DAMAGE DETECTION IN BUILDINGS CONSIDERING SSI, UTILIZING THE BASELINE STIFFNESS METHOD.

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ABSTRACT: In this work, the influence of Soil-Structure Interaction (SSI) on the estimation of damage (loss of stiffness) for multi-storey buildings is determined utilizing the Baseline Stiffness Method (BSM). This method locates damage and determines its magnitude in buildings without baseline modal information (undamaged state) using, solely, the approximated lateral stiffness of the first storey and some acceleration records of the damaged system. Controlled damage cases were simulated in a 10-storey shear-beam model, reducing the stiffness of certain storeys. Two cases were studied, one considering a fixed base and another considering the flexibility of the soil. Results demonstrate the efficiency of the proposed method to identify damage considering SSI.

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ABSTRACT: In this work, the influence of Soil-Structure Interaction (SSI) on the estimation of damage (loss of stiffness) for multi-storey buildings is determined utilizing the Baseline Stiffness Method (BSM). This method locates damage and determines its magnitude in buildings without baseline modal information (undamaged state) using, solely, the approximated lateral stiffness of the first storey and some acceleration records of the damaged system. Controlled damage cases were simulated in a 10-storey shear-beam model, reducing the stiffness of certain storeys. Two cases were studied, one considering a fixed base and another considering the flexibility of the soil. Results demonstrate the efficiency of the proposed method to identify damage considering SSI.

1 INTRODUCTION

Over time, buildings may suffer damage due to use, lack of maintenance, and mainly because of large-scale natural events such as earthquakes. During seismic events, damage in a structure may be such that will lead to collapse and consequently to economic and human losses. It is therefore vital to identify the extent of damage as a preventive decision tool for habitability and/or reinforcement. The extent of damage will depend, among other factors, on the type of soil in which the structure is supported, explicitly Soil-Structure Interaction (SSI). This effect produces an increment on the fundamental period of vibration of the building, thus SSI must be considered in damage assessment.

Methods to identify and measure damage, also known as Structural Health Monitoring methods have the main purpose of provide information about the structural state of the system studied without damaging the structure. These methods are based on the premise that a change in the system, as the damage, is manifested as a change in the dynamic response of the structure. Therefore, these algorithms use acceleration records of undamaged and damaged system conventionally.

This confronts us with a very common problem, which is the unavailability of the dynamic response of structures in a healthy state. In order to solve this problem the Baseline Stiffness Method (Rodríguez et al., 2010) is presented in this work. This method determines location and magnitude of damage utilizing solely dynamic responses from the damaged structure and the approximated lateral stiffness of the first story without damage. Since the BSM considers a fixed base, dynamic response of the structure must not include soil dynamics. Thus, the hypothesis behind this work is that damage identification results are more precise when the BSM utilizes dynamic information of the building solely (without influence of soil).

Results demonstrate the feasibility of the proposed methodology to identify damage in buildings without baseline modal parameters considering the SSI effect and the stated hypothesis is corroborated.

2 NUMERICAL MODEL OF THE STRUCTURE CONSIDERING SSI

The structure is modeled as a shear beam with flexible base with the procedure used by Fernández and Avilés (2008).

The soil flexibility under earthquake excitation can be accounted in two parts: the site effects, and the SSI.

The site effects produce the modification of the seismic movement due to the geotechnical properties of the superficial layers of soil. Otherwise the SSI effects depend of the difference between the structure and soil stiffness.

To consider the site effects, one-dimensional wave propagation in stratified media model is proposed, which for the case of depth clay deposits (Mexico City i.e.) is well addressed.

Using the transference function proposed by Wolf (1985) for a homogeneous layer the movement on the surface when a wave is started in a point of a base rock, after traveling through a soft media, is obtained.

To consider SSI it is possible to decompose that in two different topics (Whitman and Bielak, 1980). The first relates to an input movement modification, because of the presence of the foundation. The rigid foundation will experience some average horizontal displacement and a rocking component. This rigid-body motion will result in accelerations, which will vary over the height of the structure; this geometry averaging of the seismic input motion is known as the kinematic interaction (Wolf, 1985).

To consider the kinematic interaction in this work was used an approximate solution developed by Kausel et al. (1978).

On the other hand the inertial loads applied to the structure will lead to an overturning moment and a transverse shear acting at the base (Wolf, 1985). This effect is known as inertial interaction and it’s controlled by the stiffness ratio between the structure and soil.

Inertial interaction is modeled through the soil impedance functions (frequency-dependent stiffness and damping of soil-foundation). Based on the analogy with an elementary oscillator, the dynamic stiffness of the foundation for any mode of vibration is usually expressed by a complex function dependent of the frequency excitation (Gazetas, 1983).

The static stiffness for horizontal translation modes, rocking and coupling for circular foundations buried in a uniform layer with rigid base, were approximated by the expressions of Gazetas (1991), Sieffert and Cevaer (1992).

In the same way, the stiffness and damping coefficients for horizontal translation modes, rocking and coupling for circular foundations buried in a uniform layer with rigid base, were computed by the formulas presented in the works from Gazetas (1991), Sieffert and Cevaer (1992).

The structure is modeled as a shear beam in lateral translation. Considering the degrees of freedom corresponding to translation and rocking of the base, a system of N +2 degrees of freedom is established, as shown in Fig. 1. As the impedance functions (springs and dampers support) depends of the frequency excitation and there are no classical modes of vibration, to determine the response of the system is convenient to use the method of complex frequency response together with the Fourier synthesis (Chopra, 1995).

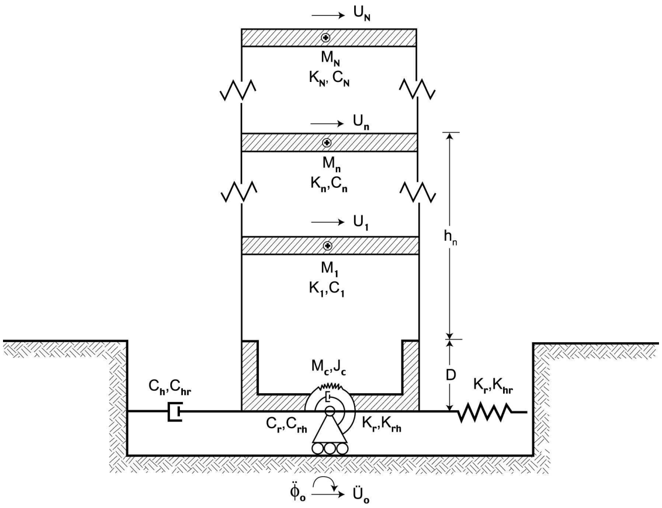

Figure 1. Complete soil-structure system (Avilés, 1991).

3 FREQUENCY DOMAIN DECOMPOSITION METHOD

According to Brincker et al. (2000) the q x q power spectral density matrix of the response must be obtained, where q is the number of responses. One way to determine this matrix is:

$$\left[\hat{G}\,yy(f)\right] = \left[\overline{Y}(f)\right]^T \left[Y(f)\right] \tag{1}$$

This matrix operates at discrete frequencies $f = f_p$ where p is a discrete series for each frequency in the domain. $[Y(f)]$ is the transformed response from time to frequency domain for each frequency value f. Eq. (2) expresses eq. (1) as a Singular Value Decomposition, SVD:

$$\left[\hat{G}\,yy(f)\right] = \left[U_p\right]\left[S_p\right]\left[U_p\right]^T \tag{2}$$

where $[U_p]$ is a matrix containing singular vectors $\{u_{pk}\}$. $[S_p]$ is a diagonal matrix containing singular values s_{pk}. These singular values can be plotted on the frequency domain and peak values may be observed which correspond to the natural frequencies of the system. A mode shape associated to each extracted frequency can be determined as well through SVD.

4 BASELINE STIFFNESS METHOD

The Baseline Stiffness Method (BSM) is presented to detect damage in buildings without baseline modal parameters (undamaged state). For a damaged plane frame of s number of floors and i mode shapes and performing signal processing techniques, natural frequencies ϖ and their corresponding mode shapes $[\phi]$ can be computed. Lateral stiffness and mass matrix, $[\overline{K}]$ and $[\overline{M}]$respectively, are unknown with dimensions $s \times s$. On the other hand, it is possible to compute a vector $\{u\}$ of ratios k_i/m_i (Barroso and Rodríguez, 2004) with dimensions $2s-1 \times 1$:

$$\{u\} = \left\{ \left(\frac{k_1}{m_1}\right) \; \left(\frac{k_2}{m_1}\right) \; \left(\frac{k_2}{m_2}\right) \; \cdots \; \left(\frac{k_i}{m_i}\right) \; \left(\frac{k_{i+1}}{m_i}\right) \; \cdots \; \left(\frac{k_s}{m_s}\right) \right\}^T \tag{3}$$

This vector $\{u\}$ is computed utilizing modal parameters from the damaged structure and the first story approximated lateral stiffness k_1 assuming a shear beam behavior. It is well known this assumption is valid for limited real cases, however, this is proposed just as an initial condition and the flexural effect will be included later on. In this sense, k_1 can be determined as:

$$k_1 = \sum \frac{12EI_1}{h_1^3} \tag{4}$$

Substituting k_1 into eq. (3), some parameters p_i are obtained using back substitution. Once all k_i are known, the lateral stiffness matrix of the structure without damage $[\overline{K}]$can be determined. In order to compute m_i, m_1 using back substitution instead of using k_1. These m_i are used to obtain the mass matrix of the structure $[\overline{M}]$. The former approach was applied to buildings without shear beam behavior and it was observed that an approximated mass matrix $[\overline{Ma}]$ is obtained, which differs in magnitude to $[\overline{M}]$. The difference is null if k_1 is k_1/c, where c is a coefficient that adjusts shear to flexural behavior and it was found to correspond to the greatest eigenvalue of $[\overline{M}][\overline{Ma}]^{-1}$. Thus, when the adjustment by k_1/c, for structures without shear beam behavior is performed, the BSM provides its undamaged state $[\overline{K}]$. Simultaneously, a mathematical model of the structure is created considering connectivity and geometry of its structural elements and a unit elasticity modulus. Thus, approximated stiffness matrices $[ka_i]$ for each element are obtained. The global approximated stiffness matrix of the structure is:

$$[Ka] = \sum [ka_i] \tag{5}$$

According to Escobar et al. (2005), $[Ka]$ can be condensed to obtain $[\overline{Ka}]$ using a transformation matrix $[T]$ as:

$$[\overline{Ka}]=[T]^T[Ka][T] \tag{6}$$

For a shear beam building, $[\overline{K}]$ and eq. (6) just differ on material properties, specifically, on the magnitude of the elasticity modulus that can be represented using the matrix $[P]$ as $[\overline{K}]=[P][\overline{Ka}]$. Solving $[P]$ from last equation yields:

$$[P]=[\overline{K}][\overline{Ka}]^{-1} \tag{7}$$

On the other hand, stiffness matrices for each structural element of the undamaged state of the structure are computed as $[k_i]=P[ka_i]$; where P is a scalar that adjusts the material properties of the structure from the proposed model. This scalar is obtained as the average of the eigenvalues of matrix $[P]$, given in eq. (7). Eigenvalue computations are performed because are useful to obtain characteristic scalar values of a matrix, in this case $[P]$. It was found that the average of these eigenvalues is precisely P. Once the undamaged state of the structure, represented by $[k_i]$, is identified and condensed, it is compared against the stiffness matrix of the damaged structure $[\overline{Kd}]$ using the Damage Submatrices Method (DSM, Rodríguez et al., 2009). This method is applied to locate and determine magnitude of damage, in terms of loss of stiffness, in percentage, at every structural element. According to Baruch and Bar Itzhack (1978), $[\overline{Kd}]$ can be computed from measured modal information. Thus, the condensed stiffness matrix of the damaged system can be reconstructed as:

$$[\overline{Kd}]=\left[\ [\overline{K}]-[M][Z]\right][H]+[M][q][\Omega]^2[q]^T[M] \tag{8}$$

Where $[H]=[I]-[Y]$; $[Y]=[q][q]^T[M]$; $[Z]=[q][q]^T[\overline{K}]$; $[q]=[\phi]\left[[\phi]^T[M][\phi]\right]^{-\frac{1}{2}}$; $[\phi]$ is the modal matrix of the structure; and $[\Omega]^2$ is a diagonal matrix containing the eigenvalues of the system.

5 NUMERICAL TESTS

A 10-storey shear-beam model was analyzed. This was reproduced from Fernández and Avilés (2008). The structure has a total mass equal to 330.28 t and a total height equal to 30.5 m, the foundation mass is equal to 79.53 t, the equivalent radius equal to 11.28 m, and an embedment of 5 m. The uniform soil layer has a βs=75 m/s (shear wave's propagation speed), a depth of 50 m and a fundamental period T_s=2.5 s.

Three damage cases were simulated, analyzing both, fixed and flexible base (model described in Fig. 1), so six damage cases were studied: D1, D2, D3 and D1SSI, D2SSI and D3SSI. The first three do not include SSI effects and thus consider a fixed base. D1 corresponds to a 86.36% reduction of stiffness on the first storey (Fernández and Avilés, 2008), D2 a 50% on the second storey and D3 a 50% on the fifth storey.

Using the acceleration records at every floor, the FDD was applied for each damage case and four mode shapes and frequencies were extracted. Table 1 shows the frequency values. As expected, fundamental frequencies are smaller when SSI is considered. Note, also, that values with and without SSI effects are the same for mode 3. This could have an influence in the damage detection results.

The BSM was applied to each damage case and location and damage magnitude was determined. Figure 2 shows the identified location and magnitude of damage. It can be observed that in all models the BSM identified correctly the simulated damage locations.

Table 1. Computed frequencies (Hz) using the FDD method.

Mode shape	D1	D2	D3	D1SSI	D2SSI	D3SSI
1	0.61	0.765	0.765	0.496	0.492	0.492
2	1.941	2.271	1.652	1.237	2.169	1.941
3	3.377	3.768	3.63	3.377	3.768	3.63
4	5.001	5.249	5.001	5.001	5.249	4.256

In the case of fixed base, just in model D2, one element was calculated wrongly, and this was smaller than the real simulated. Despite this false location is not desire, is not as prejudicial.

In the case of considering SSI, false elements are identified, as is observed in model D2SSI. Also can be observed that in this case, the false measurement is located next to the simulated storey and can be produce by the connectivity between these elements. This phenomenon is not desired, because the real damaged element is not having the major importance.

Same behavior is presented in model D3SSI. The difference is that for this model, the wrong damage location is presented close to the top of structure. In other works, the BSM has reported the same mistake, being attributed to numerical errors Rodríguez (2010).

These observations can lead to recommend cleaning the signals to eliminate soil influence, before assessing damage, since damage location was more precisely identified in models with fixed base (no SSI).

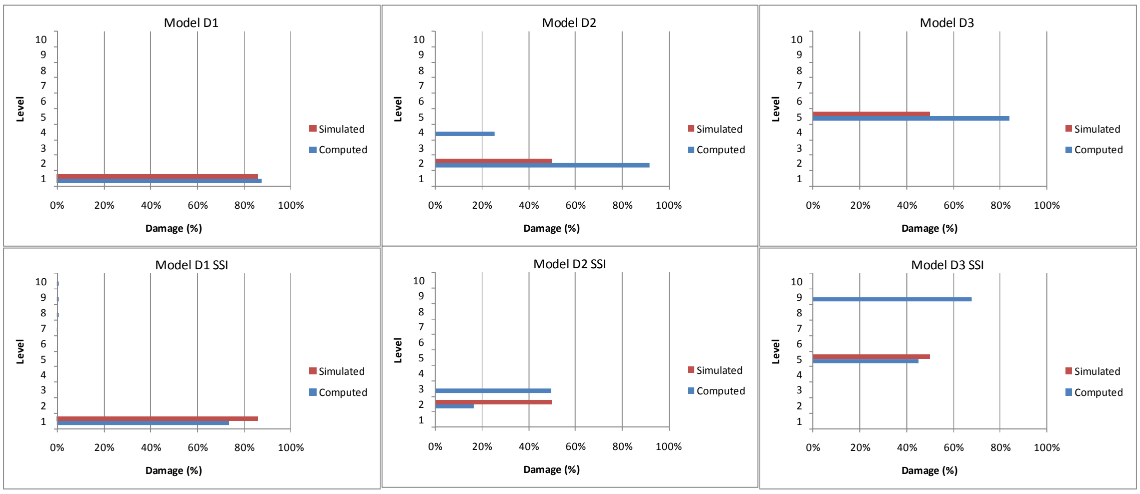

Figure 2. Damage location and measure.

Damage magnitudes and their corresponding error values were computed (Table 2). It can be observed that these values are greater than the simulated ones for D1, D2 and D3. Because of that the relative errors are negative. This means that the methodology over estimated damage magnitude when a fixed base is analyzed, being on the safe side, what is desired in engineering.

It can be observed that for D1 the magnitude of damage has a relative error smaller than 10%.

In the SSI models the magnitude of damage was underestimated, for all cases and just in model D3SSI the relative error was minor than 10%.

As mentioned the BSM was formulated considering a fixed base. Because of that better damage location and measure were obtained when the SSI is not presented.

Table 2. Measure damage and error.

D1			D2			D3		
Modes	Damage measured	Relative error	Modes	Damage measured	Relative error	Modes	Damage measured	Relative error
1 and 3	87.36%	-1.16%	1 and 3	91.68%	- 83.36%	1 and 2	83.97%	- 67.94%
D1SSI			**D2SSI**			**D3SSI**		
Modes	Damage measured	Relative error	Modes	Damage measured	Relative error	Modes	Damage measured	Relative error
1 and 2	73.47%	14.93%	1 and 4	16.36%	67.28%	1 and 3	45.02%	9.96%

6 CONCLUSIONS

In this work the BSM was applied to evaluate damage in a 10 levels shear beam model, considering a flexible base (SSI), without base modal information. Six models were studied, being three of them formulated with a fixed base, and the other ones considering the flexibility of the base.

Three damage cases were simulated decreasing the stiffness from some levels of the model. Can be concluded that BSM identified in all cases the elements with damage. When fixed base models were proved, the location of damage was more precise, reporting less false elements. Also, using a fixed base, the magnitude of damage was over estimated, letting the results on the safe side.

It is recommended to clean the signals to eliminate soil influence before identifying damage.

The authors are working to improve damage magnitude results.

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