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Seismic Vulnerability Distribution in the Central Area of Surabaya City

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Abstract: Surabaya is the second major city of Indonesia and the economic capital of eastern Indonesia. The city's central area is the governmental center of East Java Province. This area is traversed by the Surabaya section of the Kendeng Fault which could potentially generate a maximum M6.5 earthquake. The East Java megathrust zone also threatens this area with a potential maximum magnitude of M8.9 earthquake. The rock geology of this region is dominated by soft alluvial soil which could amplify earthquake shaking. This study aims to identify the distribution of seismic vulnerability index in Surabaya's central area. Therefore, microtremor measurements were carried out at 61 points in this area. The results were then analyzed using the Horizontal to Vertical Spectral Ratio (HVSR) method to determine the amplification factor values and seismic vulnerability index. The results of the HVSR analysis show that the amplification factor value and seismic vulnerability index are in the low to medium category ranging from 0.8370 - 3.8298 and 0.6041 - 14.6268, respectively. The distribution of the results shows that the northern area is more vulnerable than the southern part. This is verified by the geological conditions of the northern part which is dominated by alluvial soil.

Keywords: Amplification; HVSR; Seismic vulnerability; Surabaya

Introduction

Surabaya is the second largest city in Indonesia (Megahayati et al., 2023) with a population of 2.87 million people (BPS, 2020). According to Presidential Regulation of the Republic of Indonesia Number 80 of 2019, the Surabaya City is designated as the center for accelerating development of the Gerbangkertosusila Plus area. Surabaya is the center of the economy and is often referred to as the gateway to the Eastern Indonesia region (Hariyoko et al., 2019; Yamin Jinca, 2013). Tanjung Perak Port in Surabaya is the second busiest port in Indonesia and is also a trade center for the Eastern Indonesia region (Afiatno & Joyoutomo, 2022).

Surabaya is the capital of East Java Province (Nalle et al., 2023). The Grahadi Building as the Governor office of East Java Province is located in the central area of Surabaya. The government center of both East Java Province and Surabaya City are located in the same area, central of Surabaya City. The central area of Surabaya City is also a center for business, shopping, health, and various other community activities. There are Plaza Tunjungan and the Pasar Turi wholesale center which are the largest shopping center in East Java (Rofi et al., 2023; Sari, 2017). Regional General Hospital (RSUD) Dr. Soetomo, which is the national reference center, is also located in the central area of Surabaya city (Sartika & Sandhika, 2023).

The Surabaya City is traversed by two active faults and one of them passes through the central area of Surabaya City, namely the Kendeng Fault in the Surabaya section (Koulali et al., 2017; Larasati, 2019; Riyanto et al., 2020) which is located in accordance with the Lidah anticline (Larasati, 2019). This active fault has the potential to be a source of earthquake threat for the Surabaya City with a maximum magnitude of M6.5 (Purwaningsih et al., 2022; Triyono et al., 2021; Widodo et al., 2020). There is another source of earthquake threat

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originating from the south of East Java in the form of an active subduction zone which is the boundary where the Indo-Australian and Eurasian plates meet (Kato et al., 2007; Koulali et al., 2018; Palupi et al., 2016). This zone is called the East Java Megathrust and has high seismic activity (Hayes, 2017; Muttaqy et al., 2023; Rwabudandi et al., 2019). East Java Megathrust is a seismic-gap zone that has high stress accumulation and has the potential to be a source of large earthquakes with a maximum magnitude reaching M8.9 (Chasanah et al., 2021a, 2021b; Triyono et al., 2021; Widiyantoro et al., 2020; Zhou et al., 2020). From 2001 to mid-2023, the Agency for Meteorology, Climatology, and Geophysics (BMKG) recorded at least ten earthquakes felt in the central area of Surabaya City, with two of them triggered by active subduction in the south of East Java.

Will the strategically located central area of Surabaya City undergo great shake in the event of an earthquake? Previous studies state that the presence of sediment can cause strengthening of shake when an earthquake occurs. Theoretically, it is stated that the amplitude of earthquake waves will increase when they propagate from hard layers to soft layers (Afak, 2001). Likewise, the thicker and softer the sediment layer in subsurface, the stronger the earthquake waves which are associated with an increase in the potential for damage caused (Chen et al., 2009; Denolle et al., 2019; Wang et al., 2022; Zhang et al., 2008). In several previous studies based on the HVSR method, it is generally known that the central area of Surabaya City is dominated by soft soil (Mufida et al., 2013; Deng, 2015; Utama et al., 2014). This is supported by the geological fact that the central area of Surabaya City is dominated by alluvial soil types (Figure 1). Thus, the central area of Surabaya City has the potential for strengthening of earthquake shake.

The central area of Surabaya City has the potential threat of earthquakes. Even though the seismicity is not high, areas with these characteristics can have the potential for high earthquake wave amplification (Deng, 2015; Fah, 2006; Stanko et al., 2017, 2022). The threat of earthquakes will be increasingly at risk for regions with high level of economic growth (Kracke et al., 2004). Moreover, the study of seismic vulnerability in the Surabaya City are still regional and global in nature (Utama et al., 2014). There has been no study that has identified seismic vulnerability in the central area of Surabaya in detail. Therefore, it is necessary to conduct a study to identify the distribution of seismic vulnerability index in the central area of Surabaya City in order to minimize the risk level of hazard when an earthquake occurs.

Method

The study area is central of Surabaya City at longitude coordinates from 112.698263 E to 112.770863 E and latitude -7.310348 S to -7.239812 S. Geologically (Figure 1), the study area is dominated by Quaternary alluvium plains which are generally soft and are the result of river deposition over thousands of years (Sukardi, 1992). Apart from that, in the central area of Surabaya City there is also an overlap of three geological formations, namely the Kabuh Formation, Pucangan Formation, and Lidah Formation (Figure 1). The Kabuh Formation consists of sandstone and conglomerate. The Pucangan Formation has a lower part consisting of tuff sandstone, conglomerate, and mudstone, as well as the upper part contains tuff sandstone. Meanwhile, the Lidah Formation consists of hard blue mudstone which contains plankton fossils and is relatively more solid compared to the other two geological formations (Sukardi, 1992).

To identify the distribution of seismic vulnerability index in the central area of Surabaya City, microtremor measurements have been carried out using a single station portable seismograph. Microtremor data was acquired at 61 measurable points which are listed in Table 1.

Table 1. List of Measurement Point Locations

Points	Longitude	Latitude	District
SBYT30	112.70	-7.31	Wiyung
SBYT75	112.70	-7.25	Asem Rowo
SBY109	112.70	-7.27	Sukomanunggal
SBY131	112.70	-7.26	Sukomanunggal
SBY15	112.70	-7.24	Asem Rowo
SBY60	112.70	-7.30	Dukuh Pakis
SBY84	112.70	-7.28	Sukomanunggal
SBYT74	112.70	-7.29	Dukuh Pakis
SBYT76	112.71	-7.25	Asem Rowo
SBYT20	112.71	-7.24	Asem Rowo
SBY38	112.71	-7.31	Wiyung
SBY62	112.71	-7.30	Dukuh Pakis
SBYT79	112.71	-7.28	Dukuh Pakis
SBYT77	112.71	-7.26	Sukomanunggal
SBYT78	112.71	-7.27	Sukomanunggal
SBYT18	112.71	-7.29	Dukuh Pakis
SBYT19	112.72	-7.29	Dukuh Pakis
SBYT5	112.72	-7.26	Sawahan
SBYT4	112.72	-7.28	Sawahan
SBYT53	112.72	-7.24	Krembangan
SBY111	112.72	-7.27	Sawahan
SBY133	112.72	-7.25	Bubutan
SBY39	112.72	-7.31	Jambangan
SBY63	112.72	-7.30	Dukuh Pakis
SBYT31	112.73	-7.31	Gayungan
SBYT90	112.73	-7.29	Wonokromo
SBYT26	112.73	-7.26	Sawahan
SBYT66	112.73	-7.24	Krembangan

Points	Longitude	Latitude	District
SBY88	112.73	-7.28	Wonokromo
SBYT67	112.73	-7.25	Bubutan
SBYT64	112.73	-7.27	Tegalsari
SBYT33	112.74	-7.30	Wonokromo
SBYT32	112.74	-7.31	Wonokromo
SBYT21	112.74	-7.29	Wonokromo
SBY113	112.74	-7.27	Genteng
SBY135	112.74	-7.25	Bubutan
SBY89	112.74	-7.28	Tegalsari
SBYT54	112.74	-7.24	Pabean Cantian
SBYT6	112.74	-7.26	Genteng
SBYT22	112.75	-7.29	Gubeng
SBYT65	112.75	-7.27	Gubeng
SBY42	112.75	-7.31	Wonocolo
SBY90	112.75	-7.28	Gubeng
SBYT57	112.75	-7.24	Simokerto
SBYT56	112.75	-7.25	Genteng
SBYT14	112.75	-7.26	Genteng
SBYT3	112.76	-7.30	Gubeng
SBYT55	112.76	-7.24	Simokerto
SBY137	112.76	-7.26	Tambaksari
SBY43	112.76	-7.31	Tenggilis Mejoyo
SBY91	112.76	-7.28	Gubeng
SBYT73	112.76	-7.29	Gubeng
SBYT52	112.76	-7.25	Tambaksari
SBYT34	112.77	-7.30	Sukolilo
SBYT24	112.77	-7.29	Sukolilo
SBYT48	112.77	-7.24	Tambaksari
SBYT9	112.77	-7.25	Tambaksari
SBY92	112.77	-7.28	Gubeng
SBYT12	112.77	-7.26	Tambaksari
SBYT27	112.77	-7.27	Gubeng
SBY44	112.77	-7.31	Rungkut

The distribution of measurement points in Table 1 and the geological conditions of the research location can be seen in Figure 1.

Once the microtremor data has been collected, it is processed and then analyzed using the Horizontal to Vertical Spectral Ratio (HVSR) method developed by Nakamura (1989). The characteristics of the ground surface can be estimated using the spectral comparison value of the horizontal to the vertical component of microtremors (Nakamura, 1997). This HVSR analysis is carried out to determine the natural frequency (f_0) namely the surface soil resonance frequency and identify the H/V peak which is estimated as the magnitude of the amplification factor (A_0) (Nakamura, 2009). Furthermore, the seismic vulnerability index (Kg) Nakamura (Nakamura, 2019) is defined as:

$$Kg = \frac{{A_0}^2}{f_0} \tag{1}$$

It is noted that low frequencies are associated with soft soil (Adib et al., 2015) which have the potential to amplify earthquake waves (Afak, 2001) and means increased seismic vulnerability. This can be confirmed by equation (1).

The value of the amplification factor (A_0) can be classified into low, medium, high, and very high categories (Mawadah et al., 2023) as presented in Table 2. Because the seismic vulnerability index (Kg) is directly proportional to the value ${A_0}^2$, the Kg value can also be categorized into low to very high criteria in line with the division of the A_0 value category.

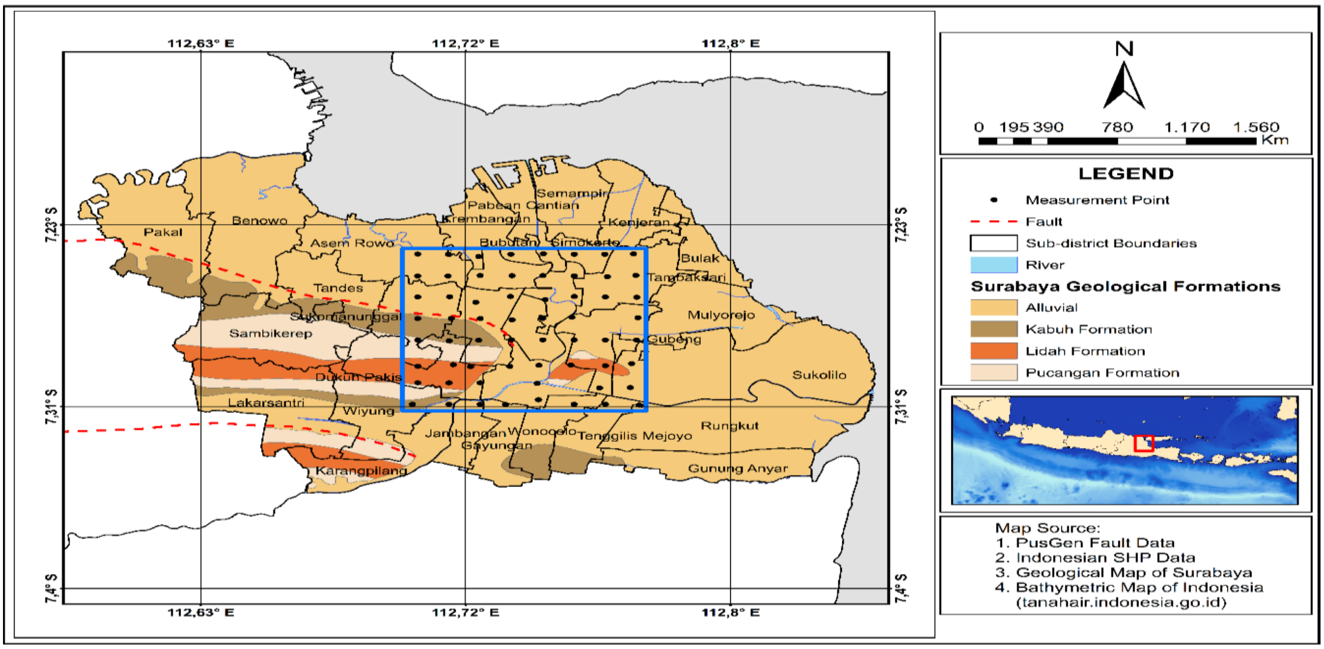

Figure 1. Research area (in blue box) and geological map (modified from Sukardi, 1992)

Table 2. Amplification factor value category (Mawadah et al., 2023)

Value Interval A_0	Category
$0 \leq A_0 < 3$	Low
$3 \leq A_0 < 6$	Medium
$6 \leq A_0 < 9$	High
$A_0 \geq 9$	Very High

In summary, the workflow in this research can be presented in Figure 2 below.

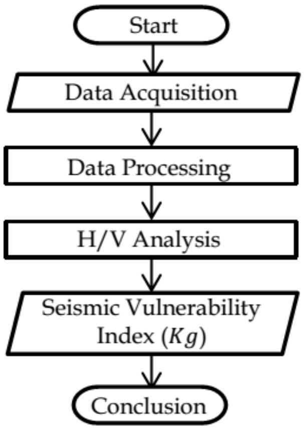

Figure 2. Research flowchart

Result and Discussion

The results of HVSR analysis of 61 microtremor measurement points show that the value of the amplification factor (A_0) at the study area is in the interval of 0.8370 - 3.8298. Through the same analysis process, the seismic vulnerability index (Kg) was also obtained in the interval of 0.6041 - 14.6268. This means that the central area of Surabaya City is included in the category of areas with a low (58 points) to medium (3 points) seismic vulnerability index. Maps of the distribution of amplification (A_0) and seismic vulnerability index (Kg) in the central area of Surabaya City can be seen in Figures 3 and 4, respectively.

Based on the distribution map of A_0 (Figure 3) and Kg (Figure 4) values, it can be seen that these two parameters have an identical pattern. In general, the central area of Surabaya City has a low seismic vulnerability index. However, the northern part of the central area of Surabaya City has a higher seismic vulnerability index than other areas. Although not detailed in the central area of Surabaya City, previous study also concluded that the northern part of Surabaya City has a higher seismic vulnerability index (Mufida et al., 2013). This is because the geological conditions of the area are dominated by alluvial which is composed of gravel, sand, and clay (Sukardi, 1992). Although the A_0 and Kg values in this study area are included in the low to medium category, we are need to be aware for this condition. Moreover, local site effects can still increase the risk of hazard when an earthquake occurs (Chieffo & Formisano, 2020; Panzera et al., 2018). It should be noted that if areas containing soft soil and hard rock have the same seismic vulnerability index, the impact will certainly be more dangerous if an earthquake occurs in an area dominated by soft soil.

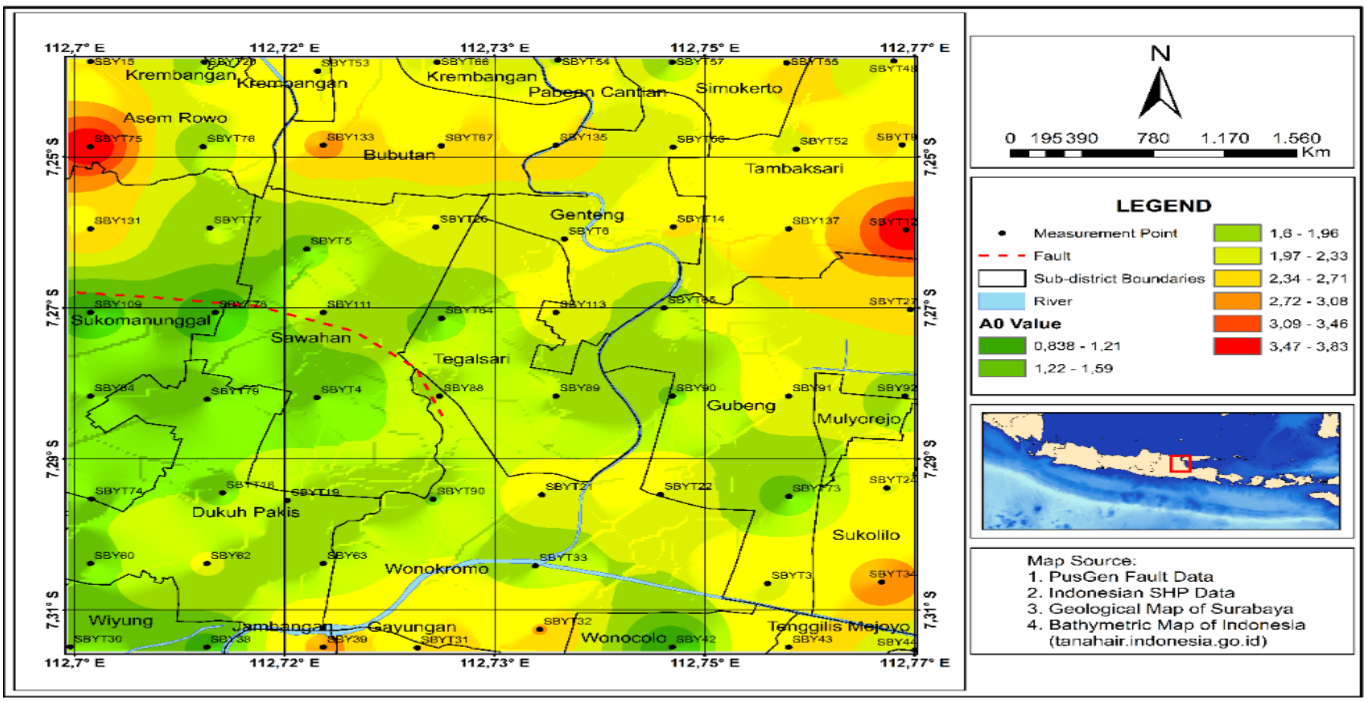

Figure 3. Map of distribution of amplification factor values in the central area of Surabaya City

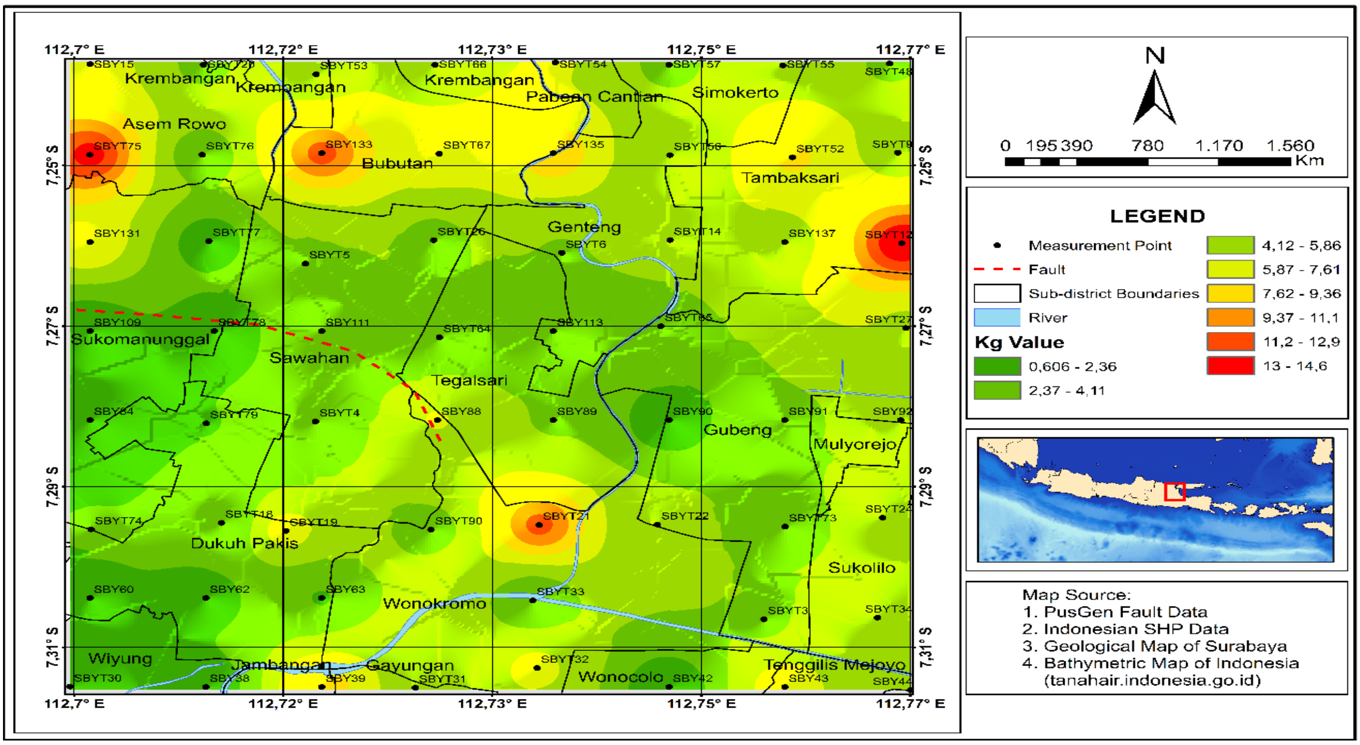

Figure 4. Map of the distribution of the seismic vulnerability index in the central area of Surabaya City

The southwest and southeast parts of the central area of Surabaya City has low level of seismic vulnerability index. Geologically, in this area there are the Kabuh, Pucangan, and Lidah Formations (Figure 1) which are relatively harder than alluvial soil. The geological formations arranged in the southwest of the study area correspond to the location of the Lidah anticline and the Kendeng Fault Surabaya section. The Lidah anticline includes the Kabuh, Pucangan, and Lidah Formations. Meanwhile, the geological formations located in the southeast of the research area consist of the Pucangan and Lidah Formations.

In the southern part of the central area of Surabaya City, there is the Wonokromo District area which has a higher seismic vulnerability index compared to the surrounding areas. This area is on the outskirts of the Kali Mas river which divides Surabaya City. It is suspected that this location has thick alluvial sediment resulting from past river deposits. This south-north river flow seems to have eroded and is seen splitting the west-east Lidah anticline into two parts: west and east. The separation of the Lidah anticline into western and eastern parts is not due to fault activity. Geologically, there is not indicate a fault there. These two parts of the Lidah anticline rock (west-east) also seem to still be one body with a very clear structural alignment, conical towards the east. This geological phenomenon south of the central area of Surabaya City is very interesting to study in more depth. Therefore, it is hoped that the results of this study can provide useful information for local governments in preparing spatial and regional planning (RTRW).

Conclusion

The results of the HVSR analysis show that the amplification factor value is in the interval of 0.8370 - 3.8298 and the seismic vulnerability index ranges from 0.6041 to 14.6268. Both values fall into the low to medium category. The distribution of A_0 and Kg values shows that the central area of Surabaya City in the north has a higher seismic vulnerability index than the southern part. This is thought to be because the northern region is dominated by alluvial rocks.

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Author Contributions
Conceptualization: DA, MSR; methodology: DA, MSR, AND; validation: DA, MSR, AND; formal analysis: DA, MSR, AND; writing - original draft preparation: DA; writing - review and editing: DA, MSR; data curation: AND; supervision: MSR; investigation: DA, AND; resources: DA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
No conflicts of interest

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