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Paper No. 1430. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EFFECTS OF GROUND MOTION CHARACTERISTICS ON THE RESPONSE OF BASE-ISOLATED STRUCTURES

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ABSTRACT

We present two examples to show the effects of ground motion characteristics on the response of base isolated structures. The first example is a six-story base-isolated building subjected to motions from simulations using 1-D and 3-D velocity models. We show that the base isolators reduce the response for the 1-D simulated motions, but increase the response for the 3-D simulated motions. The reason for this is the low-frequency, long-duration surface waves that are present in the 3-D simulations, but not in the 1-D simulations. The second example involves the 7-story, base-isolated University of Southern California Hospital, whose response was recorded during the January 17, 1994, Northridge, California earthquake. We first identify the characteristics of the building and the isolators from the recorded response, and then calculate the expected response for five other ground motions with larger amplitudes and different frequency contents. The results show that the effectiveness of base isolators is strongly dependent on the amplitudes and frequency characteristics of ground motions.

KEYWORDS

Seismic response, base isolation, ground motion characteristics, Northridge earthquake.

INTRODUCTION

Base isolation is becoming an increasingly popular method of reducing seismic forces on structures. Response of base-isolated structures and the effectiveness of isolators are strongly dependent on the characteristics of ground motion. Isolators that seem to be beneficial for one set of ground motions can actually be harmful for another set of ground motions. The frequency content and the duration of ground motions are the two key components that influence the response of base-isolated structures.

In this paper, we present two examples that show the effects of ground motion characteristics on the response of base-isolated structures. The first example is a six-story building subjected to ground motions from simulations using 1-D and 3-D velocity models, whereas the second example involves the 7-story base-isolated U.S.C. (University of Southern California) Hospital, whose response was recorded during the January 17, 1994, Northridge, California earthquake.

EXAMPLE 1

In the first example, we investigate the response of a six-story, base-isolated, reinforced concrete building to simulated ground motions. This building, which was to be constructed in Greece, is used as an example by Nagarajaiah et al. (1991) to test their computer program 3D-BASIS. The building is isolated by 22 lead-rubber bearings. The detail on structural characteristics of the building, as well as the isolators, can be found in Nagarajaiah et al. (1991). We subjected the building to two sets of simulated ground motions from a hypothetical earthquake of magnitude 6.5 in the San Bernardino Valley, California. The first set of simulations were made by using a 1-D model (i.e., a soil-column over bedrock) of the geology at the site, and the second by using a 3-D finite-difference model of the entire valley. The main difference between the 1-D and the 3-D models is that the 3-D model can simulate the large-amplitude, low-frequency surface waves that are produced by the conversion of incident S waves at the edge of the basin. The detail of the 3-D model and the simulations can be found in Frankel (1993). Simulated acceleration time histories for the city of San Bernardino are obtained by using the same model and magnitude as given in Frankel (1993), but different source parameters. The simulated horizontal accelerations from 1-D and 3-D models, and their Fourier amplitude spectra are shown in Fig. 1 for the two orthogonal directions. The accelerations from the 3-D model exhibit large, low-frequency amplitudes because of the surface waves.

We calculated the response of the building to the simulated accelerations by using the program 3D-BASIS (Nagarajaiah et al., 1991), and compared the 1-D and 3-D maximum displacements relative to the top of the isolators, and the maximum story shears in each orthogonal direction. The results are summarized in Fig. 1. The figure shows that for the 1-D motions, the base isolators reduce both maximum displacements and shear forces at all floors in both directions. For 3-D motions, however, the base isolators actually increases the maximum displacements and shear forces in the x direction, and the maximum shear forces below the third floor in the y direction. Thus, base isolation that seems to be beneficial for the 1-D motions is actually harmful for the 3-D motions.

EXAMPLE 2

The second examples involves the 7-story base-isolated U.S.C. Hospital, whose response was recorded during the January 17, 1994, Northridge, California earthquake. The instrumentation of the building includes 24 accelerometers, plus a three-component free-field station, as shown in Fig. 2 (Shakal et al., 1994). We first identify the characteristics of the structure and the isolators from the recorded accelerations. Various tests on the data (e.g., recursive filtering, time-varying spectra, force-deformation plots) have shown that the nonlinear behavior of the isolators were not significant. Therefore, we decided to use linear filters for the identification, and modeled the building as a multi-input, multi-output linear system. The preliminary investigations also showed that there was no soil-structure interaction (Şafak, 1995) and no torsion at the foundation level, so that the input to the building can be defined by the two horizontal accelerations at the center of the foundation (Sensors 5 and 7 in Fig. 2). For the output, we took the relative displacements, with respect to the foundation, of all sensors in the superstructure (sensors 9 through 24). We identified the building by considering all the inputs and outputs simultaneously, and by using the methodology given in Şafak (1991) and utilizing the MATLAB System Identification Toolbox (MathWorks, 1995). Fig. 3 shows the amplitudes of the identified transfer functions from each input (acceleration) to the each output (relative displacement with respect to the ground). As the figure shows, the response is dominated by a single frequency at 0.74 Hz at all instrumented floors. The frequency represents the natural frequency of the isolators. There is a small amount of rotational vibrations with the same frequency in the counterclockwise direction, as evidenced by the transfer functions for outputs due to the input in the perpendicular direction (e.g., 5-22, 5-23, 5-24, 7-21 in Fig. 3). Therefore, the mode at 0.74 Hz is a coupled translational-torsional mode with a large translational and a small rotational components. The calculated damping ratio of the mode is 0.15. We can identify the fixed-based (i.e., if there were no isolators) characteristics of the building by simply replacing the input accelerations with those recorded at the top of the isolators (Sensors 9 and 11). The identified lowest three natural frequencies for the fixed-based case are 1.04, 1.30, and 3.15 Hz, and the corresponding damping ratios are 0.05, 0.06, and 0.08, respectively.

In order to investigate the expected response of the building under different ground motions, we selected five sets of ground motions that had larger amplitudes and different frequency contents than what was recorded at the building site. The three of them are the Northridge records from stations that are close to the epicenter. They are the Newhall fire station, Sylmar County Hospital, and the Sepulveda Veterans Hospital. The remaining two sets are the simulated records representing the expected accelerations at the Sylmar and Sepulveda stations from a magnitude 7.3 hypothetical Northridge earthquake. The simulations were performed by taking the Northridge recordings as Green's functions and using the methodology given in Frankel (1995). The five pairs of input accelerations are plotted in Fig. 4. For each pair, we determined from the calculated transfer functions the response of the building at the instrument locations. The results are summarized in Fig. 5 for the north-south and the east-west directions in terms of the maximum relative displacements of the center of the building with respect to the bottom of the isolators (i.e., the ground)) and the top of the isolators. The relative displacements with respect to the ground show the portion of displacements absorbed by the isolators, whereas the relative displacements with respect to the top of the isolators give a measure of seismic forces in the building. The calculations are based on the assumption that the isolators behave linearly, which may not be very accurate for large ground motions. Any nonlinearity in the isolators would increase the maximum displacements relative to the ground, but decrease the maximum displacements relative to the top of the isolators. Therefore, the maximum displacements given for the top of the isolators (zeroth floor) on the left-hand side of Fig. 5 are the lower-bound for the required displacements from the isolators. Similarly, the maximum displacements relative to the top of the isolators given on the right-hand side of Fig. 5 can be considered as the upper-bound of the expected displacements in the building. The figure clearly shows that much larger displacements in the building and in the isolators would have developed if the building were closer to the epicenter and/or if the magnitude were larger. The elastic displacement demand from the isolators are as high as 50 *cm* (for the Newhall in the north-south direction, and for the simulated M=7.3 Sylmar in the east-west direction). This value would be much larger if the inelastic behavior of the isolators are accounted for. Current design codes for base isolators assume much smaller displacements. The results also show that the Northridge response of the building should not be taken as a test for the effectiveness of base isolation, because the ground accelerations at the site were not large enough.

CONCLUSIONS

The response of base-isolated structures, and the effectiveness of base isolators are strongly dependent on the characteristics of ground motions. It is possible to have a base-isolated building where the isolators reduce the building's displacements for one set of ground motions, but increase them for another set of ground motions. The analysis of Northridge data from the base-isolated U.S.C. Hospital shows that, although the building's response was reduced significantly by the isolators, the data should not be taken as a test for effectiveness of base isolators or the accuracy of current design codes. If the building were closer to the epicenter, or/and the earthquake had a larger magnitude the results would have been different.

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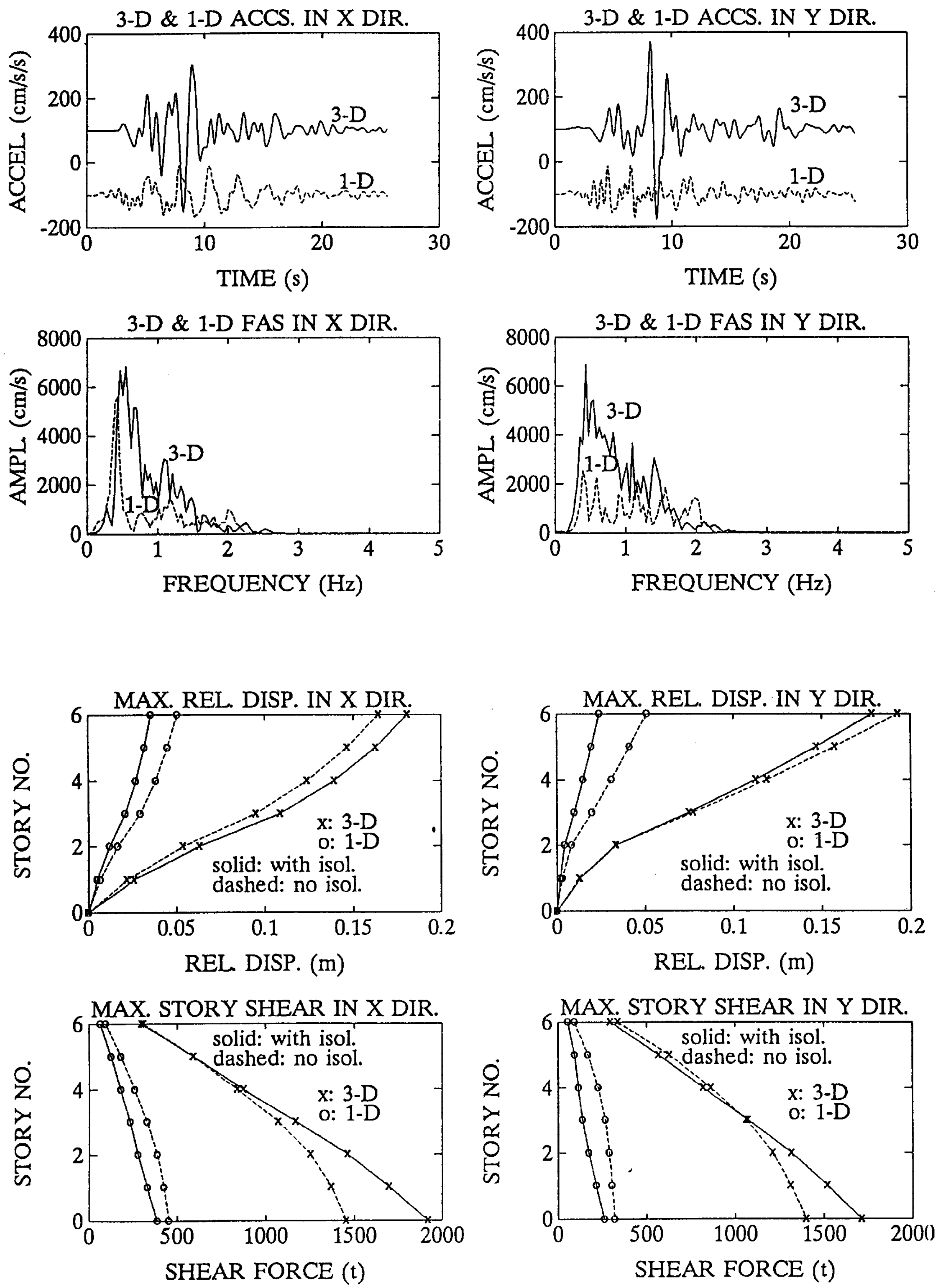

Fig. 1. Time histories and Fourier amplitude spectra of the 1-D and 3-D simulated ground motions, and the comparison of the calculated maximum displacements (relative to the ground or the top of the isolators) and the shear forces in a six-story building with and without base isolators.

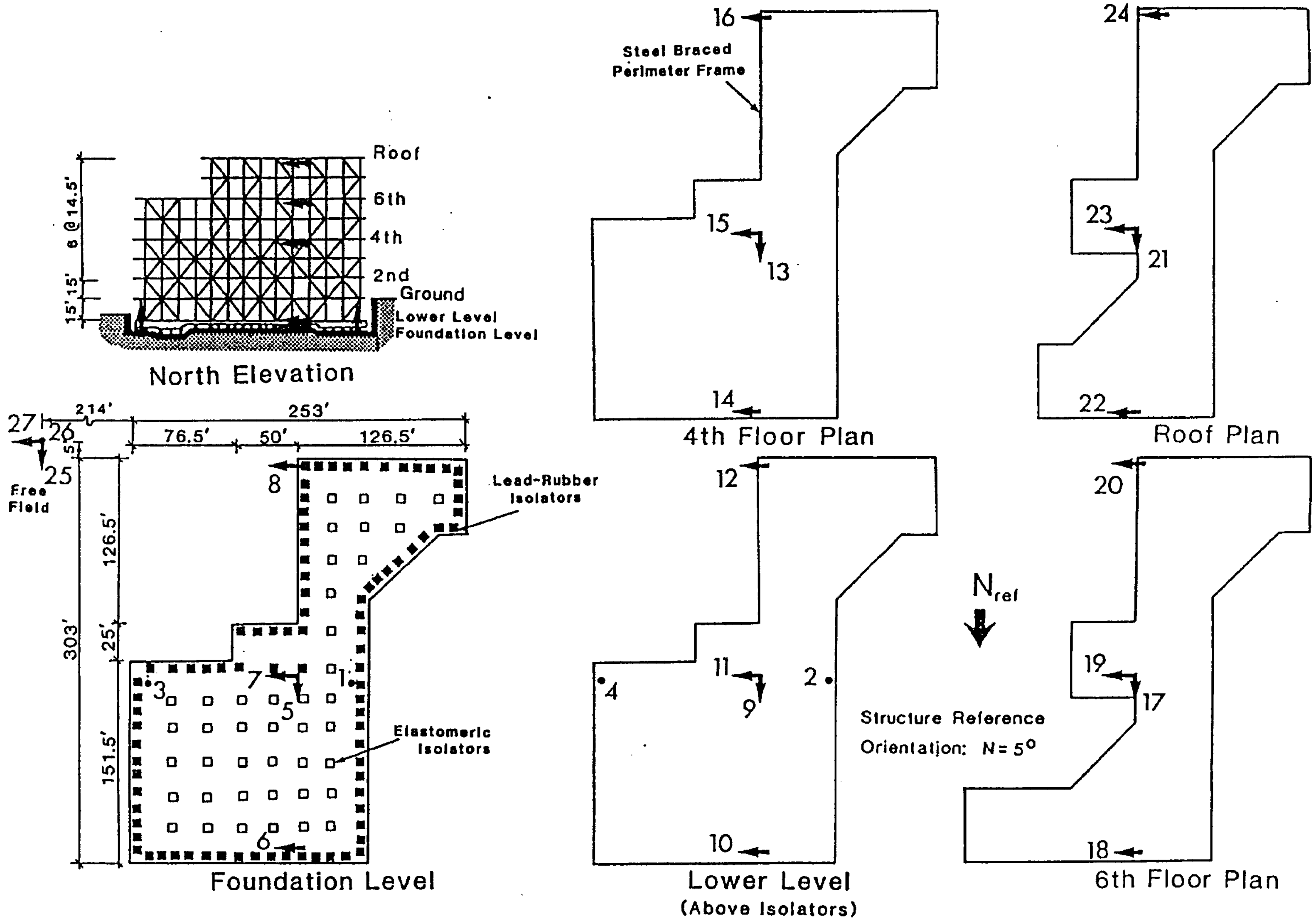

Fig. 2. Instrumentation of the base-isolated U.S.C. Hospital (from Shakal et al., 1995).

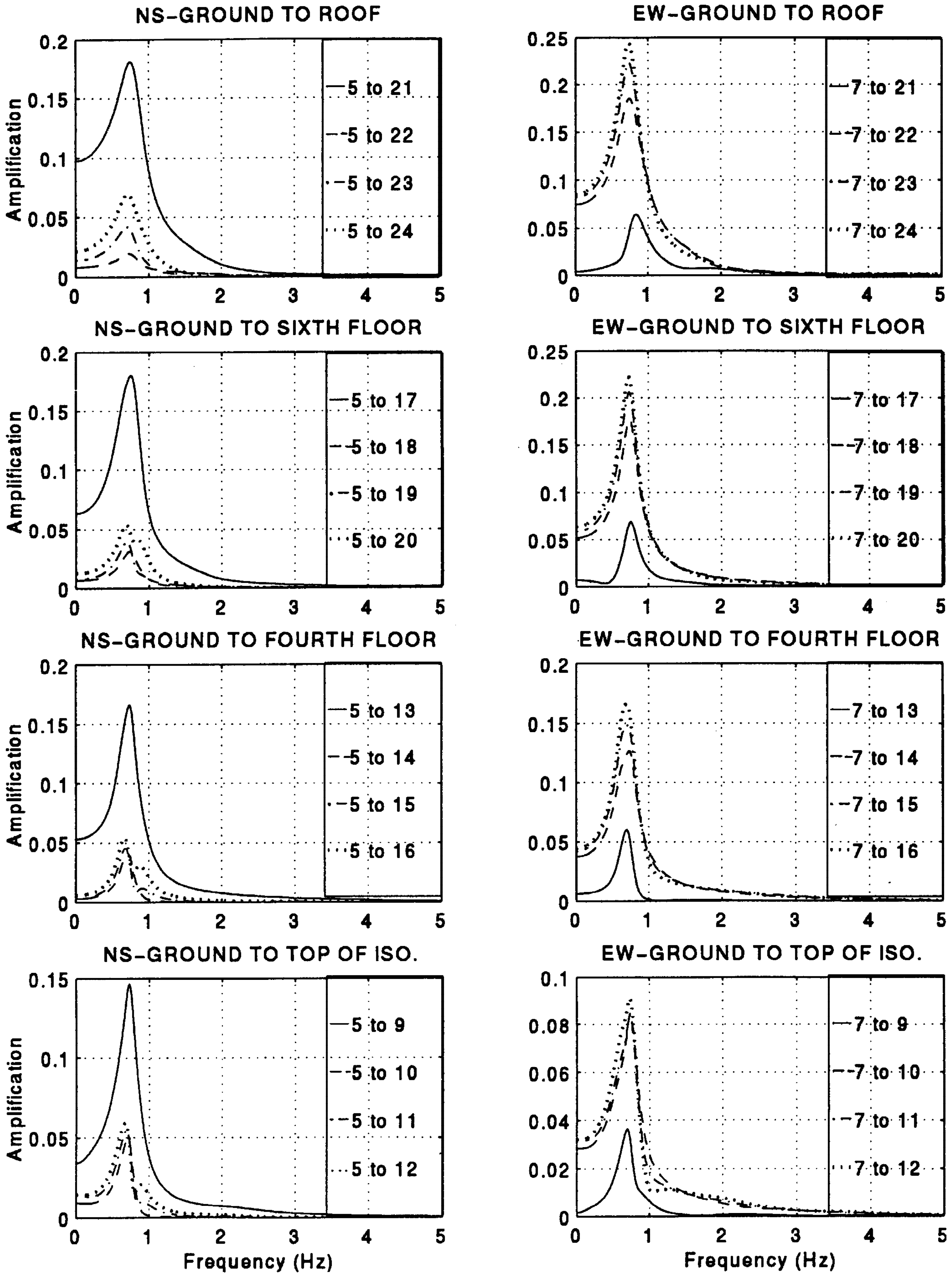

Fig. 3. Transfer functions of the U.S.C. Hospital identified from a multi-input (2 inputs), multi-output (16 outputs) model (the numbers for the transfer functions refer to the sensor numbers given in Fig. 2).

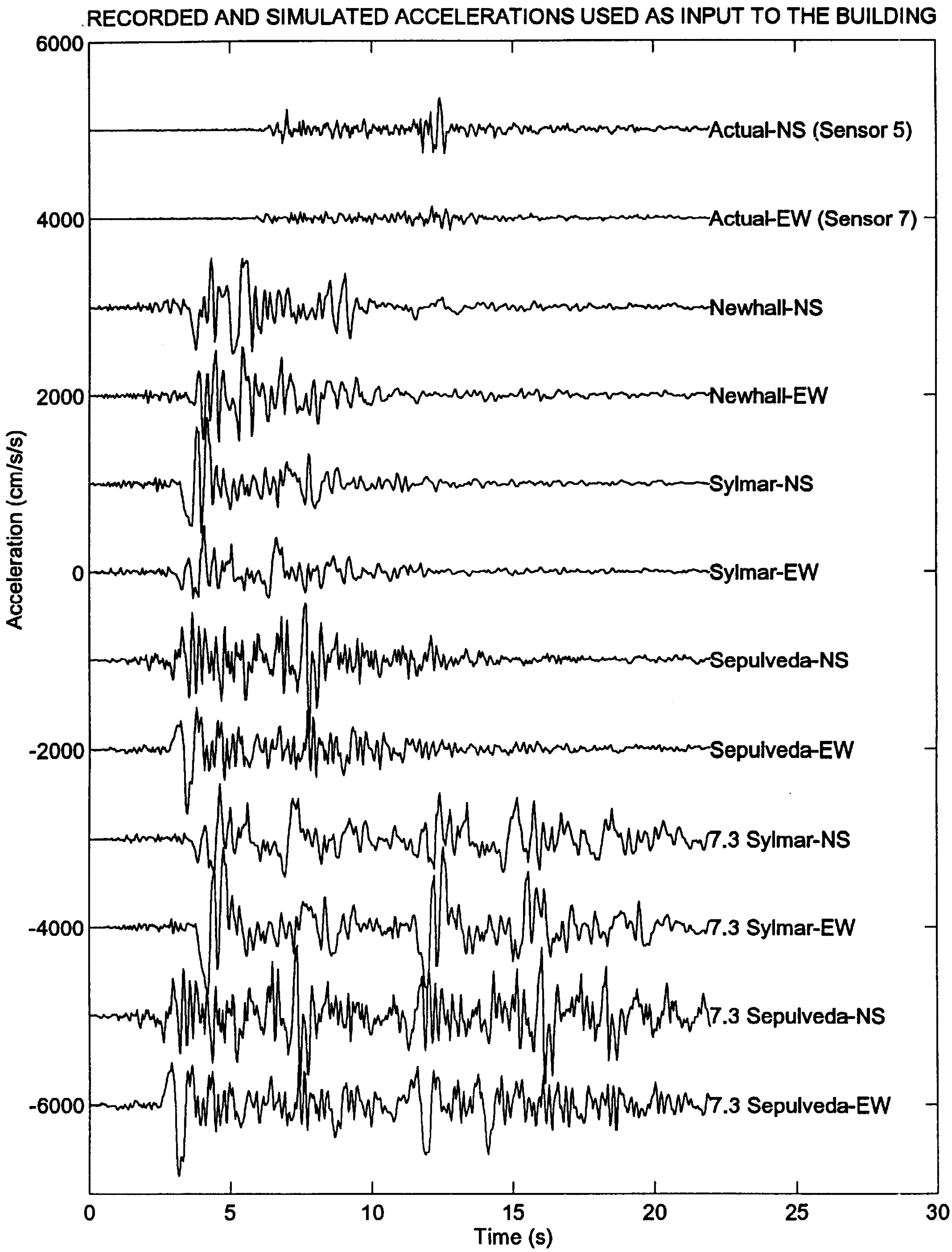

Fig. 4. Recorded and simulated time histories used as input to the U.S.C. Hospital.

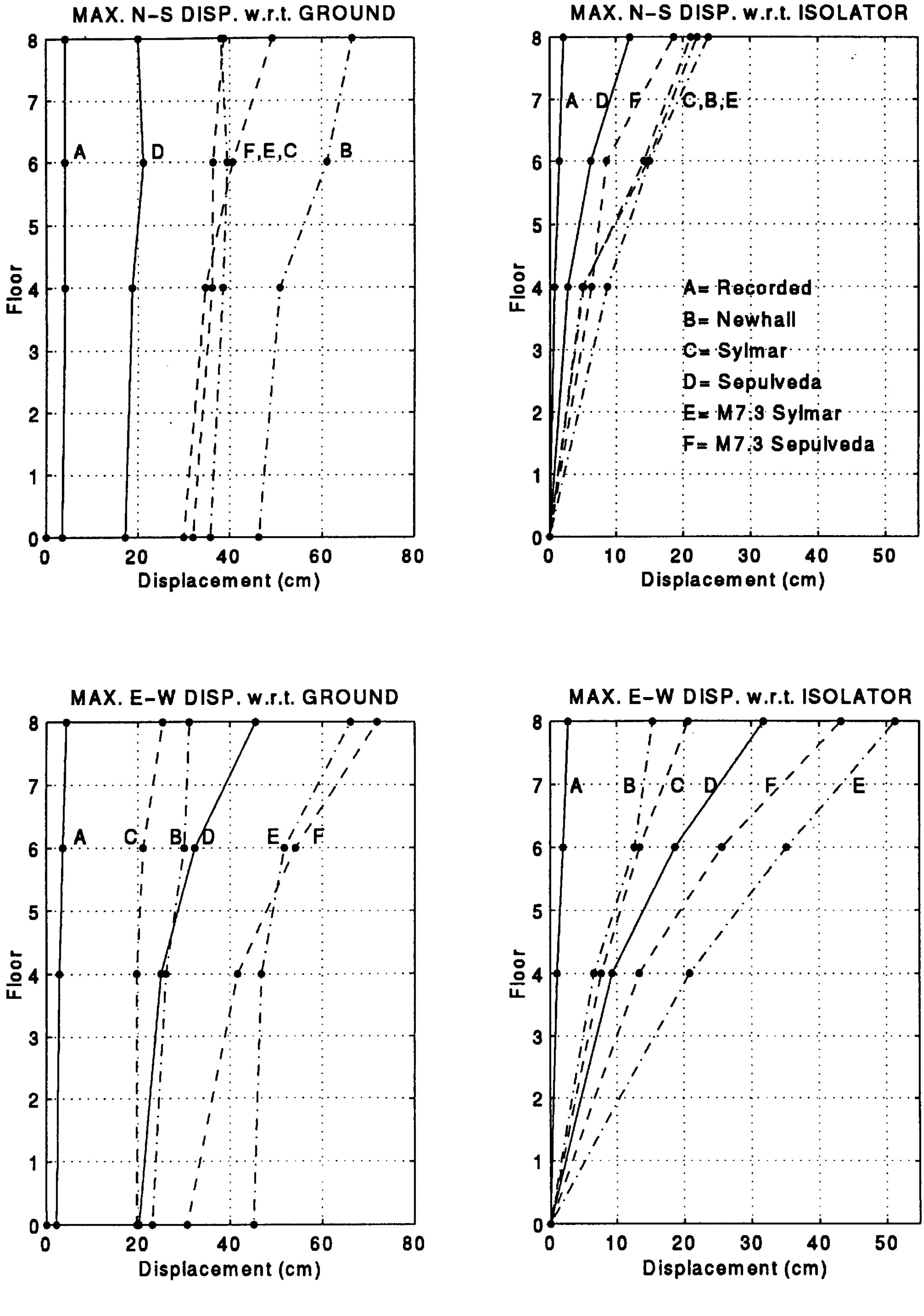

Fig. 5. Comparison of the recorded and calculated, for five other ground motions, maximum displacements with respect to the ground and the top of the isolators of the U.S.C. Hospital.