Structural Analysis Using Matched Acceleration Time Histories

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Abstract The seismic design of buildings in Indonesia is usually calculated using response spectral acceleration (RSA) design. This seismic force model can be obtained based on the Indonesian seismic code. Another seismic force model that can be used for structural analysis can be developed using acceleration time histories (TH). The TH used for structural analysis should be matched with the RSA design. This paper describes the structural analysis of buildings using two different seismic force models, response spectra acceleration and acceleration time histories. The analysis was carried out at a sample building in Semarang. Two different soil investigations were carried out at the building area: soil boring and array microtremor. The purpose of the array microtremor investigation is to predict the bedrock position and soil profile from bedrock elevation up to the earth's surface. However, the purpose of the soil boring investigation is to obtain the site soil class. In terms of horizontal floor displacement and internal drift ratio, the performance of RSA design and matched TH (matched to RSA design) earthquake force models were almost equal, and no significant output differences were obtained using these two seismic force models.

Keywords Acceleration time histories · Bedrock · Microtremor · Response spectra design

1 Introduction

The structural analysis of buildings under seismic forces is usually performed using Response Spectral Acceleration (RSA) design, the seismic force model that was developed based on the Indonesian seismic code [1, 2]. Another seismic force model that can be used for structural analysis is acceleration time histories

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(TH) [3–5]. This seismic force model can be obtained using TH data recorded from specific earthquake events or earthquake databases. For building design purposes, the TH collected from seismic events or earthquake databases cannot be directly used for building design. The TH should be matched with the RSA design calculated based on the Indonesian seismic code.

This paper describes the dynamic structural analysis of a building using two different seismic force models, response spectral acceleration and acceleration time histories. The building is located in Semarang, Indonesia. The TH used in this structural analysis was collected from a Shallow Crustal Fault (Semarang Fault) earthquake scenario located close to the building position. According to the 2017 Indonesian seismic map, the Semarang Fault is a reverse mechanism earthquake source and part of the Baribis-Kendeng seismic fault trace. Figure 1a shows the building position, site class distribution map developed by [6], and Semarang fault trace. Figure 1b shows the predicted bedrock elevation of Semarang, developed by [7] using a single station microtremor. The earthquake magnitude and epicenter distance used in this study were 6.5 Mw and ±5 km, respectively. The earthquake source and magnitude used in this study were obtained from the 2017 Indonesian seismic map [8]. Due to the existing condition of the Semarang fault seismic source, no earthquake event had a magnitude 6.5 Mw and ±5 km epicenter distance, so the TH used in the analysis was obtained from the Pacific Earthquake Engineering Research (PEER) ground motion database.

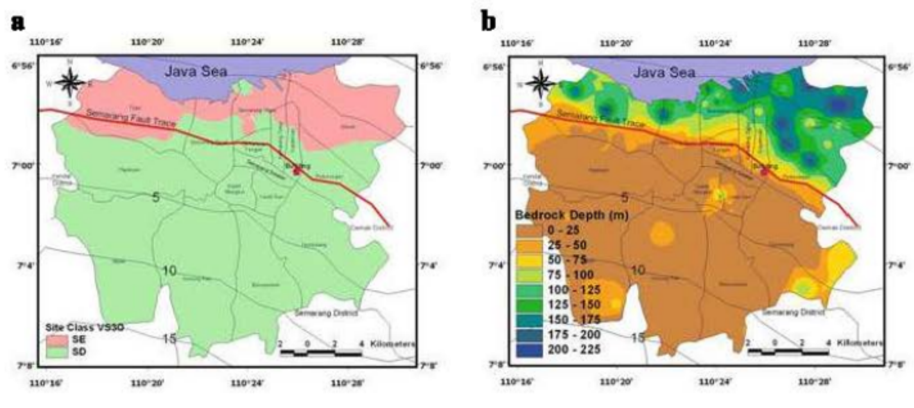

Fig. 1 **a** Building position, Semarang fault trace and predicted distance to Semarang fault, **b** predicted bedrock elevation

2 Methodology

Structural analysis of the building was carried out based on soil boring and array microtremor investigations, site-specific analysis, matching analysis, and dynamic structural analysis. The purpose of soil boring observation was to find the soil profile figure, in terms of N-SPT (Standard Penetration Test) and the site soil class. Three boring investigations were carried out in the study area. Figure 2a shows the N-SPT profile developed, based on the boring-log records. The second soil investigation carried out in the study area related to the bedrock elevation and soil profile, in terms of shear wave velocity profile (Vs) and predicted soil density (from bedrock up to the soil surface). Figure 2b shows the predicted soil profile, in terms of Vs values developed by a one array microtremor investigation. Figures 3a, b show the predicted shear wave velocity and soil density contours, obtained from one array microtremor investigation position. Based on the soil boring and array microtremor investigations, the study area is located in a medium soil class (SD). The soil profile model for site analysis was developed based on three soil boring and array microtremor investigations. Figure 3c shows the soil profile model used for site analysis. Figure 4 shows the structural analysis flowchart conducted in this study. The soil properties, such as soil density and shear wave velocity (Fig. 3c), were adjusted based on soil boring and microtremor investigation data. The shear wave of each soil layer in the top 30 m was calculated based on the average of three empirical correlations, proposed by [9–11]. The shear modulus (G) for each soil layer located in the top 30 m was developed based on the N-SPT and G empirical correlation [9, 10, 12].

Based on the soil boring and microtremor investigations, site analysis was conducted at the study area. The purpose of the site analysis is to calculate surface TH by conducting seismic wave or TH propagation analysis from bedrock up to surface elevation. The TH used for site analysis was first evaluated and adjusted

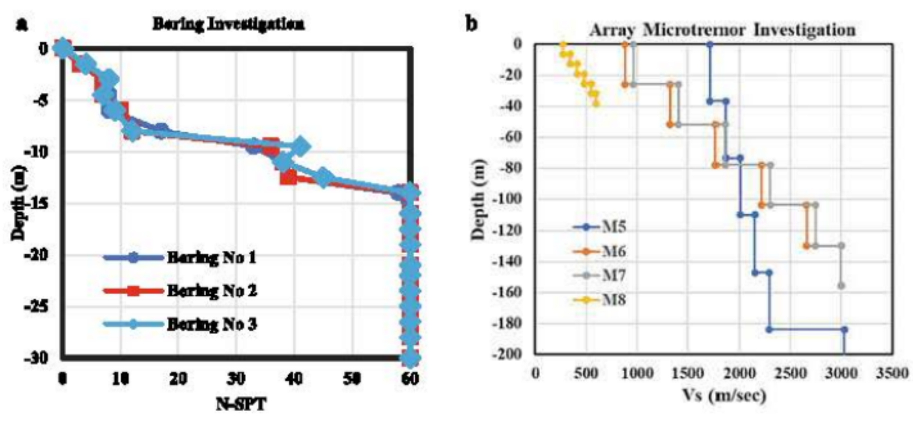

Fig. 2 a N-SPT profile, b Vs profile investigation results at the study area

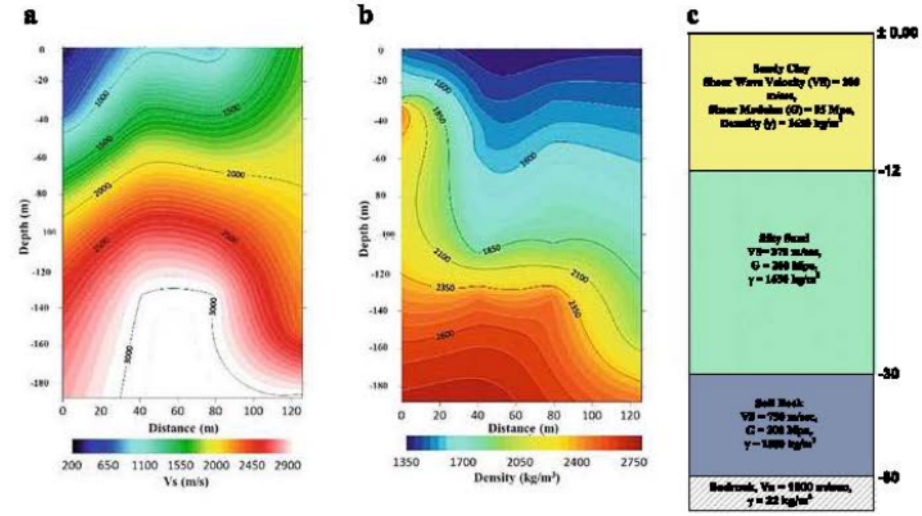

Fig. 3 **a** Shear wave velocity (Vs), **b** density contour at the study area, **c** soil profile model for site analysis

using spectral matching analysis. To perform spectral matching analysis at bedrock elevation, a scenario spectral target was calculated using deterministic seismic hazard analysis (DSHA) of a 6.5 Mw earthquake model, having an epicenter distance of ±5 km. The spectral matching analysis was carried out because no real TH data can be used or investigated from the Semarang Fault earthquake event. The TH was collected from the San Simeon earthquake event (6.52 Mw and with an epicenter distance of 6.59 km) and applied as PEER time histories. Figure 5 shows the response spectral matching analysis results from two directions, NS (North–South) and EW (East–West) TH of the San Simeon TH.

The site analysis was carried out based on one-dimensional direction propagation analysis of matched (Original) TH at bedrock position. Figure 6 shows the two different results of site analyses conducted in two matched TH directions. These two TH are also popular as surface TH.

Two directions surface TH, obtained from site analysis, were then re-calculated using response spectral matching by conducting RSA design SNI 1726:2019 as a target spectral acceleration. The spectral acceleration design used for spectral matching was developed up to a maximum period of 5 s. The maximum period of RSA design was developed based on the natural period of the building. A comparative study in developing spectral matching analysis was conducted using bedrock (original) TH. No site analysis was carried out for the second model of TH. Figure 7 shows the RSA design developed, based on SNI 1726:2019, the modified/matched two RS4 (developed using surface time histories) and modified two RS2 (developed directly from bedrock/original TH). All modified RS2 and RS4 were calculated using response spectral matching. According to Fig. 7c, no significant

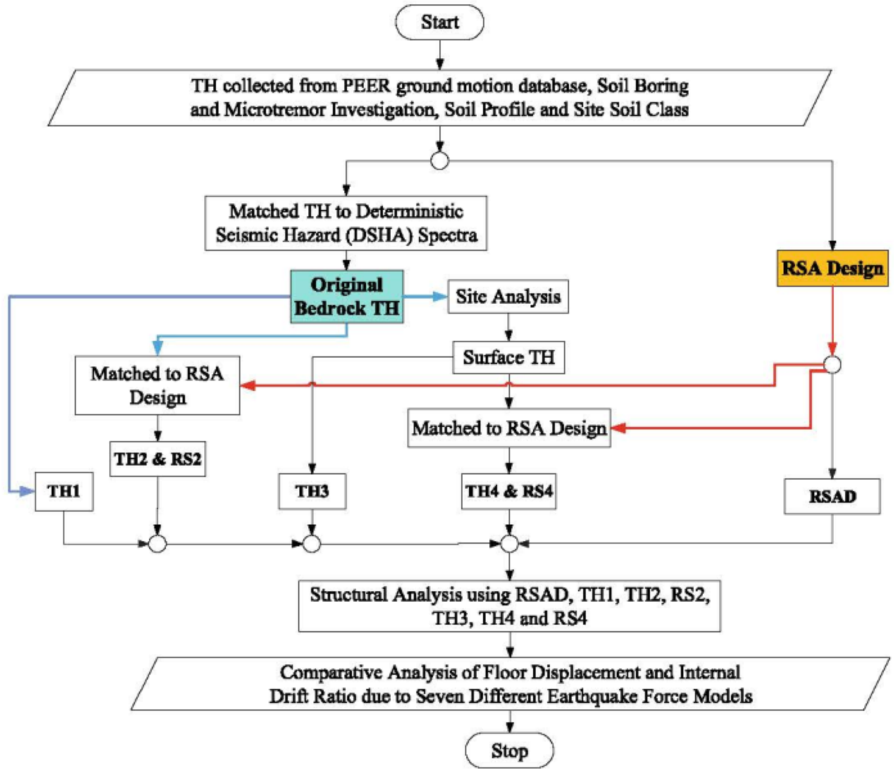

Fig. 4 Structural analysis flowchart

difference of matched response spectral acceleration was developed directly using surface TH and bedrock (original) TH.

Figures 8a, b show two TH developed using response spectral matching analysis of two direction surface TH (NS and EW) (TH4). These two surface TH (NS and EW) were obtained from site analysis. Figures 9a, b show two matched TH, developed using response spectral matching analysis of the bedrock (original) TH (TH2).

The dynamic structural analysis conducted in this study, related to the calculation of horizontal floor displacement and internal drift ratio. The results of structural analysis are not all described in this paper. The purpose of this analysis was to evaluate the performance of TH used for dynamic structural analysis. Seven different seismic force models were applied to the structure (see Fig. 4), such as RSA design (RSAD), bedrock/original TH (TH1), surface TH (TH3), matched spectral acceleration obtained from surface TH (RS4), matched spectra acceleration obtained from bedrock (original) TH (RS2), matched surface TH (TH4) and matched bedrock TH (TH2). All horizontal floor displacement and internal drift ratio results, calculated using these models of seismic forces, were then re-evaluated to

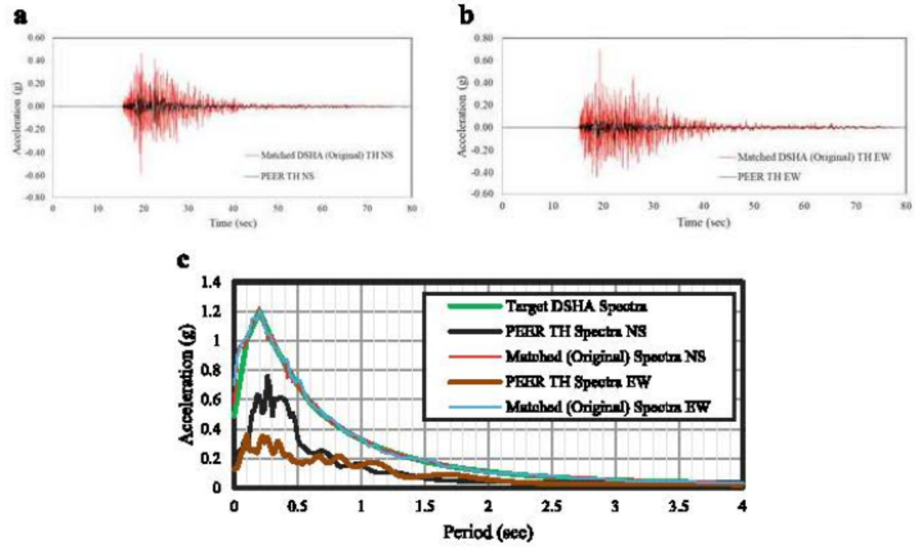

Fig. 5 **a** Response spectral matching of PEER for North–South TH direction, **b** East–West TH direction at bedrock elevation, **c** All response spectral matching analysis results

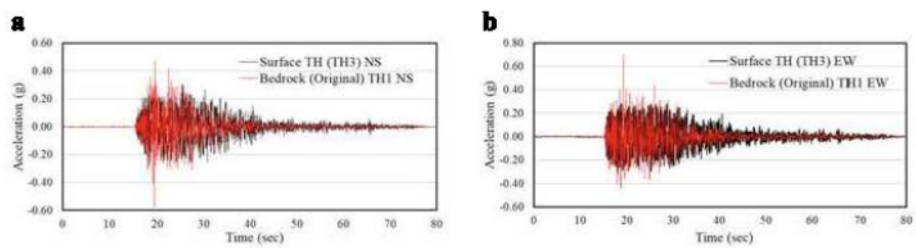

Fig. 6 Matched bedrock/original TH (TH1) and surface TH (TH3), **a** NS, **b** EW directions results developed from site analysis

observe the performance of matched response spectra and matched TH. A comparative analysis, in terms of horizontal floor displacement and internal drift ratio, between the RSAD, surface, and bedrock (original) TH was also carried out in this study. The purpose of the comparative study was to evaluate the performance of bedrock/original and surface time histories for dynamic structural analysis. Figure 10 shows the 3D and 2D structural model: 13 stories, $23.36 \times 34.75\ m^2$ plan, and 45.8 m height.

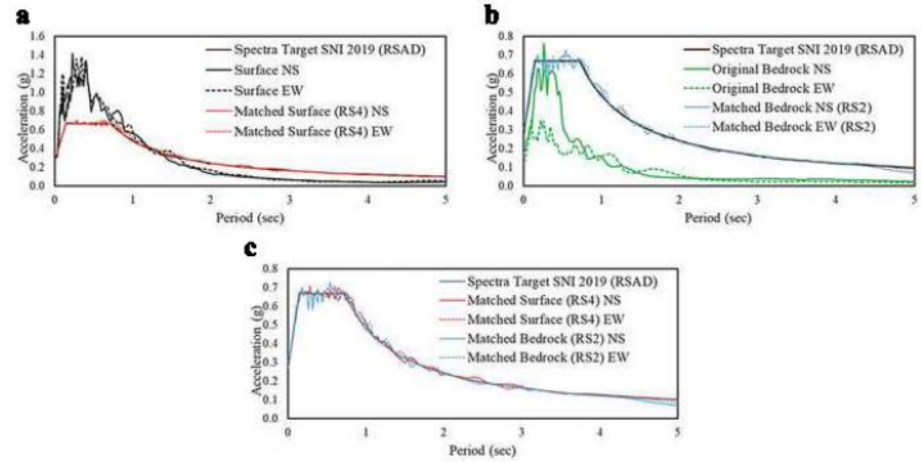

Fig. 7 **a** Response spectral accelerations developed from spectral matching to RSAD spectra target using surface TH (RS4), **b** matched bedrock/original TH (RS2), and **c** all matched response spectral acceleration

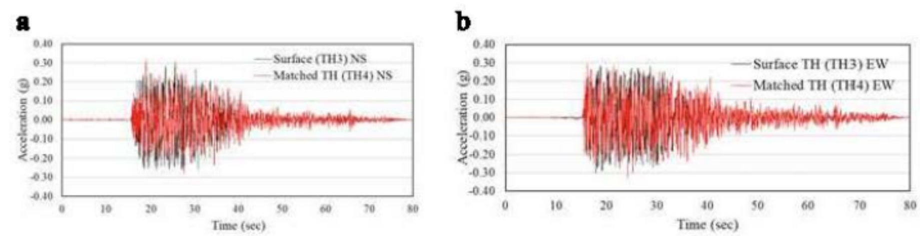

Fig. 8 Surface TH (TH3) and matched TH (TH4), **a** NS, and **b** EW directions

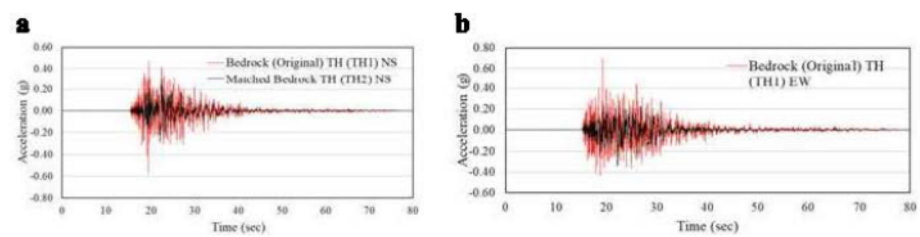

Fig. 9 Original TH (TH1) and matched TH (TH2), **a** NS, and **b** EW directions

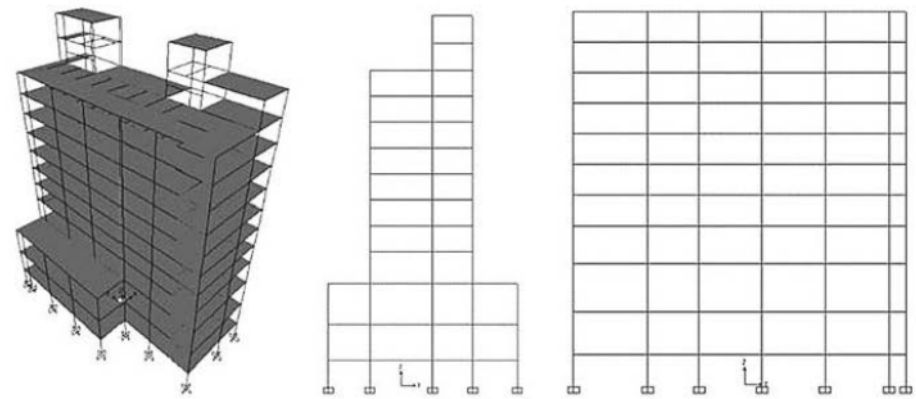

Fig. 10 Reinforced concrete structural model

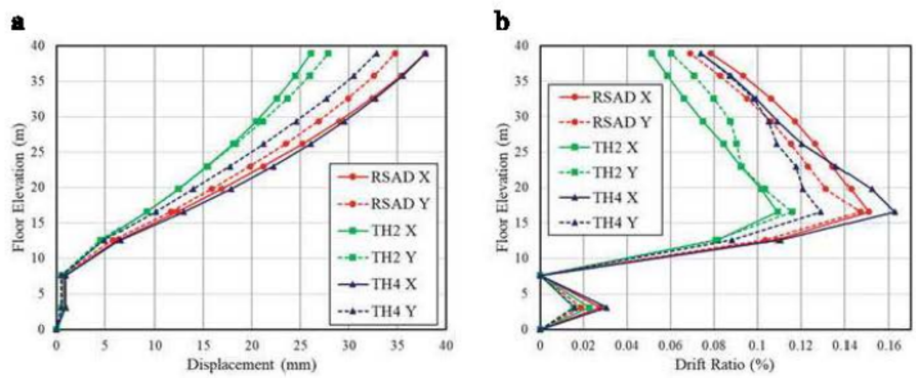

Fig. 11 **a** Horizontal floor displacement and **b** internal drift ratio due to RSAD, TH2, and TH4

3 Result and Discussions

The first structural analysis was carried out by conducting RSAD, TH2, and TH4. The structural analysis was carried out following the Indonesian Codes SNI 1726:2019 [1], SNI 2847:2019 [13], and SNI 1727:2013 [14]. Figure 11 shows the floor displacement and internal drift ratio performance of the structural model. Table 1 shows the absolute difference of floor displacement and drift ratio of RSDA compared to TH2 and TH4, respectively. The smaller the difference of displacement and drift ratio compared to the RSDA model, the better the performance of the model. As can be seen in Fig. 11 and Table 1, the performance of structural analysis, using matched surface TH (TH4), is better compared to the same analysis using matched bedrock (original) TH (TH2).

Figure 12 shows horizontal floor displacement, and internal drift ratio results performance due to RSAD, RS2, and RS4 earthquake force models. According to

Table 1 Maximum displacement and internal drift ratio due to RSAD, TH2, and TH4

	RSAD X	RSAD Y	TH2 X	TH2 Y	Absolute difference	TH4 X	TH4 Y	Absolute difference
Disp. (mm)	37.9	34.8	26.1	27.9	6.9–11.8	37.9	32.9	0–1.9
Drift ratio (%)	15.1	14.7	10.9	11.6	3.1–4.2	16.3	12.9	1.2–1.8

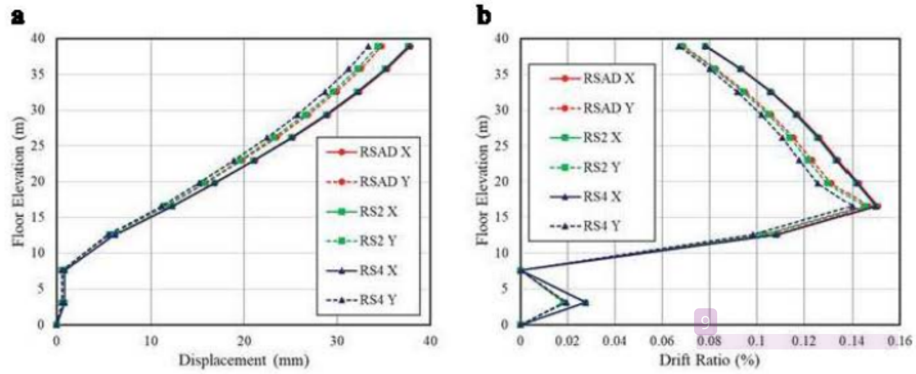

Fig. 12 a Horizontal floor displacement and b internal drift ratio due to RSAD, RS2, and RS4

Table 2 Maximum displacement and internal drift ratio due to RSAD, RS2, and RS4

	RSAD X	RSAD Y	RS2 X	RS2 Y	Absolute difference	RS4 X	RS4 Y	Absolute difference
Disp. (mm)	37.9	34.8	37.6	34.4	0.3–0.4	37.7	33.4	0.2–1.4
Drift ratio (%)	15.1	14.7	15.0	14.5	0.1–0.2	15.0	14.0	0.1–0.7

this figure, no significant differences in horizontal floor displacement and internal drift ratio were observed, using three different response spectral acceleration models. Table 2 shows the maximum absolute difference of floor displacement and drift ratio calculated using RSAD, RS2, and RS4 earthquake force models. Compared to the previous horizontal floor displacement and internal drift ratio calculation using TH2 and TH4, the performance of RS2 and RS4 earthquake models for structural analysis are better.

Figure 13 and Table 3 show the horizontal floor displacement and internal drift ratio results calculated using RSAD, bedrock (original) TH (TH1), and surface TH (TH3). According to Fig. 13 and Table 3, it seems that the differences of TH1 and TH3 to RSDA model are greater than TH2 and TH4. The surface and bedrock TH cannot be directly used for dynamic structural analysis.

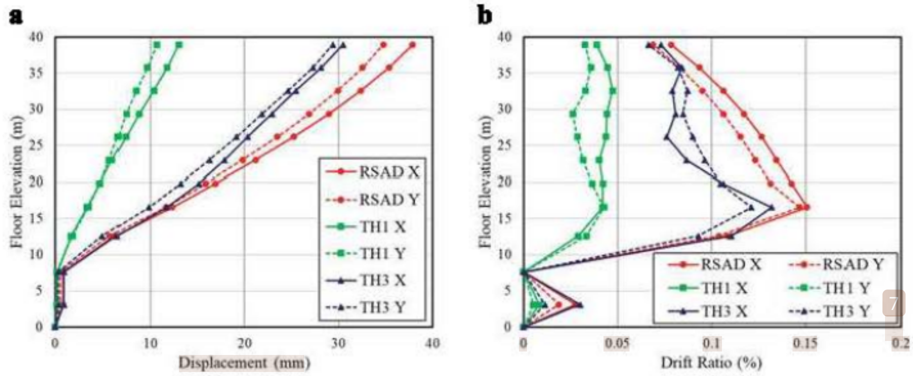

Fig. 13 **a** Horizontal floor displacement and **b** internal drift ratio due to RSAD, TH1, and TH3

Table 3 Maximum displacement and internal drift ratio due to RSAD, TH1, and TH3

	RSAD X	RSAD Y	TH1 X	TH1 Y	Absolute difference	TH3 X	TH3 Y	Absolute difference
Disp. (mm)	37.9	34.8	13.0	10.7	24.1–24.9	30.5	29.4	5.4–7.4
Drift ratio (%)	15.1	14.7	4.2	4.3	10.4–10.9	13.2	12.1	1.9–2.6

Based on the analysis conducted for the building model developed in this study, a better performance of TH used for dynamic structural analysis can be obtained for TH, developed using site analysis. The best performance of TH used for structural analysis was observed when the TH was developed using matched surface TH (TH4).

4 Conclusions

Dynamic structural analysis of buildings is usually performed using RSA design, the earthquake model calculated based on the Indonesian seismic code. The acceleration time histories (TH) collected from specific earthquake events or national/international ground motion databases can also be used as an alternative earthquake force model. For building design purposes, when TH is used as a model of earthquake force, the TH used in the structural analysis should be matched with the RSA design used at the building position.

The acceleration time histories used for building design can be obtained directly from matched bedrock (original) TH or matched surface TH, two different matched time histories developed using RSA design as a spectral acceleration target. The matched surface TH can be obtained using site analysis of bedrock (original) TH at the building location. In terms of horizontal floor displacement and internal drift ratio calculation, the performance of matched surface TH is better, compared to matched bedrock TH.

Modified response spectral acceleration can also be developed using spectral matching analysis of bedrock (original) and surface time histories and conducting RSA design as a spectral acceleration target. In terms of horizontal floor displacement and internal drift ratio, no significant difference was obtained in the results when the dynamic structural analysis was calculated using RSA design and matched response spectral acceleration, as a model of seismic force.

The bedrock/original time histories (obtained from national/international ground motion databases or from specific earthquake events) or surface time histories developed from site analysis cannot be directly used for dynamic structural analysis design. Matched analysis to RSA design as a spectral acceleration target should be performed to get a better performance of structural analysis results.

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