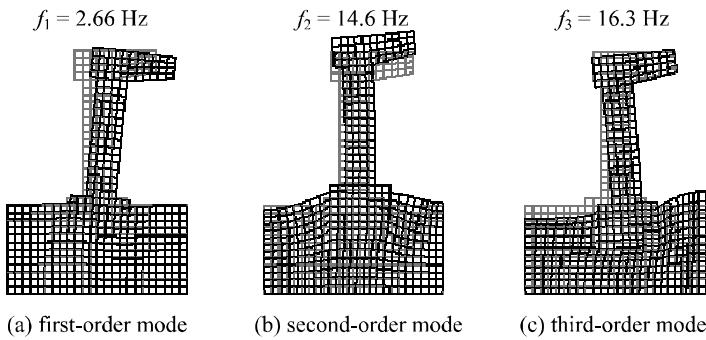
104 Figure 15 shows the lateral stress distribution calculated by three different interface stress-strain models. The  
 105 proposed model gives lower peak values of stresses compared to the linear elastic and the tension cut-off model.  
 106 Time histories of the lateral stress of a soil element located at the ground surface of the right side of the footing are  
 107 shown in Fig. 16. Time histories and Fourier amplitude spectra of the relative displacement  $\delta$  are shown in Fig. 17.  
 108 The proposed model estimates the predominant frequency of the response of the system to the applied acceleration  
 109 even lower than the tension cut-off model and the linear elastic model. These results show that different stress-strain  
 110 models of an interface element can cause different evaluation of the system response both in time domain and  
 111 frequency domain. It indicates that proper modelling of the soil-structure interaction is important in predicting the  
 112 maximum displacement and predominant response frequencies of the system.



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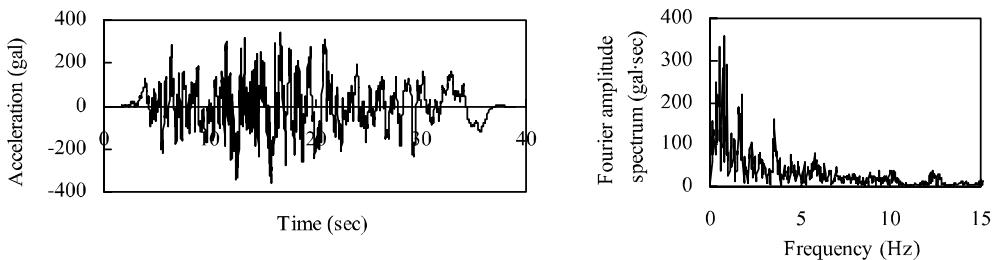
Fig. 12. Eigenmodes and natural frequencies of pier.



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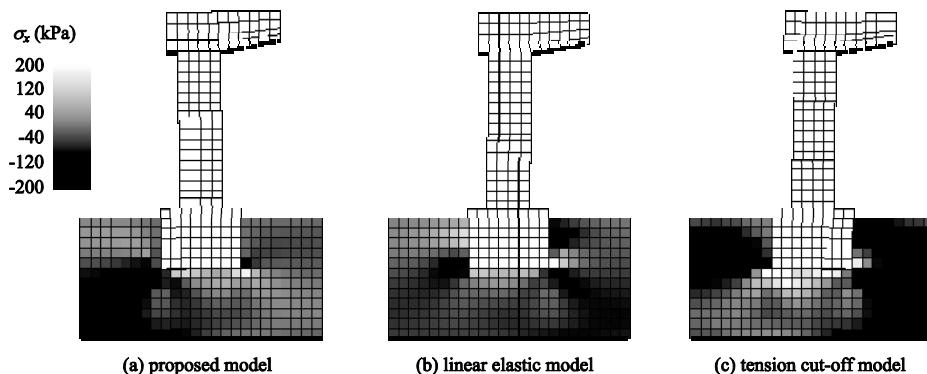
Fig. 13. Eigenmodes and natural frequencies of soil-structure system.



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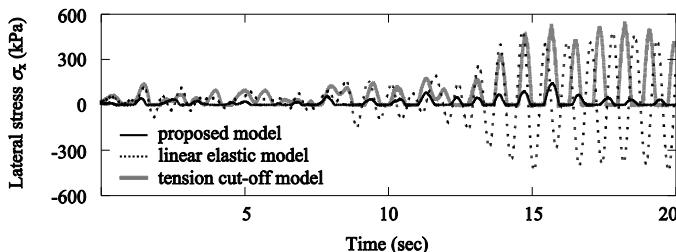
Fig. 14. Time history and Fourier amplitude spectrum of acceleration record for input waveform.



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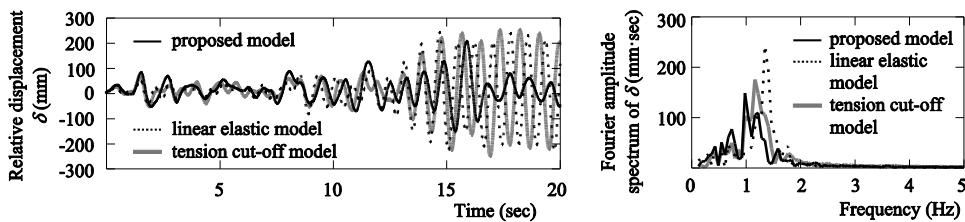
Fig. 15. Distribution of horizontal stress  $\sigma_x$  in soil at 16.4 seconds of analyses.



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Fig. 16. Comparison of time histories of lateral stress of the soil element beside the footing at the ground surface.



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Fig. 17. Comparison of time histories and Fourier amplitude spectra of relative displacement  $\delta$ .

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## 6. Conclusions

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In this paper, a new dynamic earth force transmission model for a sandy soil-structure interface was proposed based on experimental results of laboratory shaking tests.

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The proposed model gave good approximations to the earth pressure-relative displacement hysteresis curve, as well as the time histories of relative displacement and earth pressure. The effectiveness of the proposed model was shown in comparison of the simulated results of the laboratory shaking tests by different mechanical models of the soil-structure interface, namely conventional linear elastic model and the tension cut-off model.

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Two dimensional finite element analyses of the dynamic responses of a bridge pier against seismic force were carried out. The proposed interface model gave different estimations of the system response both in time domain and frequency domain compared to the results calculated by tension cut-off interface model. It indicates that to predict dynamic response of a structure against seismic earth force, it is important to use proper soil-structure interaction model.

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