Identifying Dynamic Structural Parameters of Soil-Structure System Based On Data Recorded During Strong Earthquakes

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Abstract

In many applied engineering problems, structural analysis is usually conducted by assuming a rigid bed, while imposing the effect of structure bed flexibility can affect significantly on the structure response. This article focuses on investigation and evaluation of the effects arising from considering a soil-structure system in evaluation of dynamic characteristics of a steel structure with respect to elastic and inelastic behaviors. The recorded structure acceleration during strong Chi-Chi earthquake on different floors of the structure was our evaluation criteria. The respective structure is an eight-story steel bending frame structure designed using displacement-based direct method assuring weak beam - strong column function. Results indicated that different identification methods, i.e. reverse Fourier transform and transfer functions, are capable to determine specific dynamic parameters of the structures, not all of them. Response evaluation based on the input and output data elucidated that the structure first mode is not significantly affected even considering soil-structure interaction effect, but the upper modes have been changed. Also, it was found that the response transfer function of the different stories in which plastic hinges have occurred, provides similar results.

Keywords: System identification, Dynamic characteristics, Soil-structure system, Bending steel frame structure, Displacement-based design

Introduction

System identification simply means receiving dynamic systems features using experimental data. Experimental identification of modal parameters of civil engineering structures refers to the extraction of modal parameters including frequencies, damping ratios and modal forms of dynamic measurements. In the next phase, we can use the dynamic parameters for updating the analytical model usually presented as Finite Element (FE) model to identify and locate probable damages in the structure, and to investigate health and evaluate their safety against future hard conditions such as strong earthquakes and hurricanes. Experimental-modal analysis was first applied in 1940 with the aim of understanding the behavior of aerial vehicles, while the examinations on existing buildings had been already initiated by US Coast and Geodetic Survey around 1930. As such, 400 buildings and 44 high towers were tested from 1934 to 1962. In 1964, for the first time, power spectrum of recorded signals along random wind stimulations was used to find the first three vibratory modes in a 19-floor building [1]. This method was promoted and commonly used later.

Past experiences show that the soil affects dynamic behavior of structures. Structural dynamic response during exerted vibrations changes depending on the soil types under the foundation. Therefore, without considering this effect we could not have a realistic estimation of exerted seismic forces on the structure. Besides, local characteristics such as soil type, stratification of soil, and changes in strata depth are also effective factors on structural seismic behavior to be investigated and considered in the structure analysis. Therefore, the examination of structural seismic behavior without taking soil effect into account seems not to produce realistic results. One of the first studies on extraction of interactional effects from structure dynamic response was conducted by Luko et al. [2] in 1988. In this study, they carried out compulsory stimulation experiment for a range of frequencies using a seismic stimulator on the roof and recorded the structure response in four points. Then, with the help of frequency response, they determined interactional effects. Safak [3] carried out one of the first studies on extraction of interactional effects arising from earthquake records. In 2006, Schneider and Safak [4] determined structural dynamic characteristics using impulse response function obtained from records in a 10-story building of Milikan library in Yorba-Linda earthquake (2003). Considering the structure as a continuous environment, they identified shear wave of environment and quality coefficient (Q), which is a representative of damping of environment, 322 m/s and 20, respectively. Todorovska also has conducted many studies over recent years to identify soil-structure system properties [5, 6]. They asserted that the differences of recognized features in vibrations with different ranges largely depend on local behavior of soil in different ranges of vibrations. In other words, soil behavior in short-ranged and long-ranged vibrations can be a source of significant effects in evaluation of structure characteristics. Ghahari et al. [9] conducted another study on the Milikan library using a developed blind identification method to determine some modes which have not been identified before. They used a Finite Element (FE) model in order to consider the effect of the soil-structure interaction. In case of the experimental approach, Chen et al. [10] developed a procedure using geotechnical centrifuge-based data for conducting seismic system identification for soil-structure interaction.

Method of considering and modeling of soil in soil-structure systems

Methods of considering and modeling a soil profile in soil-structure systems can be classified into two general categories: 1- direct method; and 2- substructure method. In the direct method, a part of soil accompanied by the structure is modeled and soil free field motion is exerted on artificial soil boundaries [7]. In the substructure method, soil-structure system is divided into two parts: the first part of the structure is located on the foundation and the second part is soil with a common border with the foundation. First, force-soil displacement relationships (dynamic rigidity) is determined for the existing nodes on the common border, which can be stated in a physical form with a number of springs and dampers the coefficients of which depends on stimulation frequency. Then the existing structure is analyzed on the springs and dampers by exerting stimulations on their supports. Therefore, the most complex soil-structure system is broken into two controllable parts, and analysis is conducted with lower cost. In this approach, soil and structure can be analyzed separately and insert one of them into the problem with more details to easily identify effective and important parameters in the problem [8]. One of the models used in substructure method to obtain spring and damper coefficients and mass is conical model. In this model, the soil under the foundation is modeled as a divergent cone, and displacement in soil is exerted through the foundation without mass and rigidity. Principles used in obtaining the equations dominant on these models is based on beams theory in mechanics of material in which the vertical plane on the neutral beam still remains a plane after displacement. Using this principle, spring and damper coefficients are calculated (Fig. 1) [8]. Primary idea for using conical models to estimate dynamic rigidity of surface foundation was proposed along with transferal freedom degree in 1942. Then in 1974, the results of conical models were expanded to rocking and tensional freedom degrees. After about two decades, in 1992, Wolf and Meek [11] presented conical models for different freedom degrees on foundations located on a homogenous semi-infinite environment. According to studies, horizontal and rocking freedom degrees for surface foundations were evaluated negligible and can be ignored, as we did in this study.

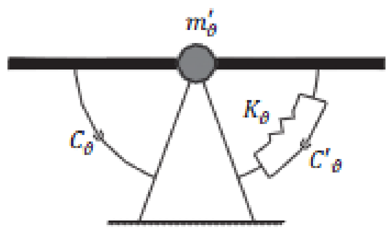


Figure 1- Cone model for considering the soil-structure interaction effect

Modeling

The respective structure is a two-dimensional eight-story steel bending frame structure designed by displacement-based direct method assuring weak beam-strong column function. This structure has equal story heights as high as 3 m and three openings of 6 m in width. For substructure modeling, we used the aforementioned conical model. In order to achieve larger soil effects, we considered shear wave velocity of 50 m/s to determine spring and damper coefficients. SAP2000 software was used for designing the structure, and OpenSees software was adopted for parametric study and analysis. The profiles designed for steel frame are presented in table 1.

Table 1- designed profiles of concrete and steel 8-storey frame

Number of story	Steel Frame							
	1	2	3	4	5	6	7	8
Column	W18x97	W18x71	W18x65	W18x60	W18x50	W18x46	W18x35	W18x35
Beam	W18x46	W18x55	W18x55	W18x50	W18x46	W18x35	W18x35	W18x35

In order to stimulate the structure input excitation, we used the recorded acceleration in Taiwan earthquake (Chichi). The maximum acceleration recorded in this earthquake is equal to the gravity acceleration (Fig. 2).

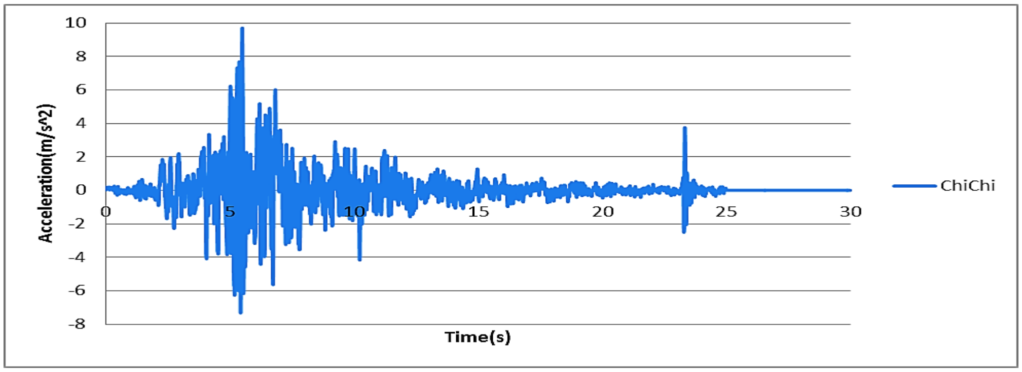


Figure 2- acceleration recorded in strong Taiwan earthquake (Chichi)

Analysis of results

After modeling, analyses were conducted for all parts assuming linear elastic and inelastic behaviors. In the first phase of structure evaluation, the values of structure modal frequencies were obtained from the output, as observed in tables 2 and 3. In dynamic time history analysis using linear elastic behavior, the values of frequencies for the structure model with fixed base and structure-soil model remained unchanged (table 2). While in analysis of nonlinear dynamic time history, the values of rigidity matrix for structural parts can change every moment. Therefore, final analysis values will be different from the initial ones. To this end, the values presented in table 3 are frequency values of last moments of analysis extracted from the software. If we use response history values to evaluate frequency changes, different values from those in table 3 will be obtained because transient changes of rigidity matrix will be constant in history of responses.

Comparison of structural model frequencies of fixed base with soil-structure model

In linear models, we expect that modeling of soil on the foundation of the structure causes a milder behavior in soil-structure system. This means a longer period or lower frequency. The results in the second and third columns of table 2 confirm this. Percentage differences of frequency values in the models with linear elastic behavior for fixed pillar and soil-structure model indicate an increase in percentage difference by increasing mode number so that the frequency change in the model with fixed pillar is about 2% compared to the soil-structure model over the first mode which has the largest effect on structure response. The difference increases for upper modes. We can observe that upper modes of the structure get a significant impact from the presence of soil along with structure model. However, the results of both analyses would be different if higher modes show enormous participation in seismic behavior of the structure, otherwise the results of analyses will be very close (Fig. 3).

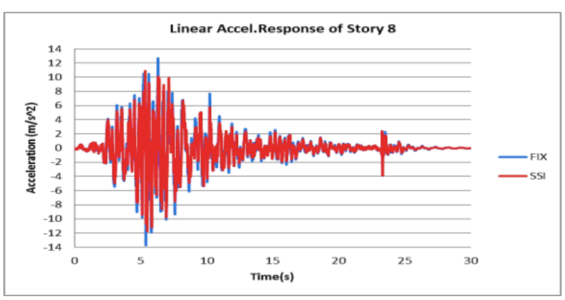
Table 3- Frequency values (Hz) and proportional frequency error for models with inelastic behavior

8 Story Steel Frame	ChiChi		
	Frequency of Structure (NonLinear)		
	Fix (Hz)	SSI (Hz)	Error (%)
Mode 1	1.030	1.005	2.472
Mode 2	2.915	2.618	11.370
Mode 3	5.291	3.086	71.429
Mode 4	8.000	4.274	87.200
Mode 5	10.989	5.319	106.593
Mode 6	14.085	8.000	76.056
Mode 7	17.544	10.989	59.649
Mode 8	21.739	14.085	54.348

Table 2- Frequency values (Hz) and proportional frequency error for models with linear elastic behavior

8 Story Steel Frame	ChiChi		
	Frequency of Structure (Linear)		
	Fix (Hz)	SSI (Hz)	Error (%)
Mode 1	1.038	1.014	2.388
Mode 2	2.924	2.625	11.404
Mode 3	5.319	3.096	71.809
Mode 4	8.000	4.274	87.200
Mode 5	10.989	5.348	105.495
Mode 6	14.085	8.065	74.648
Mode 7	17.544	10.989	59.649
Mode 8	21.739	14.286	52.174

The results of structural analysis considering inelastic behavior are very similar to those of the linear elastic analysis. If frequency changes of structures with fixed pillar go under investigation before and after the formation of plastic joints in structural elements by comparing the first columns of tables 2 and 3 and in soil-structure model by comparing the second columns of tables 2 and 3, we obtain 77% and 89% changes. These values indicate very good behavior of structure against strong earthquakes like Chichi. This subject will be discussed later in arguments on formation of plastic joints of components.



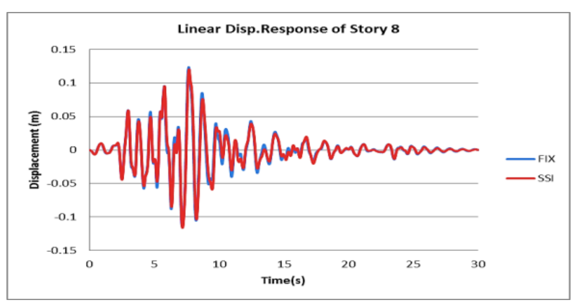


Figure 3- displacement response and accelerometer of 8th story of a steel structure assuming elastic behavior of components

If response values are compared for both models in nonlinear dynamic time history analysis, a behavior very similar to the previous mode will be encountered (Fig. 4). Comparison of responses in figures 3 and 4 verifies that the formation of plastic joints and their current layout within the structure has not changed the structural behavior dramatically.

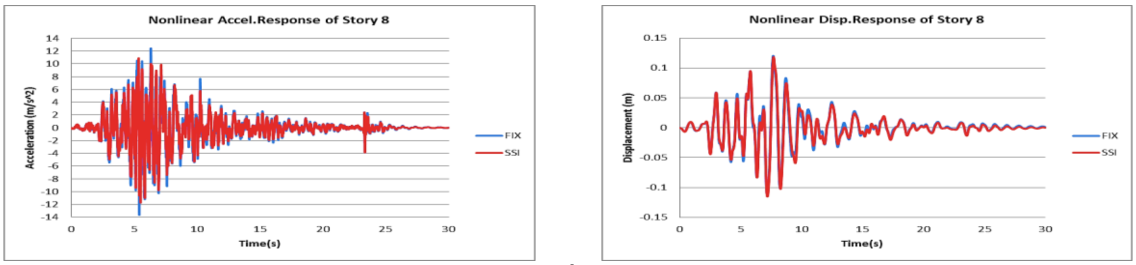


Figure 4 - displacement response and accelerometer of 8th story of a steel structure assuming inelastic behavior of components

Comparison of modal forms of structure model with fixed pillar and soil-structure model

Modal shapes of the structure were obtained based on frequency values resulted from Fourier analysis of acceleration response on structure floors. The diagrams for the first to third modal shapes for linear and nonlinear analyses are given in figures 5 and 6, respectively. Modal shapes represent small changes in the first mode and significant changes in higher modes. This is hardly recognized in structural responses. Values of differences in modal shapes of the structure with and without considering soil model is largely decreased at the end of inelastic analysis.

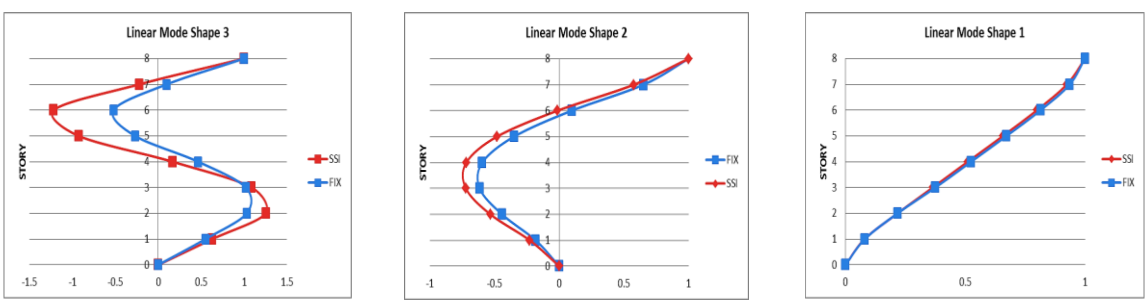


Figure 5 - modal forms of a steel structure assuming linear behavior

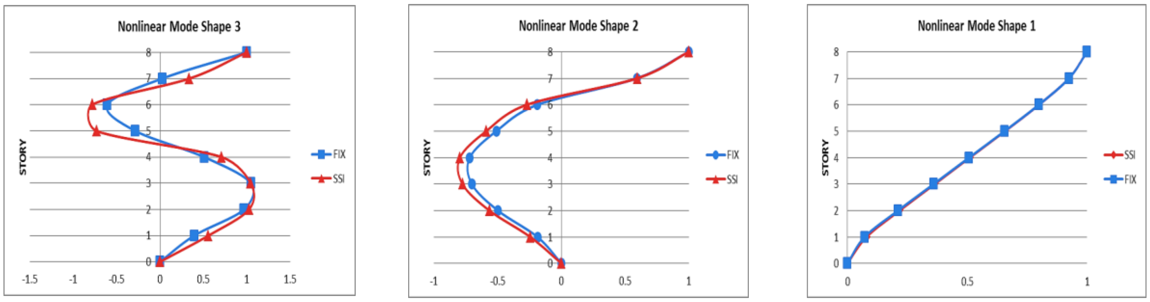


Figure 6 - modal forms of a steel structure assuming nonlinear behavior

Formation of plastic hinges in the structure model with fixed pillar and soil-structure model

One of the most important goals in identification of a structure is to achieve deterioration pattern and to estimate damage in structural systems. In analyses conducted on the models, small frequency changes in the nonlinear analysis will lead to the formation of plastic hinges on some locations of the structure. The results of investigations are presented in figure 7. Comparison of the two cases indicates that the number of plastic joints is smaller when the structure is analyzed in presence of soil than when it is analyzed with a rigid bed. As a very soft soil is selected, it is natural that soil-structure interaction has a decreasing effect on lateral imposed forces on the structure.

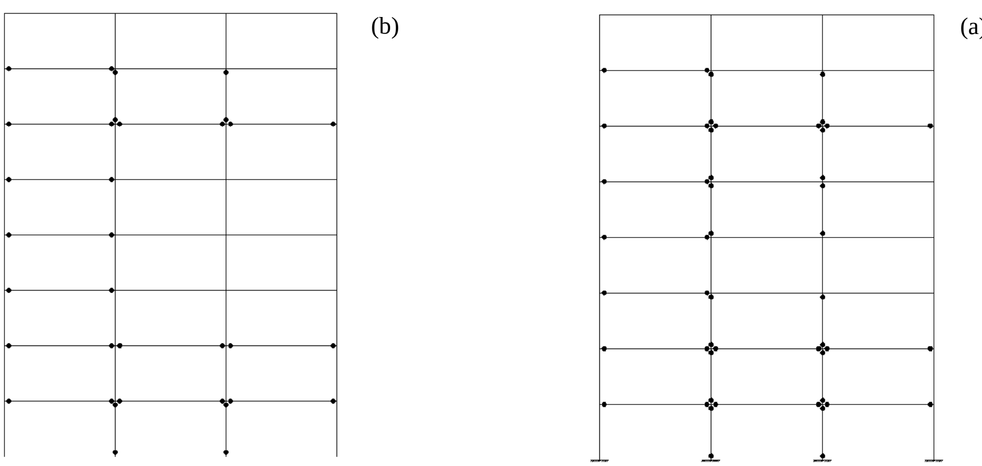


Figure 7- nonlinearity of steel structure components; a- with fixed pillar, b- considering soil-structure interaction

Comparison of both cases shows that the joints are formed on the top and bottom of 6, 5, 3 and 2 story columns, which can't be observed in soil-structure model. However, since the structure is designed well, no joint is formed in lateral columns of the frame even against a very strong earthquake like Chichi. Therefore, general frame behavior has not changed significantly. The majority of joints are formed on story beams that have not created great changes in structure properties. In other words, due to small impact of beam joints and middle columns on frequency evaluations, we do not see dramatic changes compared to the linear case.

Transfer functions of structure model with fixed pillar and soil-structure model

Another way for identification of structural systems characteristics is to examine their transfer function to have a better understanding of performance of systems. In order to investigate changes occurred in modal features arising from both models, their transfer functions after formation of plastic joints are compared and shown in figure 8. Investigations illustrate the small changes in higher structure modes. This confirms the results given in tables 2 and 3. For a better comparison, linear and nonlinear behaviors of fixed-pillar frame are again being compared in figure 9. The diagram reflects small effect of changes on both modal cases, which is due to good seismic performance of the frame.

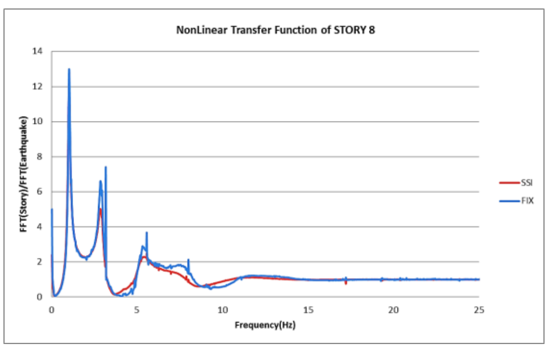


Figure 8 - comparison of transfer functions of the structure with fixed pillar and soil-structure model after formation of plastic joints

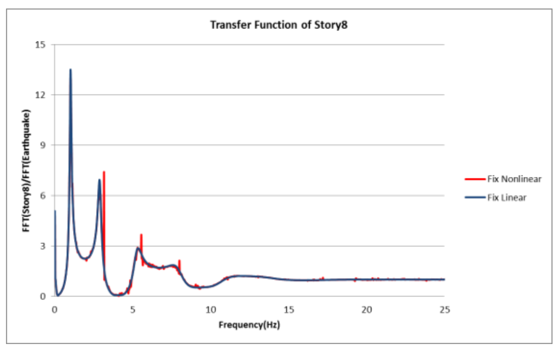


Figure 9- comparison of transfer functions for the structure model with fixed pillar during linear and nonlinear behavior of fixed-pillar structure

In investigations of plastic joint formation, we pointed out that the joints were formed on 6th, 5th, 3th and 2th floors on the top and the bottom of middle columns. To this respect, transfer functions for the third and sixth floors are presented in figures 10 and 11. These diagrams show changes in both structural models more explicitly than changes of transfer function in figure 8. However, because such changes occurred in high structure modes, they were not very effective in general behavior, and we can refer to them only to find the scope of damage area (formation of plastic joint).

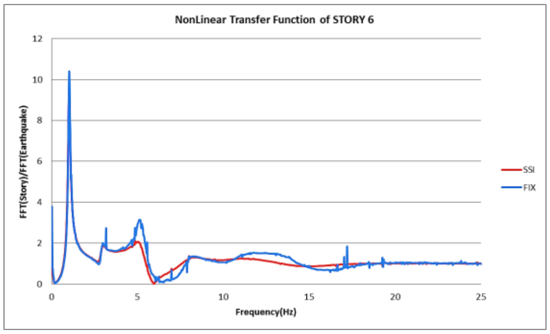


Figure 10- comparison of transfer functions for the 6th story of the structure with fixed pillar and soil-structure model after formation of plastic joints

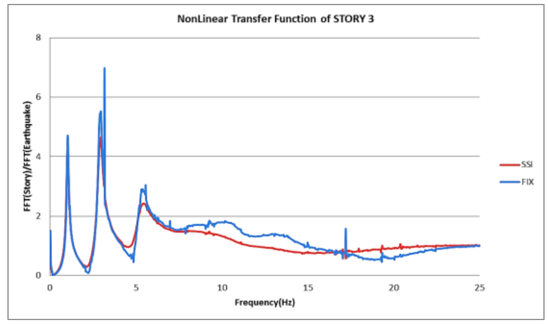


Figure 11- comparison of transfer functions for the 3rd story of the structure with fixed pillar and soil-structure model after formation of plastic joints

Conclusions

In many applied engineering problems, structure analysis is usually conducted by assuming a rigid bed, while imposing structure bed flexibility effect can have significant effects on structure response. The linear and nonlinear time history analysis are performed for an eight-story steel bending frame structure designed by using the displacement-based direct method. Based on the results, the first mode frequency of the fixed base structure has a small difference (2%) in compare with the soil-structure model, while these changes are increasing for upper modes. Also, these changes are then be elucidated by evaluating the transfer functions of different stories response. In addition, the number of plastic hinges which are occurred on the structural elements decreases in soil-structure model.

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