Responses of a High-Rise Building during the 2011 Tohoku Earthquake and Simulation Analysis for Future Mega-Thrust Earthquakes

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Summary

In this study, we investigate one of the high-rise buildings along the shoreline of the Osaka Bay, the 55-storied “S” Building, which was encountered to pretty large shaking during the Tohoku earthquake of 2011. The maximum displacement at the top reached over 1.3 m. To study the seismic safety margin of the building for future mega-thrust earthquakes in the Philippine Sea Plate subduction zone, we constructed a multi-degrees-of-freedom model and reproduced maximum story drifts during the main shock. Then we performed the response prediction for the Nankai earthquake using the system.

Keywords: dynamic response, high-rise building, natural frequency, basin response.

1. Introduction

A mega-thrust earthquake known as the Off the Pacific Coast of Tohoku earthquake hit Japan on March 11, 2011. It was a moment magnitude of 9.0 and one of the most devastating earthquakes in Japan’s history, primarily due to its huge tsunami. Despite of the high peak ground accelerations in the prefectures along the coast of the Pacific Ocean, we did not have devastating damages on the buildings and houses. However, the 55-storied “S” Building, which is located 769 km away from the epicenter, was also encountered to pretty large shaking; the maximum displacement at the top reached over 1.3 m and several instrumental and non-structural damages occurred. Thus it is necessary to find the reason why we had such large responses only in the Sakishima Building. First we constructed a single-degree-of-freedom model in order to know the transition of the natural periods and the damping ratios during the long-lasting shaking of 600 seconds. We found that the damping seems quite low. Then we introduced a multi-degrees-of-freedom (shear and bending) model created based on the design documents by the design company and reproduced maximum story drifts during the main shock. The model can reproduce the acceleration and velocity responses quite well. Finally we performed the response prediction using the same multi-degrees-of-freedom model for the Nankai earthquake. It turns out that when we install dampers to the building to increase the critical damping ratio up to 2.5% or 5 %, we can control the maximum story drift to be less than 1/100.

2. Target Structure

The target structure of this study is a 55-storied, 256m high building with the footprint of 11,000m^2 and the total area of 149,300 m^2. Above the ground the steel moment-frame structure is used while below the ground the reinforced concrete structure is used. The long-span direction in the basic floor plan has 75m and the short-span direction has 36m. This building was approved to construct on September 1990 and completed in 1995. The design base-shear coefficient was 0.05 for the long-span direction and 0.075 for the short-span direction.

Just before the 2011Tohoku earthquake the Building Research Institute deployed the strong motion sensors on the basement floor, 18th floor, 36th floor, and 52nd floor.

3. Observed Data

The whole duration of observed data is 600 seconds. The observed PGAs and PGVs on the 52nd floor are about 80 to 120 cm/s^2 and 80 to 120 cm/s, respectively, and it shows rapid increase of amplitude from about 150 to 200 seconds from the beginning of the record. Since time histories of acceleration and velocity are quite similar to each other, apparently sinusoidal motions are dominant.

4. Vibration Response Analysis

We have performed single-degree-of-freedom (SDOF) analysis. To determine model parameters, we first divide time histories into segments of 50 seconds with 1 second interval, and then we obtain predominant period from the Fourier spectra. The damping in one segment is determined as such when the best matching with data on the 52nd floor is achieved. The results of SDOF matching are shown in Fig.1. The predominant period is basically stable during the whole mainshock duration. Damping factors are changing rapidly as the amplitude is increasing. In the short-span direction (229 degree) shows quite a small value of damping, less than 0.05%. We plot 52nd floor velocity responses by using the period and the damping averaged over every 50 seconds and corresponding basement acceleration time histories in Fig.2 for short- and long-span directions.

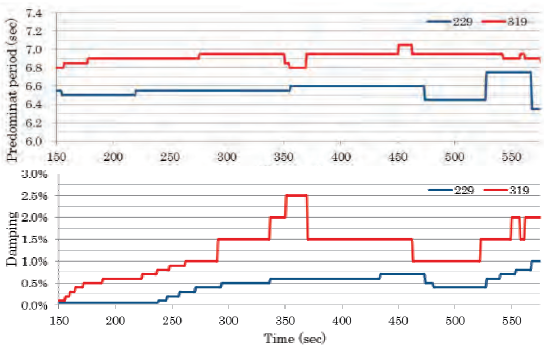
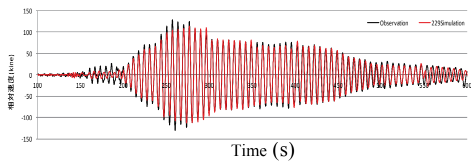


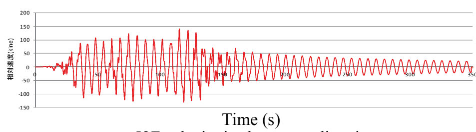
Fig. 1: Time variations of predominant periods and damping for each 50 seconds time segment.



52F velocity in short-span direction

Fig. 2: Velocity response from SDOF system (red) in comparison to the observed (black).

Finally we constructed a multi-degree-of-freedom (MDOF) system with bending and shear deformation for every floors. After the analysis of the initial model from the design farm we tuned up the MDOF system to reproduce the observed response. Damping for long- and short-span directions are assumed to be 2% and 0.5%, respectively.



52F velocity in short-span direction

Fig. 3: Velocity response for the Nankai earthquake simulated motion.

5. Mega-Thrust Earthquake

We have simulated strong ground motions at OSKH02 KiK-net site 2 km away from the Sakishima Building for the Nankai earthquake. Fig.3 shows the velocity response on the 52nd floor for short-span direction. When we look at the story drift (deformation angle) the maximum story drift was more than 1/100 in both directions and frames are getting nonlinear in several floors. When we increase the assumed structural damping to be 2.5 %, we can reduce the maximum story drift to be less than 1/100 for the short-span direction. However, peak ground velocity and displacement are almost the same because damping could not reduce the peak values.