World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:11, No:6, 2017

Open Science Index, Civil and Environmental Engineering Vol:11, No:6, 2017 publications.waset.org/10007117.pdf

Identifying Dynamic Structural Parameters of Soil-Structure System Based on Data Recorded during Strong Earthquakes

Vahidreza Mahmoudabadi, Omid Bahar, Mohammad Kazem Jafari

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 Taiwan's 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 a displacement-based direct method assuring weak beam - strong column function. The results indicated that different identification methods i.e. reverse Fourier transform or transfer functions, is capable to determine some of the dynamic parameters of the structure precisely, rather than evaluating all of them at once (mode frequencies, mode shapes, structure damping, structure rigidity, etc.). Response evaluation based on the input and output data elucidated that the structure first mode is not significantly affected, even considering the 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 in the structure components, provides similar results.

Keywords**—**System identification, dynamic characteristics, soil-structure system, bending steel frame structure, displacement-based design.

I. INTRODUCTION

SYSTEM identification simply means receiving dynamic systems features using experimental data [1]. 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 to update the analytical model, which is usually presented as a 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 [2]-[4]. 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 already been initiated by the 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, a power spectrum of recorded signals along random wind stimulations was used to find the first three vibratory modes in a 19-floor building [5]. This method was promoted and commonly used later on.

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 [6]-[8]. 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 the soil, and changes in the strata depth are also effective factors on structural seismic behavior to be investigated and considered in structural analysis. Thus, the examination of structural seismic behavior without taking soil effect into account, would not deliver realistic results. One of the first studies on extraction of interactional effects from structure dynamic response was conducted by Luko et al. [6]. In this study, a compulsory stimulation experiment for a range of frequencies was carried out using a seismic stimulator on the roof and the structure response was recorded at four points. Then, with the help of frequency response, the interactional effects were determined. Safak [7] carried out one of the first studies on the extraction of interactional effects arising from earthquake records. Schneider and Safak [8] determined structural dynamic characteristics using impulse response function obtained from records from the 10-story Millikan Library building in the Yorba-Linda earthquake (2003). Considering the structure as a continuous environment, they identified the shear wave of environment and the quality coefficient (Q), which is a representative of damping of the environment (322 m/s and 20 respectively). Todorovska also conducted many studies over recent years to identify soil-structure system properties [9], [10]. They asserted that the differences of recognized features in vibrations with different ranges largely depend on the 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 the evaluation of structure characteristics. Ghahari et al. [13] conducted another study on the Millikan Library building using a developed blind identification method to determine some modes which have not been identified before. They used a FE model in order to consider the effect of the soil-structure interaction. In the case of the experimental approach, Chen et al. [14] developed a procedure using geotechnical centrifuge-

Vahidreza Mahmoudabadi Graduate Student, Clemson University, Clemson, SC, USA (e-mail: vmahmou@clemson.edu).
Omid Bahar, Assistant Professor, and Mohammad Kazem Jafari, Professor, are with the International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran.

based data for conducting seismic system identification for soil-structure interaction.

II. METHOD FOR CONSIDERING AND MODELING OF SOIL IN SOIL-STRUCTURE SYSTEMS

Methods for 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 [11]. In the substructure method, the 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) are 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 the lower cost. In this approach, soil and structure can be analyzed separately and one of them is inserted into the problem with more details to easily identify effective and important parameters in the problem [12]. One of the models used in the substructure method to obtain spring and damper coefficients and mass, is conical model [15], [16]. In this model, the soil under the foundation is modeled as a divergent cone, and displacement in the soil is exerted through the foundation without mass and rigidity. The principles used in obtaining the equations dominant in these models are 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) [12]. The primary idea for using conical models to estimate the dynamic rigidity of the surface foundation was proposed along with transfer freedom degree in 1942. Then in 1974, the results of the conical models were expanded to rocking and tensional freedom degrees. After about two decades, in 1992, Wolf and Meek [17] presented conical models for different freedom degrees on foundations located on a homogenous semi-infinite environment. According to the studies, horizontal and rocking freedom degrees for surface foundations were proved to be negligible, and so, are done in this study.

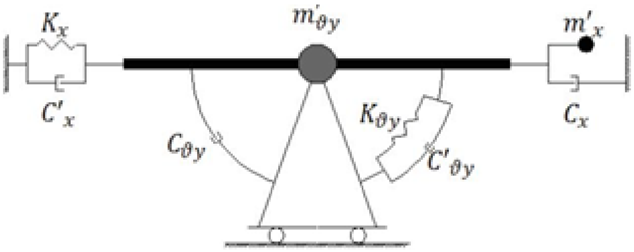

Fig. 1 Cone model for considering the soil-structure interaction effect

III. MODELING

The structure at issue 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 3m and three openings of 6m 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 the 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 the steel frame are presented in Table I.

TABLE I
DESIGNED PROFILES OF THE EIGHT-STORY STEEL 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

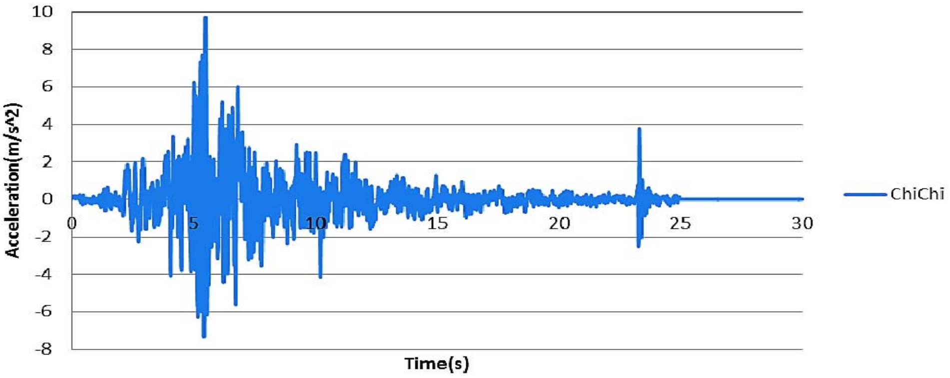

Fig. 2 Acceleration recorded in strong Taiwan earthquake (Chi-chi) in 1999

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).

IV. 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 II and III. In the dynamic time history analysis using linear elastic behavior, the values of frequencies for the structure model with the fixed base and structure-soil model remained unchanged (Table II), while in the analysis of the nonlinear dynamic time history, the values of the rigidity matrix for the structural parts can change every moment. Therefore, the final analysis values will be different from the initial ones. To this end, the values presented in Table III are frequency values of the last moments of analysis extracted from the software. If we use response history values to evaluate frequency changes, different values from those in Table III will be obtained because transient changes of the rigidity matrix will be constant in the history of responses.

V. 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 the soil-structure system. This means a longer period or lower frequency. The results in the second and third columns of Table I confirm this. Percentage differences of frequency values in the models with linear elastic behavior for the fixed pillar and soil-structure model indicate an increase in percentage difference by increasing the 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. Whereas, it can be observed that considering the soil-structure model will cause a significant impact on the upper modes of the structure during the analysis. However, the results of both analyses would be different if higher modes showed enormous participation in seismic behavior of the structure; otherwise, the results of the analyses will be very close (Fig. 3).

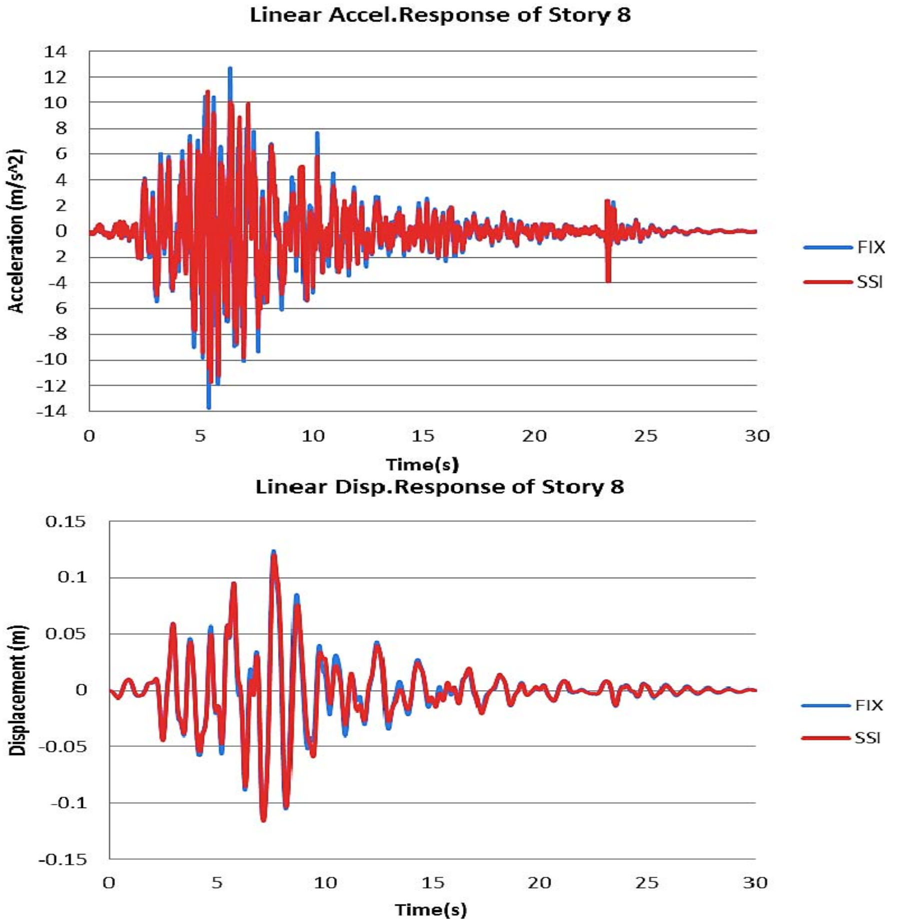

Fig. 3 Displacement response and accelerometer of the 8th story of a steel structure assuming elastic behavior of the components

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 II and III and in the soil-structure model by comparing the second columns of Tables II and III, we obtain 77% and 89% changes. These values indicate very good behavior of structure against strong earthquakes like Chi-Chi. This subject will be discussed later in arguments on the formation of plastic joints of components.

TABLE II
FREQUENCY VALUES (HZ) AND PROPORTIONAL FREQUENCY ERROR FOR MODELS WITH LINEAR ELASTIC BEHAVIOR

Mode No.	**Structure Frequency (Linear)**		
	Fix (Hz)	**SSI (Hz)**	**Error (%)**
1	1.038	1.014	2.388
2	2.924	2.625	11.404
3	5.319	3.096	71.809
4	8.000	4.274	87.200
5	10.989	5.348	105.495
6	14.085	8.065	74.648
7	17.544	10.989	59.649
8	21.739	14.286	52.174

TABLE III
FREQUENCY VALUES (HZ) AND PROPORTIONAL FREQUENCY ERROR FOR MODELS WITH INELASTIC BEHAVIOR

Mode No.	Structure Frequency (Nonlinear)		
	Fix (Hz)	SSI (Hz)	Error (%)
1	1.030	1.005	2.472
2	2.915	2.618	11.370
3	5.291	3.086	71.429
4	8.000	4.274	87.200
5	10.989	5.319	106.593
6	14.085	8.000	76.056
7	17.544	10.989	59.649
8	21.739	14.085	52.348

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 Figs. 3 and 4 verifies that the formation of plastic joints and their current layout within the structure has not changed the structural behavior dramatically.

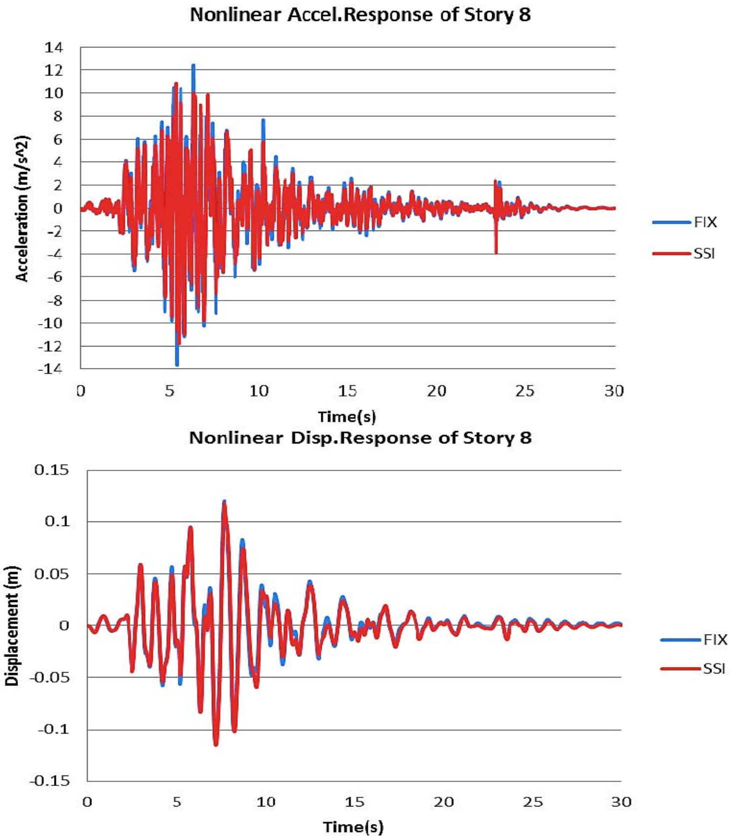

Fig. 4 Displacement response and accelerometer of the 8th story of a steel structure assuming inelastic behavior of the components

VI. COMPARISON OF MODAL FORMS OF STRUCTURE MODEL WITH FIXED PILLAR AND SOIL-STRUCTURE MODEL

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

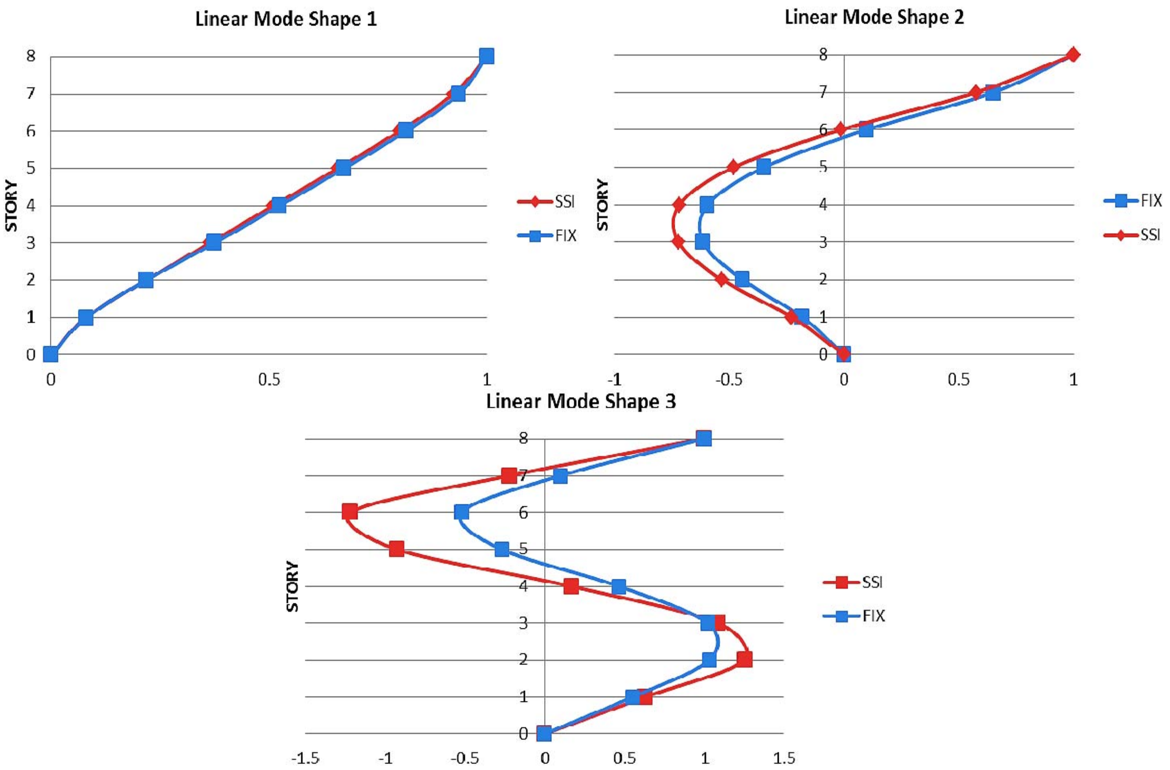

Fig. 5 Modal forms of a steel structure assuming linear behavior

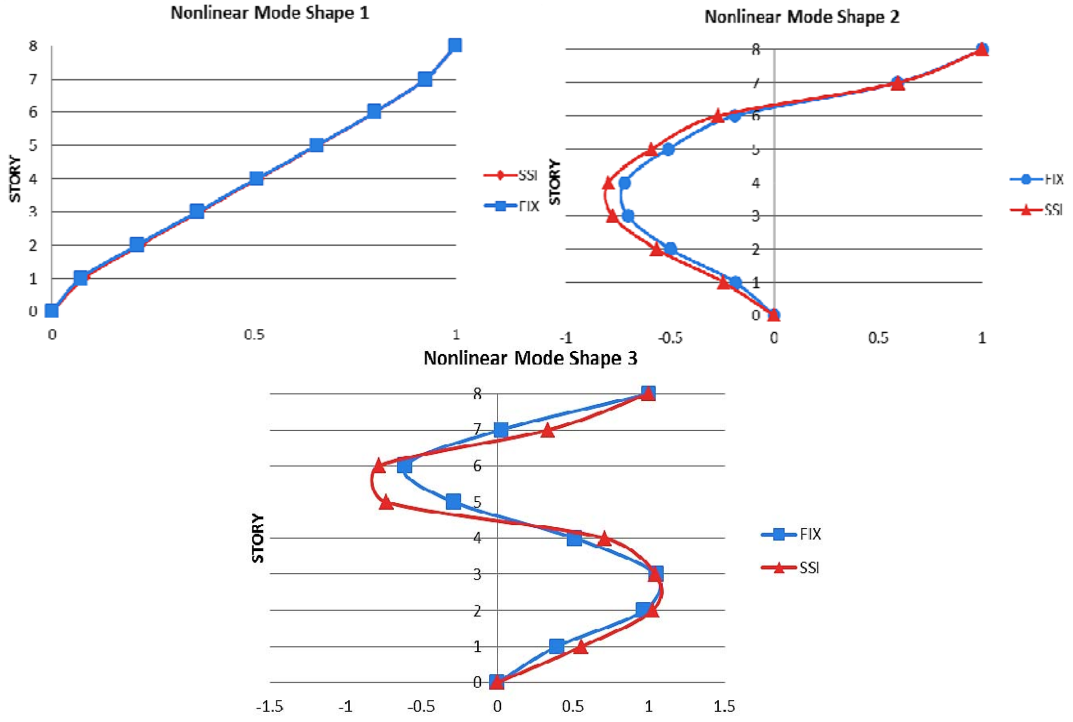

Fig. 6 Modal forms of a steel structure assuming nonlinear behavior

VII. 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 find the deterioration pattern and to estimate the 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 structure components. The results of investigations are presented in Fig. 7. Comparison of the two cases indicates that the number of plastic joints is smaller when the structure is analyzed in the

Open Science Index, Civil and Environmental Engineering Vol:11, No:6, 2017 publications.waset.org/10007117.pdf

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.

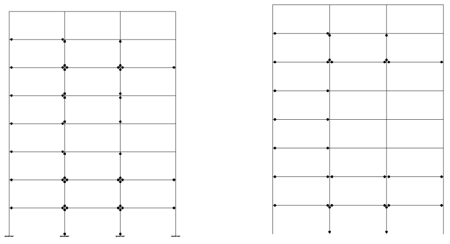
(a) (b)

Fig. 7 Nonlinearity of steel structure components (a) with fixed pillar (b) considering soil-structure interaction

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

VIII. TRANSFER FUNCTIONS OF STRUCTURE MODEL WITH FIXED PILLAR AND SOIL-STRUCTURE MODEL

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

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

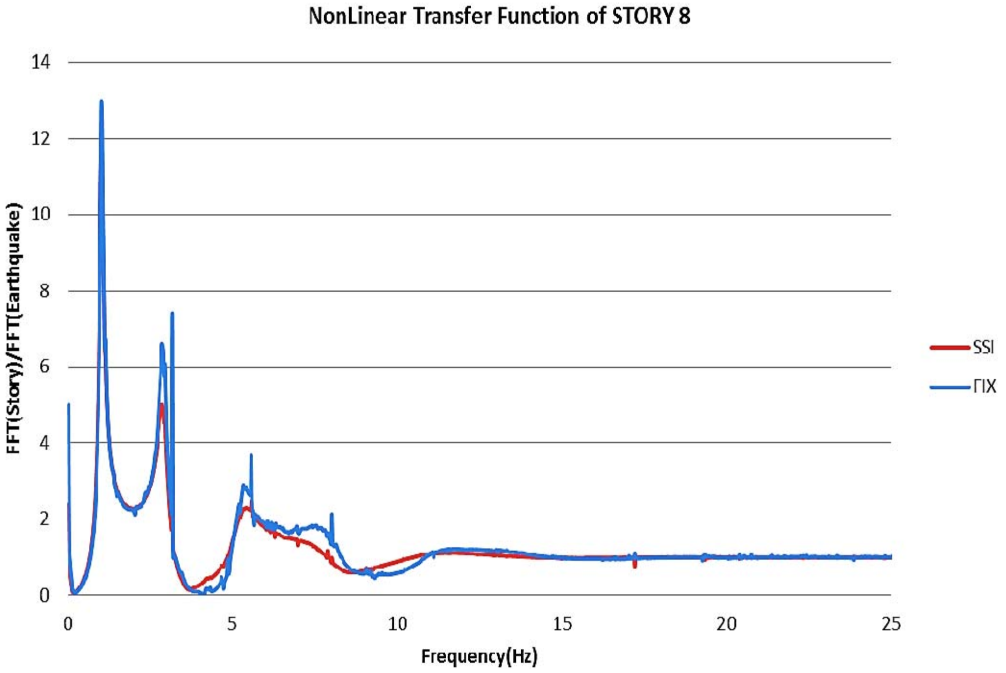

Fig. 8 Comparison of the transfer functions for the structure with fixed pillar and soil-structure model after formation of plastic joints

Open Science Index, Civil and Environmental Engineering Vol:11, No:6, 2017 publications.waset.org/10007117.pdf

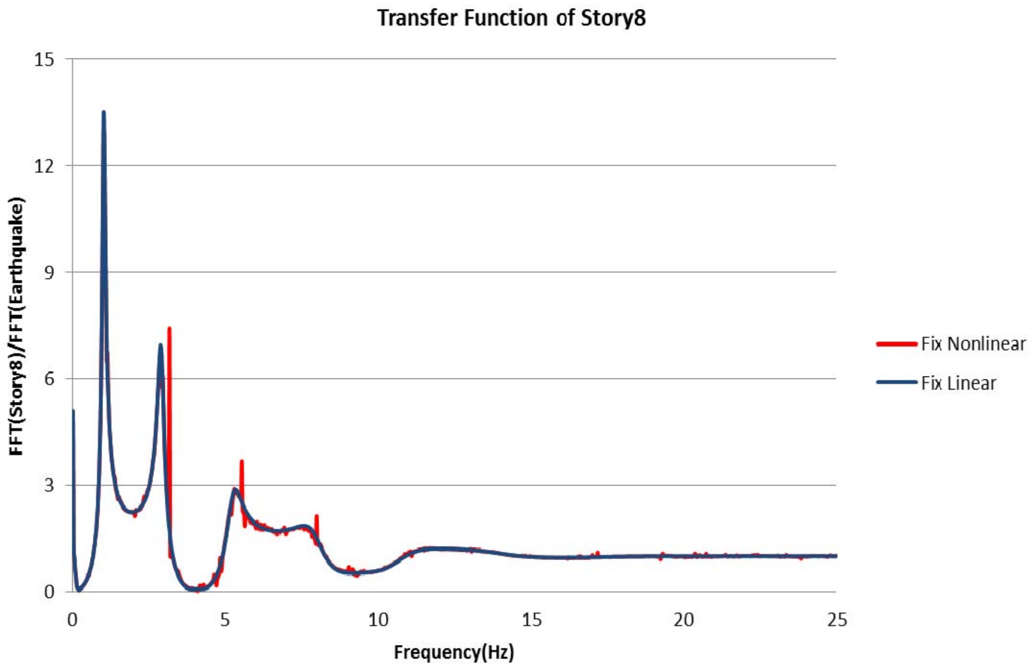

Fig. 9 Comparison of the transfer functions for the structure model with fixed pillar during linear and nonlinear behavior of fixed-pillar structure

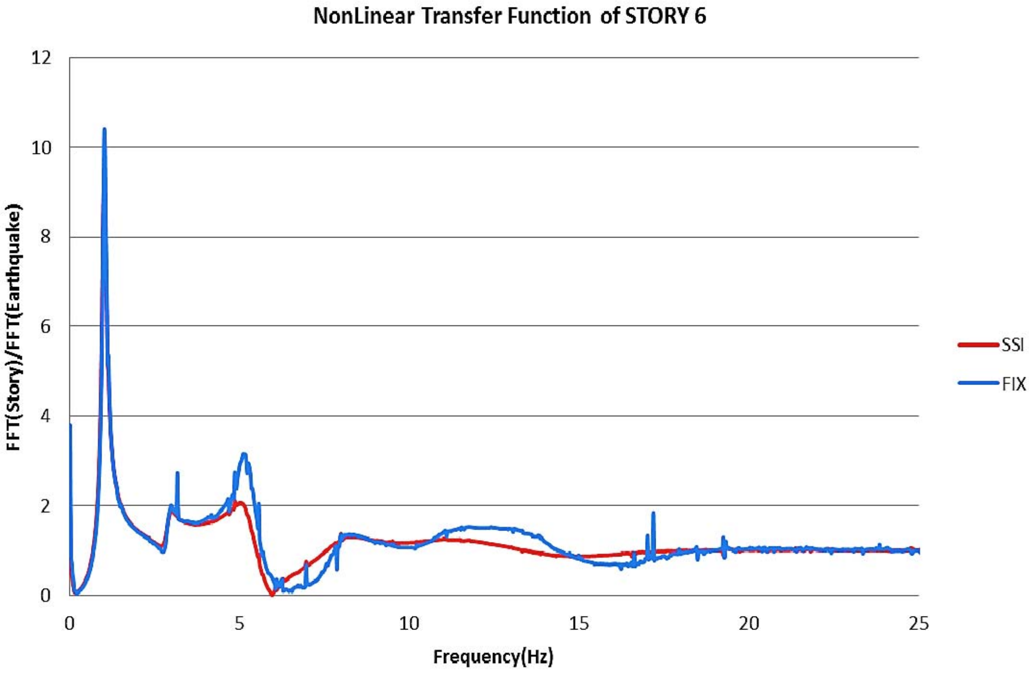

Fig. 10 Comparison of transfer functions for the 6th story of the structure with fixed pillar and soil-structure model after formation of plastic joints

Open Science Index, Civil and Environmental Engineering Vol:11, No:6, 2017 publications.waset.org/10007117.pdf

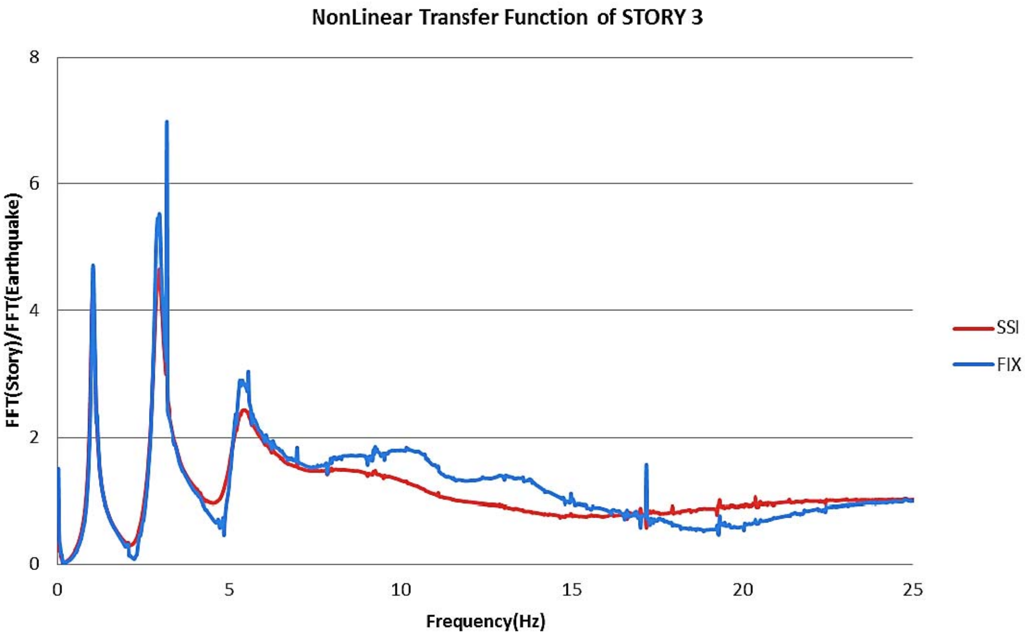

Fig. 11 Comparison of transfer functions for the 3rd story of the structure with fixed pillar and soil-structure model after formation of plastic joints

IX. 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 comparison with the soil-structure model, while these changes are increasing for upper modes. Also, these changes are then elucidated by evaluating the transfer functions of the different stories responses, while, the number of plastic hinges which occurred on the structural elements decreases in the soil-structure model.

REFERENCES

[1] Ljung. L. “System Identification — Theory for the User." Prentice-Hall, Englewood Cliffs, N.J., 1987.

[2] Mottershead, J. E. and M. I. Friswell, 1993, “Model Updating in Structural Dynamics: A Survey,” Journal of Sound and Vibration, 167(2), 347–375.

[3] Teughels A., Roeck G. D. (2005) “Damage detection and parameter identification by finite element model updating.” Arch Comput Method E, 12 (12), pp. 123–164.

[4] Ebrahimian, H. (2015). “Nonlinear finite element model updating for nonlinear system and damage identification of civil structures.” ProQuest Dissertations & Theses, 448 pp.

[5] Crawford, R., Ward, H. S. (1964). “Determination of the normal periods of building” Bull. Of the Seis. Of Am., Vol. 54, No. 6, pp.1743-1756.

[6] Luco, J. E. Trifunac, M. D., Long, H. L. (1988). “Isolation of Soil-Structure Interaction effects by full-scale forced vibration tests.” Earthquake Engineering and Structural Dynamics, 116(1), 1-21.

[7] Safak, E. (1995). “Detection and identification of soil structure interaction in buildings from vibration recordings.” Journal of Structural Engineering, Vol. 121, No.5; 899-906.

[8] Snieder, R., Safak, E (2006). “Extracting the building Response using seismic interferometry: theory and application to the Millikan Library in Pasadena, California.” Bulletin of the seismological society of America. 96, No.2, 586-598.

[9] Todorovska, M. I. (2009). “Seismic Interferometry of a soil-structure Interaction model with coupled horizontal and rocking response.” Bulletin of the seismological society of America, Vol. 99, No. 2A, 611-625.

[10] Todorovska, M. I. (2009). “Soil-structure identification of Milikan Library north-south response during four earthquakes (1970-2002): what caused the observed wandering of the system frequencies” Bulletin of the seismological society of America, Vol. 99, No.2A, 626-635.

[11] Wolf, J. P. (1994). “Cone Model as a strength-of-materials approach to foundation vibration.” 10th European Conference on Earthquake Engineering, Vienna, Austria, A. A. Balkema, Invited paper, pp. 1-10.

[12] Wolf, J. P. (1985).”Dynamic soil-structure interaction.” Prentice-Hall, Englewood Cliffs, New Jersey.

[13] Ghahari, S. F., Abazarsa, F., Avci, O., Çelebi, M., Taciroglu, E. (2016). “Blind identification of the Millikan Library from earthquake data considering soil-structure interaction.” Journal of Structural Control and Health Monitoring, v 23, n 4, p 684-706.

[14] Chen, Z., Trombetta, N. W., Hutchinson, T. C., Mason, H. B., Bray, J. D., Kutter, B. L. (2013). “Seismic system identification using centrifuge-based soil-structure interaction test data.” Journal of Earthquake Engineering, v 17, n 4, p 469-496.

[15] Wolf, J. P. and Meek W. (1993) “Cone models for a soil layer on a flexible rock half-space.” Earthquake Engineering and Structural Dynamics, v 22, n 3, p 185-193.

[16] Lu Y., Hajirasouliha I., Marshall A. M. (2016) “Performance-based seismic design of flexible-base multi-storey buildings considering soil–structure interaction.” Engineering Structures, Volume 108, Pages 90–103.

[17] Wolf, J. P. and Meek W. (1992). “Cone models for homogenous soil.” ASCE, Journal of Geotechnical Engineering, Vol. 118, No. 5, pp. 667-685.