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NORMALIZED INPUT-OUTPUT MINIMIZATION ANALYSIS OF EARTHQUAKE WAVE PROPAGATION IN DAMAGED AND UNDAMAGED BUILDINGS

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SUMMARY

This paper presents a wave propagation modeling analysis of strong motion records for actual undamaged and damaged buildings. Normalized input output minimization (NIOM) method, which can model wave propagation in multiple linear systems by considering the statistical correlation among the strong motions at different observation locations, is used in this work. Output wave models simplified by the NIOM method show two clear peaks that correspond to incident and reflected waves propagating through the building in the vertical direction. Obtained wave travel times at each story of the building are found to reflect the structural properties at that story.

We have developed a new method for wave-propagation analysis—called evolutionary normalized input-output minimization (NIOM)–that models time-variant wave propagation by considering the time-variant statistical correlation between the strong motions recorded at different levels in the building. The NIOM results for actual damaged buildings (which experienced the 1994 Northridge earthquake [1] or the 1971 San Fernando earthquake [2]), as well as those from an analytical elastic building model, were compared. All of these results showed two clear peaks that correspond to the incident and reflected waves propagating through the building in the vertical direction. The wave travel time was determined from these two peaks. In the case of the damaged buildings, the travel time increased during the earthquake; however, in the case of the elastic model, it remained almost constant during the earthquake. It was found that the change in the travel time is related to the change in the structural properties and to the degree of damage to a building. These results show that evolutionary NIOM is an effective new method for investigating the change in structural properties and the damage to buildings.

INTRODUCTION

Analyzing the behavior of a structure during an earthquake involves two problems, vibration and wave propagation, because the vibration of a structure results from seismic-wave propagation in it. Vibration methods are well known and have been developed mainly for structural engineering. In contrast, wave-

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propagation approaches have been mainly used to investigate ground motions due to earthquakes, and researchers use several methods (such as impulse response and correlation functions) to simplify and clarify the wave propagation in soil layers and to determine soil properties. However, a wave-propagation method can be applicable also in structural engineering, because the wave-propagation velocity depends much on the characteristics of the materials through which the wave propagates.

One of the wave-propagation modeling methods–the normalized input-output minimization (NIOM) method (Kawakami [3]; Haddadi [4]) is used in the present work. The NIOM method models wave propagation by considering the statistical correlation of the earthquake motions at different observation locations. The capability and applicability of the method are checked by analyzing soil media and analytical building models, and presented previously (Kawakami [5]). Analysis results of actual building records show that wave propagation properties at each story of the building reflect the structural properties at that story. We used narrow windows and developed a so-called evolutionary NIOM method for examining the time-variant properties of buildings. This method can simplify the relationships between waves observed at several levels in the building at different times from the beginning to the end of the earthquake, and it can determine the change in travel time of the wave propagating through the building (Oyunchimeg [6]). The travel time was found to be a very good indicator of damage, and its change was related to the change in the degree of damage, i.e., the change in the structural properties of the building.

METHODOLOGY

NIOM method

The normalized input-output minimization (NIOM) method can model wave propagation by considering the statistical correlation between earthquake motions observed at different points. This method can simplify the relationship between the observed waves and give arrival times, as well as their relative amplitudes, of incident and reflected waves. Since the wave-propagation velocity depends much on the characteristics of the materials through which the wave propagates, such a method is applicable not only to ground-motion analysis but also to building-record (i.e., of earthquakes) analysis. A brief review of the NIOM method is given below [3]; [4].

NIOM method for a linear system

When a time-invariant linear system is subjected to an earthquake motion, the input and output of the system in the frequency domain can be related by means of the transfer function $H(\omega)$. In the case of digitized earthquake motions, the output at each frequency is given by

$$G(\omega_i)=H(\omega_i)F(\omega_i) \tag{1}$$

$$(i = 0,...,N-1 \text{ and } \omega_i = i\frac{2\pi}{N\Delta t}),$$

where Δt is the sampling rate in the time domain; N is the number of samples; and $F(\omega_i)$ and $G(\omega_i)$ are the Fourier transforms of the digitized earthquake input and output motions, respectively. Transfer functions depend only on the physical properties of the system. Therefore, the same transfer function as the one that defines the relationship between the observed input $F(\omega_i)$ and output $G(\omega_i)$ [Eq. (1)] should satisfy the relationship between the simplified input model $X(\omega_i)$ and the simplified output model $Y(\omega_i)$.

$$Y(\omega_i) = H(\omega_i)X(\omega_i) \tag{2}$$

Minimizing the summation of the squared values of Fourier amplitude spectra of the input and output when a constraint is in existence ([3], [4]) would result in a simplified input model of $X(\omega_i)$ and a simplified output model of $Y(\omega_i)$. The procedure that gives the simplified input and output models is shown schematically in Fig.1.

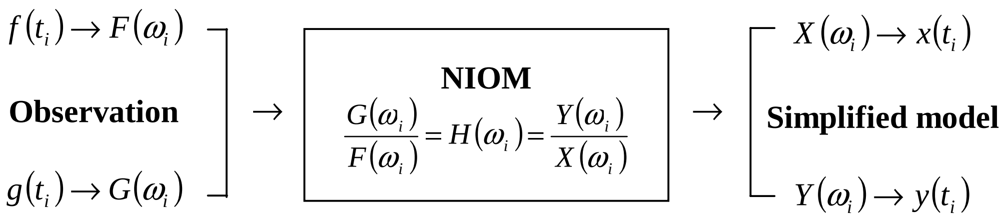

Fig. 1: Schematic procedure of the NIOM method

In the analysis of a feedback system, it should be noted that input cannot be separated from output and that the input motion in this paper is not the incident-wave motion. The motion observed at one arbitrary location (always the building's roof in this paper) is called the input motion in the following numerical analyses.

NIOM method for multiple linear system

Controlling the contribution of high- or low-frequency components in the procedure and generalizing to multiple linear systems gives the following equations:

$$X(\omega_i) = N\Delta t \frac{\dfrac{1}{\left\{1+\dfrac{k_0}{c_0}\omega_i^2\right\}\left(c_0+\sum_{m=1}^{M} c_m \left|H_m(\omega_i)\right|^2\right)}}{\sum_{n=0}^{N-1} \dfrac{1}{\left\{1+\dfrac{k_0}{c_0}\omega_n^2\right\}\left(c_0+\sum_{m=1}^{M} c_m \left|H_m(\omega_n)\right|^2\right)}} \tag{3}$$

$$Y_l(\omega_i) = N\Delta t \frac{\dfrac{H_l(\omega_i)}{\left\{1+\dfrac{k_0}{c_0}\omega_i^2\right\}\left(c_0+\sum_{m=1}^{M} c_m \left|H_m(\omega_i)\right|^2\right)}}{\sum_{n=0}^{N-1} \dfrac{1}{\left\{1+\dfrac{k_0}{c_0}\omega_n^2\right\}\left(c_0+\sum_{m=1}^{M} c_m \left|H_m(\omega_n)\right|^2\right)}} \tag{4}$$

where l=1,…,M; M is the number of outputs; c_0 to c_M are weighting constants of the squared Fourier amplitude spectra of the input and outputs, and k_0 is weighting constant of time derivative of the squared Fourier amplitude spectrum of the input. Effects of these weighting constants on the results are shown in the referred papers [3]; [4].

The inverse Fourier transforms of Eqs. (3) and (4) give simplified input and output models in the time domain. These simplified input and output models illustrate the statistical correlation between the observed motions, and the procedure for obtaining these models is called the NIOM method. It should be noted that the Fourier transform defined in Eq. (3) is real and symmetric with respect to the folding frequency. This means that the input model is real and symmetric with respect to time zero as in the case of auto-correlation functions.

NIOM ANALYSIS OF UNDAMAGED BUILDINGS

We applied the NIOM method to a number of earthquake strong motion records observed in actual buildings [5], but because of the space limitation, the results for only few are presented in this paper.

19-story office building in Los Angeles

This is a moment-resisting steel frame building in Los Angeles located 20 km from the epicenter of the January 17, 1994 Northridge earthquake. The building is rectangular in plan, and is 82.3 m high above ground level and has four levels below ground. The lateral load carrying system is moment-resisting steel frames in the longitudinal direction and X-braced steel frames in the transverse direction. The vertical load carrying system is RC slabs supported on the steel frames. The ground floor is 9.14 m high while other floors are 4.06 m high, giving the building an irregular stiffness with height [7].

NIOM analysis results for the NS component of the acceleration records in the east side of the building are shown in Fig. 2(a).

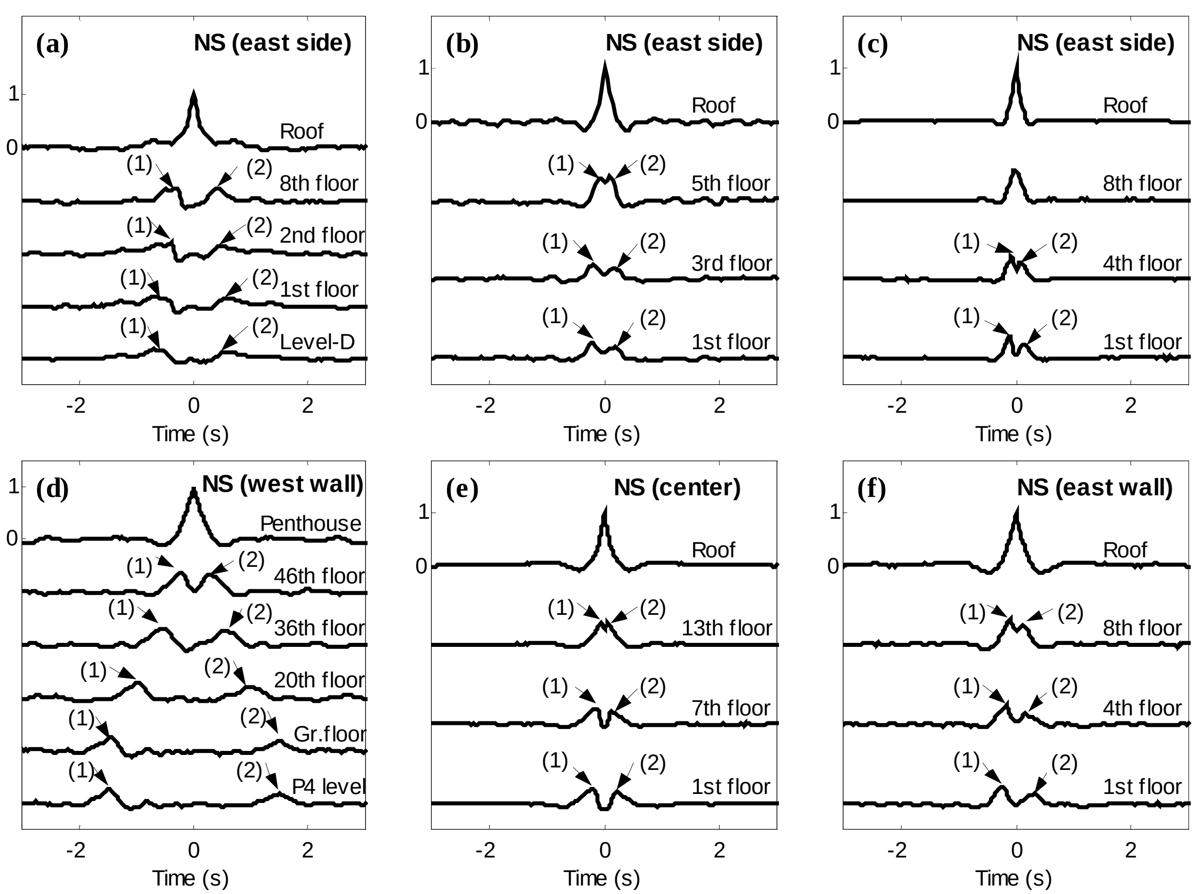

Fig. 2: NIOM analysis result of actual building records (NS component): (a) 19-story office building in Los Angeles; (b) UCLA Math-Science building; (c) Burbank 10-story residential building; (d) 54-story office building in Los Angeles; (e) 17-story residential building in Los Angeles; (f) 9-story building in Los Angeles

Simplified wave models obtained at each story in the building show two clear peaks (arrow (1) and (2) in the figure) that correspond to incident and reflected waves propagating through the building in the vertical direction. Arrival times of the incident and reflected waves were mostly the same, and reflected wave amplitude was smaller than incident wave amplitude.

Figure 3 shows wave arrival times obtained at the instrumented floors in the NS direction. As seen from Fig. 3, there were clear changes in wave velocities in NS direction (it is also same in the EW direction), and their locations coincide with the locations of floors having different properties. Wave travel time from basement to the ground floor was very short: $\tau \approx 0.04$ s ($v_s \approx 300$ m/s) and $\tau \approx 0.02$ s ($v_s \approx 700$ m/s) in the NS and EW directions, respectively. The reason is that these floors are much stiffer than the floors above ground, because they consist of concrete and concrete-encased steel columns. Meanwhile, the wave travel time in the first floor was $\tau_1 \approx 0.18$ s ($v_s \approx 50$ m/s) and $\tau_1 \approx 0.12$ s ($v_s \approx 80$ m/s) in NS and EW directions, respectively, and average wave velocity between the second floor and the roof was $v_s \approx 130$ m/s and $v_s \approx 90$ m/s in the NS and EW directions, respectively.

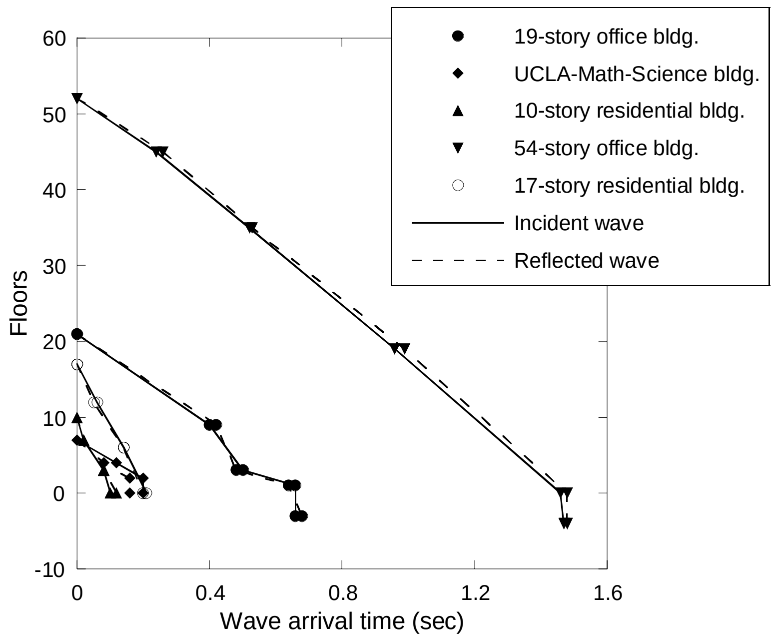

Fig. 3: Wave arrival times at instrumented floors of some actual buildings

UCLA-Math-Science building

The Math and Science building of the University of California, Los Angeles, is located about 18 km from the epicenter of the January 17, 1994 Northridge earthquake. The total height of the building is 28.8 m, and it consists of two different structures; the older two-story RC structure houses a nuclear reactor surrounded by a rigid reinforced concrete shear wall structure, and a more recent 5-story moment resisting steel frame structure was built on top of the reactor building [7].

NIOM analysis result of the acceleration records (NS component in east side) in the building is shown in Fig. 2(b). Figure 3 shows the wave arrival times obtained at the instrumented floors in the NS direction. The difference in wave velocities in the steel frame part (floors 3-7) and RC wall part (floors 0-2) is obvious from Fig. 3. The wave velocity in the first two floors (RC shear wall structure) was more than 400 m/s, when wave travel time from the ground floor to the third floor is considered to be 0.02 s (sampling rate of the record), because no difference in the arrival times is observed between the first and third floors, which means that wave travel time in the first two floors was less than 0.02 s. Meanwhile, wave travel time obtained between the third floor and the roof (steel frame structure) gives a wave velocity of $v_s \approx 100$ m/s.

Burbank-10-story residential building

This buildings is located in Burbank, California, 21 km from the epicenter of the January 17, 1994 Northridge earthquake. The total height of the building is 26.8 m, distributed over 10 stories: The first is 3.0 m high and the 2nd through 10th are 2.64 m high. The lateral force resisting system in the building consists of precast RC shear-walls interconnected through steel plates embedded in the walls. The building is regular in plan and elevation.

NIOM analysis result of the acceleration records (NS component in east side) in the building is shown in Fig. 2(c), and Fig. 3 shows the wave arrival times obtained at the instrumented floors in the NS direction. This building has no significant difference in structural properties with its height, which explains why no significant change of wave velocity between floors was observed. Wave travel time from the ground floor to the roof was about 0.1 s, and wave velocity was about 270 m/s (total building height is 26.8 m). The accuracy of the wave travel time is 0.02 s, because the sampling rate of the record was 0.02 s.

NIOM ANALYSIS OF DAMAGED BUILDING RECORDS

NIOM analysis of whole length of data

Elastic model of a seven-story building

To test the method thoroughly, it was applied to an elastic analytical seven-degrees-of-freedom shear-spring model, which represents of a seven-story building. In the model, all floors have the same mass M of 45.3 t and all the stories have equal stiffness K of 200 kN/cm, and the fundamental period by modal analysis, T, is 1.43 s. Elastic response of the model was computed by the conventional vibration method. In this calculation, the ground motion was considered as the strong motion (NS component) recorded at the ground floor of the seven-story hotel in Van Nuys during the 1994 Northridge earthquake. The acceleration responses are computed by conventional direct integration when the damping ratio in the first mode is assumed to be 10%, which is the number estimated by De La Llera and Chopra [8] for the damaged 7-story hotel in Van Nuys.

The NIOM method was used to calculate the simplified models of the computed response motions by considering the response at the roof as an input and those at the other floors as the outputs. The obtained NIOM results are shown in Fig. 4(a). Two peaks can be clearly seen in the case of the simplified output models; the left one (negative time) corresponds to the incident wave from the ground to the roof, and the right one (positive time) corresponds to the reflected wave from the roof to the ground. Incident-wave travel time from the ground floor to the roof, τ, is 0.36 s, which corresponds to the fundamental period $T=4\tau$ of 1.44 s, which is very similar with the period obtained by the modal analysis (T=1.43 s). Note that the accuracy of the wave travel time is 0.02 s, which can be considered as the sampling rate of the record used.

Actual buildings

Actual data on earthquake motions recorded in several buildings were used in this study. It includes records of the 1994 Northridge earthquake in five buildings, namely, the seven-story hotel in Van Nuys, the 20-story hotel in North Hollywood, the 13-story commercial building in Sherman Oaks, the 10-story residential building in Burbank, and a six-story office building in Los Angeles. The records of the 1971 San Fernando earthquake recorded at the Holiday Inn (on 8244 Orion Avenue) were also used. The name of this building was changed later, and this is the same building as the seven-story hotel in Van Nuys mentioned above [6].

Figure 4(b) shows the NIOM result for NS component of the observed strong motion record in seven-story hotel in Van Nuys, when the whole length of the data was used. Similarly to those shown in Fig. 4(a), the two clear peaks indicated by arrows (1) and (2) in the simplified outputs in Fig. 4(b) correspond to the incident wave from the ground to the roof and the reflected wave from the roof to the ground, respectively.

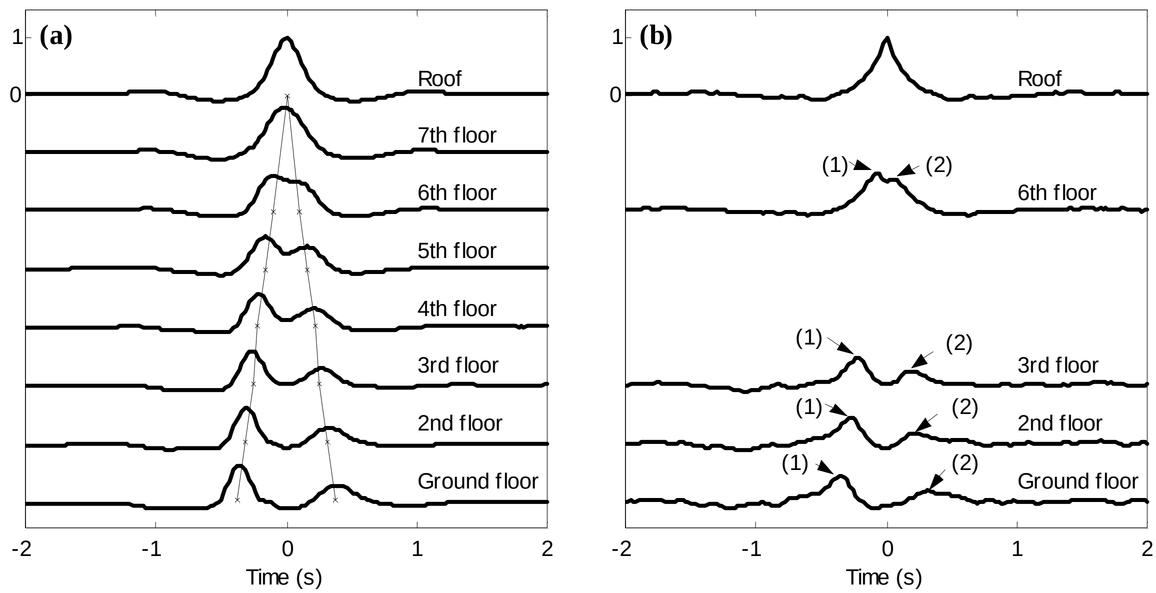

Fig. 4: (a) NIOM result for computed responses of 7-story elastic model; (b) NIOM result for acceleration records in 7-story hotel in Van Nuys during 1994 Northridge earthquake (NS component)

Evolutionary NIOM method

Strong motions recorded in a damaged building, which has deformed into the plastic range, give different information from that expressed by the elastic characteristics of the building. To reveal the damage process of such a building during an earthquake, the change in building characteristics with time should be examined from the beginning to the end of the earthquake. Because the NIOM method can give simplified models of input and output motions as shown in Fig. 4, we tried to analyze the records segmentally in time and compared the results.

The observed strong motions were divided into short (but long enough to obtain reliable results) portions, and NIOM was applied to each portion. We named this method as the "evolutionary NIOM method". The shortest length of each portion was chosen to be from 2τ to 4τ (τ is the wave travel time from the basement to the roof) so that a reliable correlation between motions at different levels in the building could be obtained. Windows with length of 5.12 to 10.24 s, shifted by 1 or 2 s from the beginning to the end of the record, were used.

Comparison between evolutionary NIOM results for elastic model and damaged seven-story hotel in Van Nuys

Figures 5(a) and 5(b) show the evolutionary NIOM results for the elastic 7-story model and 7-story hotel building, respectively. The lowest curve in this figure shows the output model at the ground floor when only the data from 0 to 2.56 s (window W-1) was used, the second curve shows the output model when the data for 0-3.12 s (W-2) were used, the third curve shows the output model when the data for 0-4.12 s

(W-3) were used, the fourth curve shows the output model for 0-5.12 s (W-4) were used, the fifth curve shows the output model for 1-6.12 s (W-5) were used, and so on.

The incident-wave arrival times corresponding to the peaks in negative time are shown by crosses in Fig. 5, and the arrival times when the whole data was used (0.36 s and 0.34 s, respectively, as shown in Figs. 4(a) and 4(b)) were shown by dashed lines in Fig. 5. In the case of the elastic model, the arrival times are almost the same; however, in the case of the damaged building, the change in the arrival time is apparent, as shown in Figs. 5(a) and (b).

According to the elastic model, there should be no change, theoretically, in wave travel time during the earthquake, because the model is assumed to be elastic. Figure 5(a) proves the above-mentioned theory; namely, differences in the arrival times obtained between windows were only ±0.02 s, which is the same as the sampling rate. Meanwhile, the seven-story hotel in Van Nuys located 7 km from the epicenter of the 1994 Northridge earthquake experienced serious structural and nonstructural damage [7]. It was found that incident-wave arrival time changed from 0.24 s to 0.42 s (see Fig. 5(b)) at the ground floor in the NS direction. In the EW direction, the arrival time changed from 0.24 s to 0.40 s. As seen in Fig. 5(b) (the results for the NS and EW components are similar), the first change in the incident-wave arrival time occurred at around 3-4 s, and an additional change occurred at around 7-8 s. These results indicate how the damage developed in the building during the earthquake. The possibility to locate the damage and identify the extent of damage depends on the availability of the strong motion records in the building.

Other actual damaged buildings

Holiday Inn, 8244 Orion Avenue

The building stood about 13 km from the epicenter of the 1971 San Fernando earthquake, and suffered minor structural damage and extensive nonstructural damage [6]. At that time, the building had been instrumented at three levels, namely the 1st floor, the 4th floor, and the roof (Foutch et al., [9]). We analyzed the records of the strong motion by the NIOM method. Figure 5(c) shows the result at the first floor in the NS direction. A significant change in the incident-wave arrival time at the first floor can be seen; the arrival time changed from 0.16 s (t=2 s) to 0.35 s (t=40–50 s) in the NS direction and from 0.18 s to 0.35 s in the EW direction. In contrast with that in the case of the Northridge earthquake (Fig. 5(b)), incident-wave arrival time changed gradually from the beginning to the end of the earthquake, and it shows the different progress of damage during the two different earthquakes.

North Hollywood, 20-story hotel

This building was located 19 km from the epicenter of the 1994 Northridge earthquake and experienced heavy nonstructural and content damage [6]. Figure 5(d) shows the evolutionary NIOM analysis result at the basement in the NS direction, and incident-wave arrival time obtained in the basement changed from 0.52 s to 0.63 s in the NS direction and from 0.58 s to 0.66 s in the EW direction. This implies that the damage that occurred in the building had affected its dynamic property.

CONCLUSIONS

Simplified wave models obtained by the NIOM method at each story in the building show two clear peaks that correspond to incident and reflected waves propagating through the building in the vertical direction. Arrival times of the incident and reflected waves were mostly the same, and reflected wave amplitude was always smaller than incident wave amplitude. Wave travel times obtained in each story in actual buildings were found to reflect the structural properties in that story, such as irregularity in height and difference in structural types.

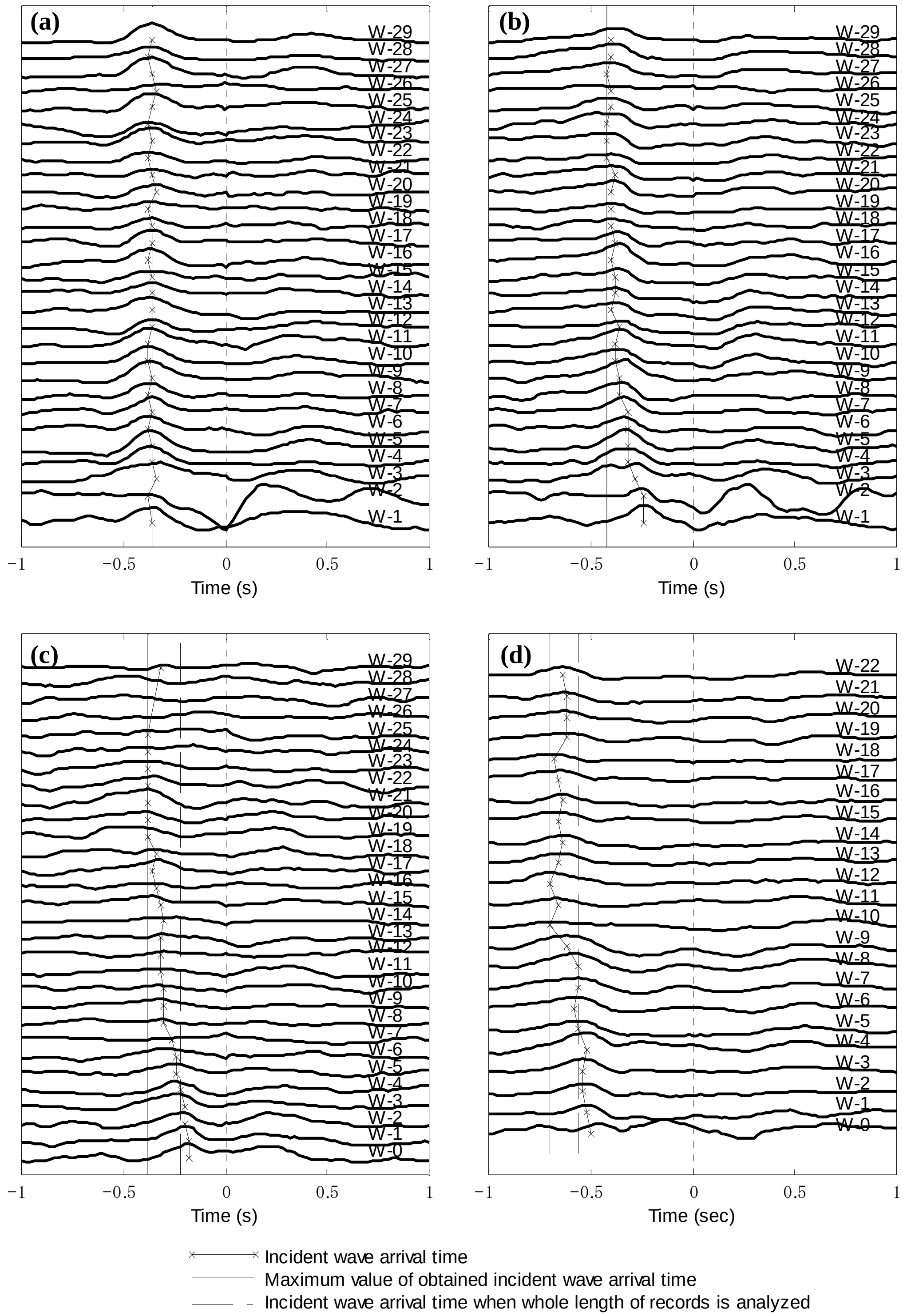

Fig. 5: Evolutionary NIOM results when using narrow windows are used: (a) Elastic 7-story building model, Ground floor; and (b) 7-story hotel in Van Nuys, Ground floor (NS component); (c) Holiday Inn, 8244 Orion Avenue (NS component); (d) North Hollywood, 20-story hotel (NS component)

Evolutionary method for normalized input-output minimization (NIOM) enables time-variant wave propagation modeling by taking into account the time-variant statistical correlation among the strong motions recorded at different levels in a building. The NIOM results for actual damaged and undamaged buildings, as well as those from an analytical elastic building model, were compared. In the case of the damaged buildings, the travel time increased during the earthquake; however, in the cases of the undamaged buildings and the elastic model, it remained almost constant during the earthquake. It was found that the change in the travel time is related to the change in the structural properties and to the degree of damage to a building. These results show that evolutionary NIOM is an effective new method for investigating the change in structural properties and the damage to buildings. This method has an advantage of investigating building behavior during earthquakes without assuming any structural properties, because only strong motion time histories recorded in the building are needed.

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