

Reproducing Ground Motions with Shaking Tables with Limited Stroke

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Abstract

Shaking tables are widely used for testing structural models under earthquake excitations. Real ground motions are reproduced by a moving shaking table platform, which is controlled according to appropriate algorithm that considers the limitations in the platform's maximum displacement. Usually the real ground motion record is scaled to allow reproduction within the platform stroke limitations. Such scaling yields distortion in the spectrum of a ground motion record and the influence of the earthquake on the tested structure. A method for minimization of the undesired effects was developed by the authors previously. It was based on linear models of the tested structure. Closeness of power spectral density and response spectra were chosen as the main optimization criteria of scaling. As known, strong earthquakes lead to nonlinear effects in structural response. Additionally, supplemental dampers that are widely applied in order to enhance the structural seismic response have essentially non-linear characteristics. This should be considered in shaking table testing, including the earthquakes scaling. An earthquake record scaling method, proposed in the present study, is based on criteria that are more consistent with nonlinear nature of the investigated structure. Therefore, it has a much wider range of applications for investigating both linear and nonlinear behavior of structural models. A mathematical formulation of the problem is developed. The effectiveness of the proposed method is demonstrated by comparing the total earthquake energy and response spectrums of real and simulated earthquakes as well as by comparative evaluation of the distortions of their time histories. Additionally, response of a multistorey structural model to real and simulated seismic records is compared. It is shown that using the proposed method for scaling real ground motions yields more accurate reproduction and causes minimum distorsions.

Keywords: ground motion record, scaling, shaking table platform, response spectra, optimization criteria.

1 Introduction

Forming a signal, reproducing the ground acceleration records of real earthquake motions with high accuracy, is a very important problem, related to shaking table experiments. Based on this signal, a PC generates appropriate control commands for the shaking table actuators that correspondingly move the shaking table platform.

Any shaking table has limitations in modelling real earthquake records. The most essential limitations are the maximum platform stroke and peak velocity. Therefore an earthquakes acceleration record must be modified to accommodate these restrictions without significant changes in the earthquake's affect on the tested model.

There are several known methods for earthquake records' scaling, allowing certain decrease in the required shaking table platform's stroke. Scaling in time [1] keeps the form of the given ground acceleration record and its amplitude unchanged, but the spectrum of the scaled acceleration moves to the low natural period range. Centring the ground acceleration or of the ground velocity signal [2] yields no changes in the real earthquake spectrum and reduces the shaking table platform's stroke; however this reduction may be insufficient. In such cases time scaling is used additionally to centring.

A most suitable scaling method should maximally consider the features of the real earthquake record and cause minimum distortion in the earthquake spectrum. A method of earthquake records scaling, enabling effective reduction of shaking table platform's stroke, was developed previously [3]. It includes trend elimination, piecewise linear approximation of integrated earthquake ground acceleration and further smoothening of the modifying function, allowing creating a scaled earthquake with a response spectrum close to the original ground motion.

The optimization procedures, which have been applied in the design and implementation were based on linear models of the structure [3]. For this reason, the closeness of the spectral characteristics (power spectral density, response spectra) was chosen as the main optimization criterion of the scaling procedure. However, strong earthquakes lead to nonlinear effects in structural response. Supplemental energy dissipation systems, used for improving structural seismic response, have essentially non-linear characteristics. These facts should be considered during all stages of the design and testing, including the earthquakes scaling. The method of scaling the earthquake, proposed in this study, is based on criteria that are more consistent with the nonlinear nature of the structure.

2 Mathematical formulation of the problems

The proposed method is based on representation of the earthquake record by ground displacement, obtained by double integration of the ground acceleration. The ground velocity is obtained by single integration of the ground acceleration. The scaled shaking table platform displacement $x_{gs}(t)$ and velocity $v_{gs}(t) = \dot{x}_{gs}(t)$, should satisfy the following conditions:

$$|x_{gs}(t)| \leq x_{gs}^{max}, \quad |v_{gs}(t)| \leq v_{gs}^{max}, \quad 0 \leq t \leq t_f \quad (1)$$

where t_f is the real earthquake duration.

It is more practical to replace the first inequality in (1) by

$$\max x_{gs}(t) - \min x_{gs}(t) \leq s_{gs}, \quad |v_{gs}(t)| \leq v_{gs}^{max}, \quad 0 \leq t \leq t_f \quad (2)$$

where s_{gs} is the designed stroke of the shaking table platform.

The scaled earthquake is obtained in the following form:

$$\dot{x}_{gs}(t) = v_{gs}(t), \quad \dot{v}_{gs}(t) = a_{gs}(t) \quad (3)$$

where $a_{gs}(t)$ is the shaking table platform acceleration, which should be an approximation of the real ground acceleration $a_g(t)$ and satisfy conditions (1) or (2), (3).

The desired task is formulated as an equivalent LQR optimization problem. The problem is to find optimal control $a_{gs}(t)$ on $0 \leq t \leq t_f$, which minimizes the following performance index

$$J(a_{gs}) = \frac{1}{2} q_{1f} x_{gs}^2(t_f) + \frac{1}{2} q_{2f} v_{gs}^2(t_f) + \frac{1}{2} \int_0^{t_f} q_1 x_{gs}^2(t) + q_2 v_{gs}^2(t) + r[a_{gs}(t) - a_g(t)]^2 dt \quad (4)$$

with constraint (3).

The problem (3), (4) can be represented in matrix form as

$$\dot{X}(t) = AX(t) + Ba_{gs}(t), \quad X(0) = 0 \quad (5)$$

$$J(a_{gs}) = \frac{1}{2} X^T(t_f) Q_f X(t_f) + \frac{1}{2} \int_0^{t_f} X^T(t) Q X(t) + r[a_{gs}(t) - a_g(t)]^2 dt \quad (6)$$

where

$$X(t) = \begin{bmatrix} x_{gs} \\ v_{gs} \end{bmatrix}, \quad A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}, \quad Q_f = \begin{bmatrix} q_{1f} & 0 \\ 0 & q_{2f} \end{bmatrix}$$

It can be shown that the solution of the optimal control problem (5), (6) is

$$\dot{S}(t) + S(t)A + A^T S(t) + Q - \frac{1}{r} S(t)BB^T S(t) = 0, \quad S(t_f) = Q_f \quad (7)$$

$$\dot{V}(t) + (A^T - \frac{1}{r} S(t)BB^T)V(t) + S(t)Ba_g(t) = 0, \quad V(t_f) = 0 \quad (8)$$

where $S(t)$ is $n \times n$ matrix.

For verifying the effectiveness of the proposed method the response spectrums of real and simulated earthquakes are compared. Additionally, response of a multistorey structural model to real and simulated seismic records is analyzed.

3 Numerical example

The described above procedure was applied to the following earthquakes: El Centro, Hachinohe and Parkfield. The scaling method that was developed previously [3] is effective for most ground motions, but it is relatively complicated, as it requires selection and decision that should be done manually, based on engineering experience. The proposed method is based on an optimal control algorithm needs no manual operations and decisions for scaling. That is why it can be applied automatically by the shaking table software. It yields more easy application and enables to scale even earthquake records with high values of peak displacements that are more complicated for accurate reproduction.

The peak ground displacements for the selected earthquakes after trend elimination and shaking table platform stroke, required for accurate reproduction of these ground motions, are shown in Table 1. As it follows from the table, even after the trend elimination the peak displacements cannot be reproduced by a shaking table with a stroke of ± 6 cm.

Earthquake record	Peak displacement (cm)		Required shaking table platform stroke (cm)
	Max. value	Min. value	
Parkfield	7.2	-6.7	± 6.95
El Centro	10.0	-11.8	± 10.9
Hachinohe	32.2	-61.0	± 46.6

Table 1. Peak parameters of original earthquakes records after trend elimination

The proposed method was used to reproduce the earthquakes by a shaking table with maximal platform stroke of ± 6 cm. The results are compared with those, obtained using the previously developed scaling algorithm. Figures 1, 2 and 3 show the displacement and acceleration time histories of the original ground motion after trend elimination (case 1), scaled earthquakes obtained using the previously developed method (case 2) and in the proposed method(case 3).

Following the figures, the peak displacements for cases 2 and 3 are similar and are within the allowed shaking table stroke limit. However using the previously developed method (case 2), requires more energy for reproducing the scaled earthquakes, compared to the proposed one (case 3), because the amplitude of the shaking table platform after the peak displacement is much higher for case 2, compared to case 3. The acceleration time histories show that peak accelerations for cases 2 and 3 are also similar, but the acceleration distortion for case 3 is much lower, compared to case 2. Therefore, using the proposed method allows more accurate reproduction of the ground motion.

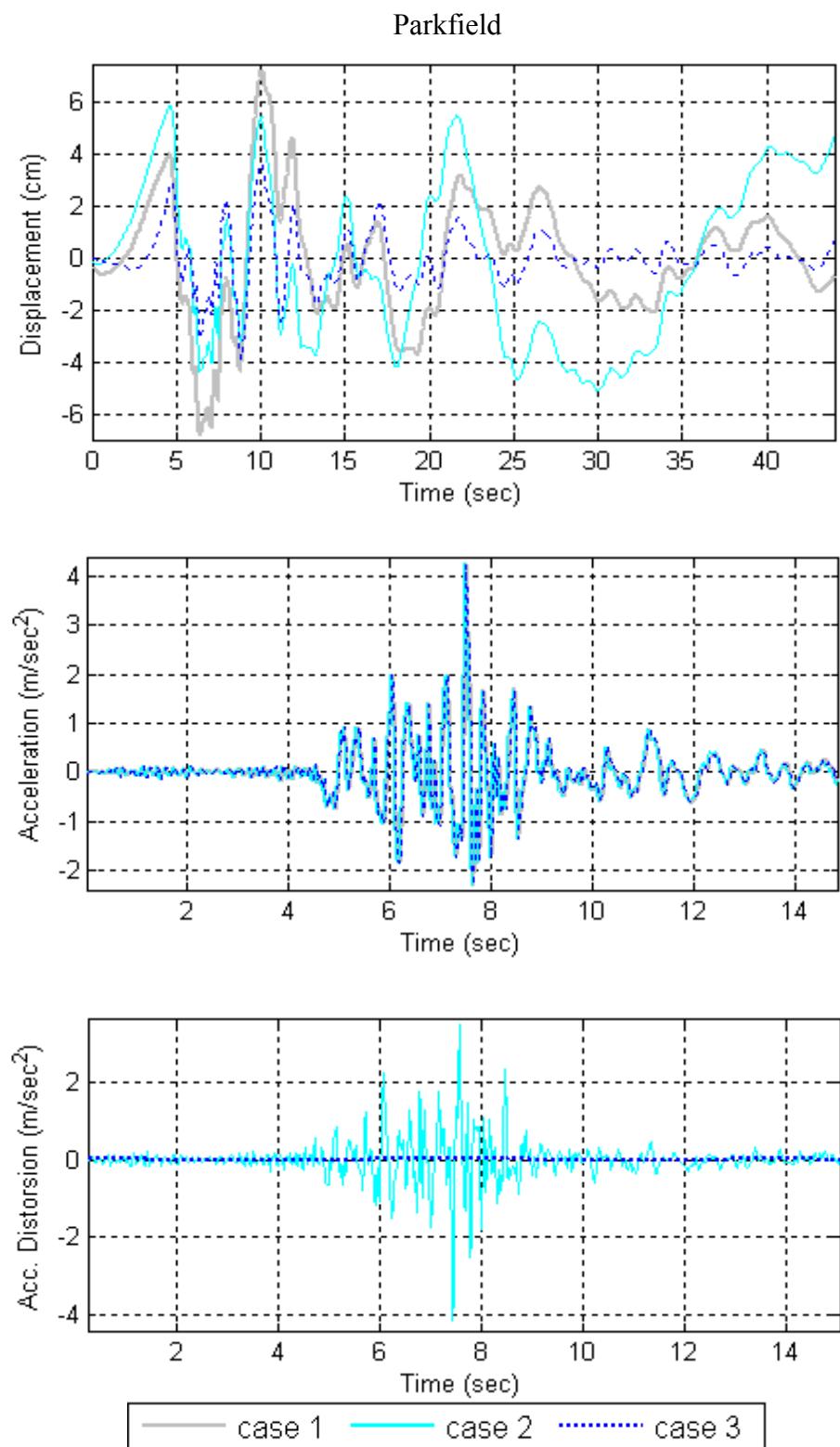


Figure 1: Time histories of original and scaled Parkfield earthquake.

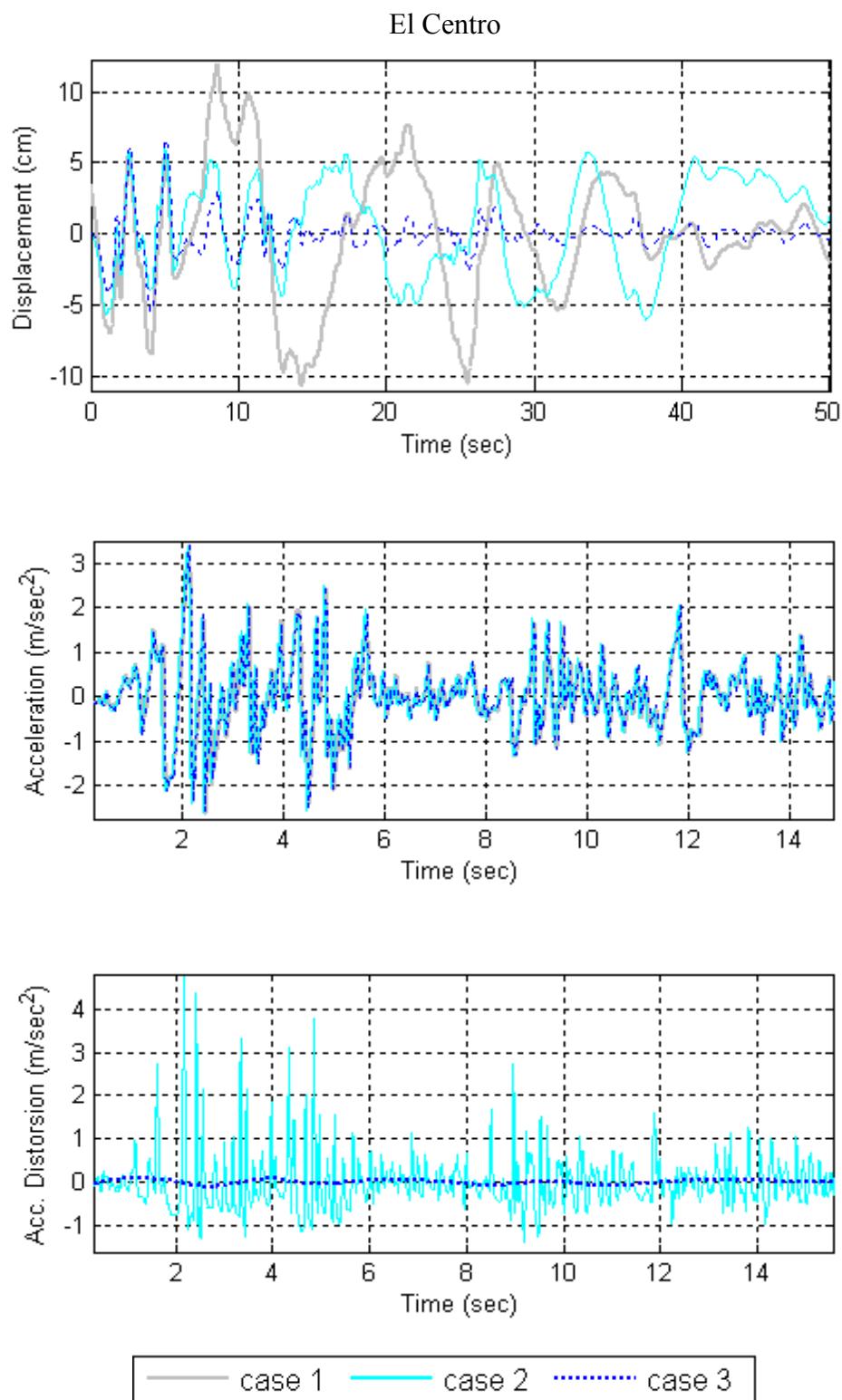


Figure 2: Time histories of original and scaled El Centro earthquake.

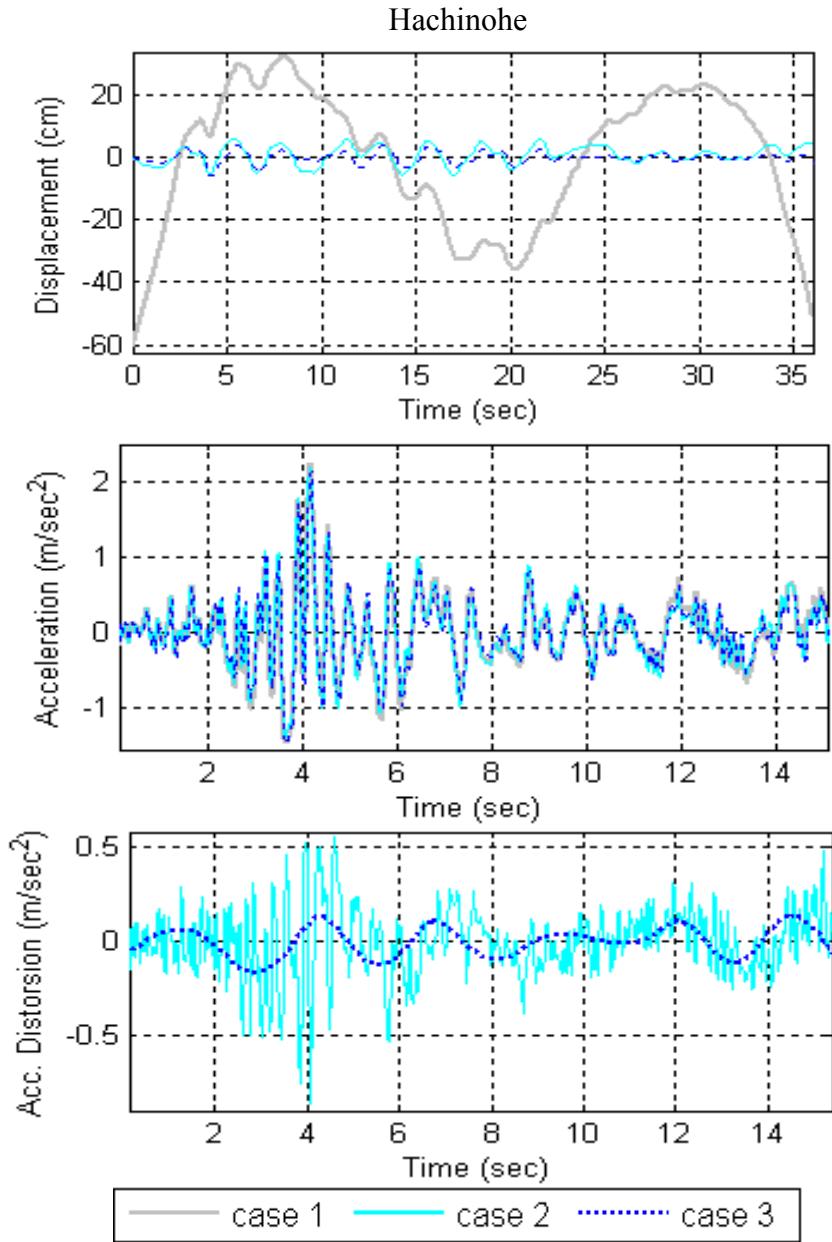


Figure 3: Time histories of original and scaled Hachinohe earthquake.

To verify the effectiveness of the proposed scaling method, response of a building model to original and scaled earthquakes was obtained numerically. A six-storey steel frame has been analyzed. A schematic view of the selected structure is shown in Figure 4. All floor masses of the model are equal to 175 ton. The peak values of the building's floor accelerations, relative floor displacements and absolute floor displacements (relative to the base) are shown in Figures 5, 6 and 7.

As it can be followed from the figures, the response of the analyzed structure to both original and scaled earthquake is close each to other, which demonstrates the effectiveness of the proposed method.

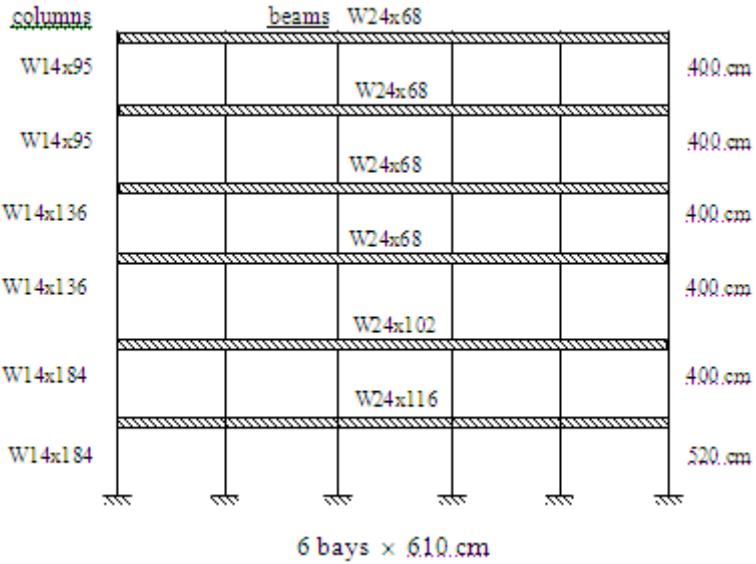


Figure 4: A six-storey structure used for numerical analysis.

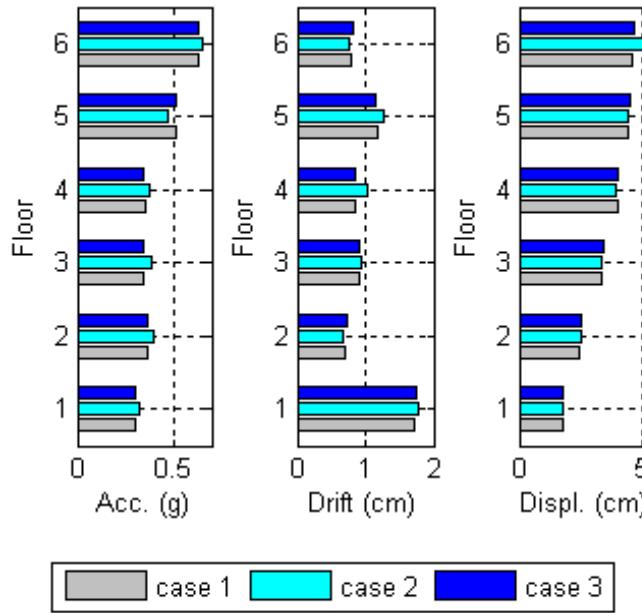


Figure 5: Peak inter-storey drifts, floor displacements and accelerations under the Parkfield earthquake.

4 Conclusions

A method for scaling original earthquake ground acceleration records, aimed to limit shaking table platforms displacements, was proposed. It is based on representation of earthquake record scaling as an equivalent quadratic optimal control problem. The method allows creating of a scaled earthquake with a response spectrum close to

the original ground motion. It significantly reduces the distortion of the scaled earthquake acceleration compared to the known scaling methods.

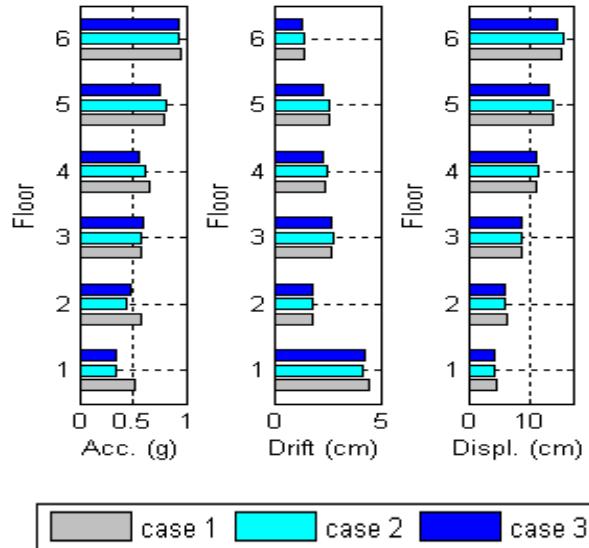


Figure 6: Peak inter-storey drifts, floor displacements and accelerations under the El Centro earthquake.

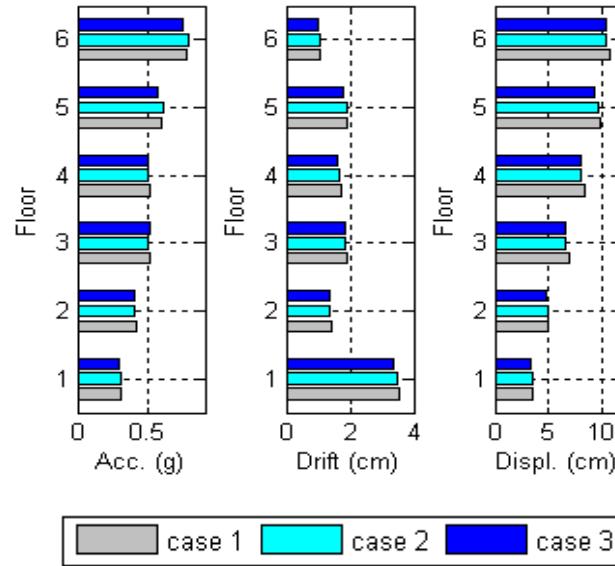


Figure 7: Peak inter-storey drifts, floor displacements and accelerations under the Hachinohe earthquake.

The total earthquake energies of the original and of the simulated earthquakes are close each to other. It is possible to obtain good simulation of real earthquakes by platform maximum displacements that are significantly lower compared to the real peak ground displacements.

The peak structural displacements, inter-storey drifts and accelerations for the original ground motion and for both scaling methods were almost the same. However, the acceleration distortion, caused by scaling procedure that was developed previously, was significantly higher, compared to that, obtained by using the proposed method.

References

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- [3] Y. Ribakov and G. Agranovich, "Improving Seismic Response of Structures using Optimal Dampers", Research Report No. 290-17-20, Ariel, 2010.