Seismic Response and Vulnerability Evaluation of Jammu Region (Jammu and Kashmir)

Abdullah Ansari1 • Falak Zahoor1,2 • K. S. Rao1 • A. K. Jain1

Abstract In this study, an attempt is made to generate hazard maps for the Jammu Region (JR) in Jammu and Kashmir in terms of surface peak ground acceleration ($\text{PGA}_{\text{surface}}$), liquefaction zonation, and vulnerability index ($K_g$). To do this, the seismic response of 200 sites was examined, and amplification factors at 0.01 s, 0.2 s, 1 s, and 10 s were estimated based on site-specific $\text{PGA}_{\text{surface}}$. The calculated factor of safety from field approaches was normalised to produce an integrated liquefaction zonation map. Field data from geophysical testing was also used to generate a vulnerability distribution for the study area. According to the findings, the southern portion of the JR has young sediments and alluvium deposits, resulting in low shear wave velocity ($V_s$) and very strong amplification. As a result, these sites are kept in high to very high vulnerable zones with $K_g$ values of more than 35. This study provides a database for designers working on the construction, development, and expansion-related projects in J&K for developing any prospective earthquake-induced liquefaction mitigation strategies.

Keywords Seismic response • Vulnerability • Probability of liquefaction • Jammu and Kashmir • Indo-Gangetic Plains

Introduction

Jammu and Kashmir (J&K) is located in the north-western part of the Himalayas triggered during 1555, 1828, 1885, 1905, 2005, 2013, and 2019 earthquake events [1–3]. Jammu Region (JR) and Kashmir Valley (KV) are the two major sections of J&K. JR is located around 232 and 112 km from the epicentres of the 2005 and 2019 earthquakes in Kashmir and Mirpur, respectively [4, 5]. JR experienced property damages, slope failures, and liquefaction hazards during these two far-field earthquakes, particularly in the southern regions. This area is a part of the Indo-Gangetic Plains (IGP), where the availability of soft soil and thick sedimentary strata is at its highest. Significant damages at distant sites demonstrate the impact of the dynamic soil characteristics that lead to local site effectiveness. The clearest illustration to support the idea of liquefaction hazards is the damages seen after the 1985 Mexico earthquake, 1999 Izmit earthquake, 2001 Bhuj earthquake, 2004 Niigata earthquake, and the most recent earthquake in Central Italy in 2016 [6–10]. There are site-specific challenges involved in designing the foundation of buildings and infrastructure utilities in an earthquake-prone area [11]. It becomes essential to comprehend the regional geology and lithological variety of underlying strata that are conducive to strong ground motion resulting in building damages and foundation instability [12–15].

In the present study, an attempt has been made to provide the hazard maps in terms of surface peak ground acceleration ($\text{PGA}_{\text{surface}}$), liquefaction zonation, and vulnerability index ($K_g$) for the JR. Connectivity and access to the site are difficult and challenging in the Himalayan region. Geotechnical consultants for the study region provided extensive geotechnical data from boreholes (Fig. 1). Tromino® ENGY 3G [16] is used to measure the shear
wave velocity ($V_s$) and resonance frequency ($f_0$). For data acquisition, Multichannel Simulation with One Receiver (MSOR) and Microtremor Horizontal to Vertical Spectral Ratio (MHVSR) techniques are utilised. According to the findings, more than half of the JR is classified under moderate to high-risk zones. The proposed zonation will aid in understanding the dynamics of subsurface layers, local geology, and lithological formations in JR. This study provides a database for designers working on the construction, development, and expansion-related projects in J&K for developing any prospective earthquake mitigation strategies.

Geological Formation and Seismotectonic Settings of Jammu Region (JR)

The JR is located in the NW Himalayas, especially in the Lesser Himalaya Zone, from a regional geological standpoint [13, 17]. The Main Central Thrust (T1) in the north and the Main Boundary Thrust (T4) in the south define the Lesser Himalayan Zone [11]. The lower Himalaya’s geological unit is mostly made up of sedimentary rocks that have been sheared and over-thrust to the south into the Siwalik Molasse (Sub-Himalaya Zone) following the NNE dipping Reasi Thrust (T8). The southern boundary of the JR including the bank of the Tawi River in the Samba and Kathua area presents the Indus-Alluvium plains [18]. North of this region, the Siwaliks are exposed. Near Reasi and Vaishnodevi, Sirban formation is mostly visible [19]. This formation comprises dark grey dolomite and limestone with a back thrust concerning the overlying Subathu Formation. After a considerable time interval, the fine-grained detrital sediments of the Murree Formation were deposited above the Subathu Formation [20]. The Panjal Volcanics and the Upper Palaeozoic to Lower Tertiary Agglomeratic Slate Sequence are unconformably overlain by the Ramban Formation [21]. Slate, phyllite, quartzite, and gneiss are the main rocks that make up this formation. The Panjal Thrust (T10) is the Main Central Thrust in this area and passes

Fig. 1 Study area map of the Jammu Region (JR) showing the locations for boreholes and geophysical testing

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through the Ramban and some parts of Reasi. Rocks of the Salkhala Formation constitute a low to high-grade meta-sedimentary suite comprising phyllite, schist, quartzite, and limestone [22, 23]. The local geology of JR is illustrated in Fig. 2.

The JR has been impacted due to the near-field as well as far-field earthquakes in the Himalayan region extending up to Hindu Kush in Afghanistan [24, 25]. The Jhelum Fault (F3), Attock Fault (F1), Reasi Thrust (T8), Balakot-Bagh Fault (F8), Deosai Fault (F13), Jwalamukhi Thrust (T3), Hanna Fault (F14), Batal Fault (F12), and Mawer Fault (F7) are few of the active seismic source that surrounds this area [26]. The T1 distinguishes the crystalline rocks of the higher Himalayas from the formations of the lower Himalayas [27]. Along the JR’s northern boundary, the T4 and T10 run parallel. NNW-SSE and NW–SE trends are shown by the Jhelum Fault (F3) and Balapur Thrust (T7), respectively [28, 29]. The Kishtwar Window (KW) and Jhelum Fault (F3) are the two major local strike-slip faults in the JR. The F8, which is NE dipping in Pakistan, is the primary cause of the 2005 Kashmir earthquake [30]. Active T8 and Udhampur Fault Zone (F9, F10, and F11) pass through the core centre section of the JR in addition to the T4. As a result of the imbrication of the lower Himalayas into a deeper structural level, the Kishtwar Window (KW) developed inside the crystalline upper Himalayas [31]. Recently occurred far-field June 2022 Paktika earthquake ($M_w = 5.9$) in Afghanistan and the 2019 Mirpur earthquake ($M_w = 5.6$) in Pakistan are also showing the active dynamics of the tectonic plates in this region. An updated seismotectonic map of JR is presented in Fig. 3.

**Subsurface Investigations**

In the present study, geotechnical and geophysical data were collected from local consultants and field investigations, respectively. An extensive geophysical field study is conducted at 200 locations from where SPT (N) data is provided for boreholes. Site locations are marked in the study area map, as presented in Fig. 1. For data acquisition, Tromino® ENGY 3G [16] is used which is provided by the Geotechnical Division of National Institute of Technology Srinagar, Jammu and Kashmir. The shear wave velocity ($V_s$) based on MSOR is measured for shallow depth [32–36]. The resonance frequency ($f_0$) is recorded based on the concept of ambient noise measurements [37–39]. The liquefaction features such as sand blows and ground rupture were found in Jatah and Simbal villages. The only factor used to classify a site under the NEHRP is the averaged shear wave velocity to a depth of 30 m ($V_{s30}$) [40]. In the northern and western regions (Sonder and Gattigali), where there is access to rock outcrops, $V_{s30}$ values have reached as high as 1150 m/s (Fig. 4). The central part of the JR showed $V_{s30}$ values ranging from 350 to 425 m/s, whereas locations on the southern side have

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**Fig. 2** Geological formations of the JR showing: a Indus-Alluvium plains, b outcrops of the conglomerate c outcrops of dolomite, d Main Central Thrust (MCT) crossing the Sangaldan area, e contact between the Murre Formation and Ramban Formation, f outcrops of Phyllites
lower average shear wave velocities of 182 to 312 m/s. Beyond the Ravi River, particularly in the central region of Kathua, where it ranges between 380 and 570 m/s, an increase in $V_{s30}$ values is seen. $V_s$ up to 30 m depth for various site locations is shown in Fig. 4.

The shear wave velocity ($V_s$) is high for sites with high SPT ($N$) values, according to the results of both geotechnical and geophysical studies. As shown below, a correlation between the $V_s$ and the $N$ has been developed for Jammu (Fig. 5). The performance of the proposed empirical correlation is evaluated by comparing measured and calculated shear wave velocity values (Fig. 6).

Various researchers have proposed the relationship for various regions. Figure 7 shows a comparison of the proposed correlation with the existing correlations in the literature. Depending upon the variation in shear wave velocity and the frequency of an area, the relationship may differ. This relationship is helpful when SPT ($N$) values or $V_s$ needs to be established for the locations in and around Jammu. The plotted data are dispersed between lines with slopes of 1:0.5 and 0.5:1, with the majority of the values close to slope line 1:1, demonstrating that the proposed correlation provides an acceptable fit for the assembled data for the tested soils.

**Seismic Response Analysis**

In this study, ten different bedrock motions from the Himalayan region were considered and a one-dimensional seismic response analysis for the equivalent linear case has been done using DEEPSOIL [4, 50–52] at all sites marked in Fig. 1. Actual ground motions of five earthquakes in the region, i.e. Uttarkashi (1991), Chamba (1995), Chamoli (1999), South Hindukush (2010) and Kishtwar (2013), were considered for analysis. Figure 8 depicts the ground motion history for all input motions at bedrock. To prevent the influence of probable seismic amplification effects, the
The first criterion used in the selection is to include only accelerograms recorded on outcropping rock [53, 54]. Furthermore, real accelerograms were chosen with a tolerance on seismological parameters, magnitude, and epicentral distance that are regarded adequate for J&K. The deaggregation results were used as a basis to establish the magnitude and distance range. Based on these criteria, 10 records were chosen from a pool of 149. Typically, the
effect of magnitude on spectral response is greater than the effect of epicentral distance. As a result, shorter magnitude range and broader epicentral distance range records were chosen. The frequency response of the chosen ground motion is illustrated in Fig. 9 by Fourier amplitude spectra. The damping versus shear strain curves and modulus reduction curves are used to represent the soil parameters of each soil layer. In this study, shear modulus reduction curves and damping ratios for clays and sands have been defined using discrete points by Seed and Sun [55], Seed and Idriss [56], and Idriss [57]. Table 1 shows the estimated amplification factors for 0.01 s, 0.2 s, 1 s, and 10 s. In the study area, amplification is higher at rock sites and lower at alluvium sites for short periods. The amplification is higher at alluvium sites and lower at rocky sites for long periods.

The JR is separated into three major classes based on the PGA_{surface} value, which is fixed at 0.3 g, 0.3–0.45 g, and > 0.45 g. The spectral acceleration values are highest in the northern region for rocky sites compared to alluvium sites in the southern region, which is part of the IGP. The PGA_{surface} in Shareef Bagh, Banihal, and Baflaiz is greater than 0.45 g. Maximum sites in Jammu, Samba, Kathua, and the central part of Udhampur have very low PGA_{surface}.
due to younger sediments and alluvium deposits near the Tawi and Ravi rivers, as illustrated in Fig. 10. $\text{PGA}_{\text{surface}}$ value of 0.05 g is considered to be sufficient to cause damage to poorly designed buildings. However, $\text{PGA}_{\text{surface}}$ is not the only criteria for damage; there are various additional parameters that are essential from a damage standpoint, such as strong motion duration, building natural period and ground motion amplitude. The main causes of the low $\text{PGA}_{\text{surface}}$ are the short duration of input bedrock motion, the longer source-to-site distance, and impedance contrast. Travelling a long distance with weak ground motion is likely to inflict less damage. Local site effects, on the other hand, play a significant part in devastation in the case of far-field earthquakes.

**Vulnerability Assessment for Jammu Region**

The standard penetration test (SPT), cone penetration test (CPT), and seismic tests to assess the shear wave velocity of soil deposits are the most often utilised field testing-based procedures for obtaining soil samples for liquefaction hazard study. The most recent technique proposed for SPT ($N$) value [58] and shear wave velocity [59, 60] was employed in this work to assess the factor of safety against liquefaction in the present study. The empirical correlation proposed by [61] is used to determine the probability of liquefaction ($P_L$) for all sites. Local geology and field investigation results were considered to change the ranges for liquefaction zones. Table 1 highlights the intended range for several zonation classes (Table 2).

The factor of safety is derived using the SPT ($N$) value, and $V_s$-based approaches were given equal weightage for normalisation in order to estimate the probability of liquefaction ($P_L$). A liquefaction zonation map for JR is presented in Fig. 11. Majority of the sites in the southern part are classified under High or Very High liquefaction zones. At all of these locations, $V_s$ less than 230 m/s is observed. High amplification is seen due to the presence of young sediments. The northern and northern western ends of JR include rock outcrops. Shear wave velocity of more than 600 m/s was measured at all such sites where very low amplification levels were detected.

Nakamura [38] presented a vulnerability index ($K_g$) value for precisely predicting earthquake damage to surface ground and buildings. The $H/V$ amplitude ($A$) and resonance frequency ($f_0$) estimated from the MHVSR can be used to evaluate the vulnerability index, as described in Eq. (1).

$$K_g = \frac{A^2}{f_0}$$  

(1)

Based on the calculated values of $K_g$, the JR is divided into five zones of vulnerability. These zones show the severity as very low, low, moderate, high, and very high. The vulnerability map in Fig. 12 is in accordance with the local lithological and geological formations. The highest point on JR is at Sinthan Top, at the maximum altitude of 3784 m. Mountainous topography may be seen in most places in Reasi, Poonch, Ramban, Doda, and Kishtwar. Testing locations in these districts fall under one of two vulnerability categories: low or very low. The IGP, which makes up the southern portion of JR, has exceptionally soft alluvium. Soft soils and thick sedimentary layers in southern locations make them susceptible to potential damage from intense motion caused by either near-field or far-field earthquakes. Sites near the Tawi, Ravi, and Chenab Rivers have extremely high vulnerability.

In the event of moderate to large magnitude earthquakes, low resonance frequency ($f_0$) and high $H/V$ amplitude ($A$) are the most lethal and catastrophic damage-producing combinations. Outstanding $f_0$ and $A$ values in the regions of Khorbani, Jatah, and Simbal will cause...
Fig. 8  Input ground motions at bedrock considered from the Himalayan seismic stations
Fig. 9 Fourier amplitude spectra for input ground motions at bedrock considered from the Himalayan seismic stations

Table 1 Amplification factor at various periods for sites in Jammu Region (Jammu and Kashmir)

| Location                  | Amplification Factor |
|----------------------------|----------------------|
|                            | 0.01 s  | 0.2 s  | 1 s    | 10 s   |
| Gulab Garh                | 2.83    | 3.05   | 1.08   | 1.06   |
| Chak Malal                | 2.96    | 3.02   | 1.15   | 1.08   |
| USBRL T2 Tunnel Portal 2  | 2.06    | 3.50   | 1.02   | 1.02   |
| Chodial Kot               | 1.97    | 2.61   | 1.04   | 1.02   |
| Vishwa Bharti Public School, Panjpeen | 2.22 | 2.46 | 1.08 | 1.04 |
| Sazgar                    | 2.66    | 2.83   | 1.15   | 1.07   |
| Gurukul Public School, Reasi | 2.20 | 3.27 | 1.05 | 1.01 |
| Sonder                    | 2.85    | 2.83   | 1.15   | 1.07   |
| Bagani                    | 2.91    | 2.46   | 1.20   | 1.07   |
| Kangral Sangral           | 2.87    | 1.78   | 1.03   | 1.01   |
| Khari                     | 2.85    | 1.59   | 1.03   | 1.01   |
| Taba                      | 2.96    | 1.87   | 1.04   | 1.02   |
| Sawijian                  | 2.53    | 3.33   | 1.02   | 1.03   |
| Sonder                    | 2.69    | 2.89   | 1.09   | 1.06   |
| USBRL Tunnel T2 Portal 1  | 1.73    | 2.64   | 1.05   | 1.00   |
| Mughal Road, Morha        | 1.07    | 1.18   | 1.00   | 1.00   |
| Jagti                     | 1.07    | 1.20   | 1.01   | 1.00   |
| Mustafa Nagar             | 1.09    | 1.21   | 1.00   | 1.00   |
| Kot Bhalwal               | 1.25    | 1.22   | 1.01   | 1.00   |
| Patial Construction Camp, Bhaga | 1.25 | 1.26 | 1.01 | 1.00 |
| Gattigali                 | 1.07    | 1.18   | 1.00   | 1.00   |
| Qadar Pur                 | 1.16    | 1.35   | 1.01   | 1.00   |
| Khan Pora                 | 1.17    | 1.25   | 1.01   | 1.00   |
| Degwar Maldayalan         | 1.29    | 1.33   | 1.01   | 1.00   |
| Govt. Degree College, Bishnah | 1.15 | 1.24 | 1.01 | 1.00 |
| Berigal                   | 1.16    | 1.32   | 1.01   | 1.00   |
| Gundi                     | 1.16    | 1.28   | 1.01   | 1.00   |
| Phagla                    | 1.23    | 1.34   | 1.01   | 1.00   |
| Mahar                      | 1.16    | 1.27   | 1.01   | 1.00   |
| Sandel                    | 1.29    | 1.68   | 1.01   | 1.01   |
| Siksha Niketan School, Jeevan Nagar | 1.20 | 2.31 | 1.04 | 1.05 |
| Govt. School, Reasi       | 1.66    | 2.47   | 1.19   | 1.23   |

Table 1 continued

| Location                  | Amplification Factor |
|----------------------------|----------------------|
|                            | 0.01 s  | 0.2 s  | 1 s    | 10 s   |
| St. Peter’s School, Karan Bagh | 2.02  | 2.66  | 1.39   | 1.27   |
| Nagrota                    | 2.36    | 2.48   | 1.53   | 1.27   |
| Chenab Bridge Kauri Side   | 1.67    | 2.83   | 1.17   | 1.23   |
| Paloura                    | 1.77    | 2.44   | 1.18   | 1.25   |
| Govt. College of Engg. & Tech., Chak Bhalwal | 2.43  | 2.60 | 1.58 | 1.27 |
| Domi                       | 1.66    | 2.45   | 1.12   | 1.17   |
| Govt. Ploytechnic, Sanjay Nagar | 1.88 | 1.54  | 1.27   | 1.26   |
| Baji Pur                   | 1.23    | 2.44   | 1.06   | 1.07   |
| Dhar Shiv Garh             | 2.22    | 2.50   | 1.53   | 1.26   |
| Eidgah, Banihal            | 2.05    | 3.11   | 1.40   | 1.27   |
| Batna                      | 1.63    | 2.84   | 1.15   | 1.21   |
| Kulu Chak                  | 1.78    | 2.33   | 1.13   | 1.17   |
| Kotli Mian Fateh           | 2.15    | 2.33   | 1.54   | 1.26   |
| Indian Institute of Management (IIM) Jammu, Canal Road  | 1.34  | 1.38  | 1.04   | 1.00   |
| Rani Park, Near J&K Legislative Assembly | 1.56 | 1.78 | 1.05 | 1.00 |
| Abdullah Bridge, Gujjar Mandi | 2.36 | 2.47 | 1.09 | 1.00 |
| Khan Market               | 1.88    | 3.12   | 1.07   | 1.00   |
| Sangaldan                 | 1.97    | 2.44   | 1.04   | 1.00   |
| Mehmoordpur               | 2.02    | 2.63   | 1.04   | 1.00   |
| Anji Khad Bridge          | 1.33    | 1.38   | 1.04   | 1.00   |
| Devi Kund                 | 1.71    | 3.32   | 1.07   | 1.00   |
| Jammu University          | 3.06    | 3.90   | 1.80   | 1.02   |
| Janipur                   | 1.69    | 1.86   | 1.06   | 1.00   |
| Khorbanie                 | 1.79    | 2.60   | 1.06   | 1.00   |
| Jatath                    | 1.71    | 3.32   | 1.07   | 1.00   |
| Thiloo                    | 2.26    | 3.57   | 1.45   | 1.02   |
| Simbal                    | 2.10    | 3.45   | 1.32   | 1.01   |
| Kotijijjan                | 2.40    | 2.49   | 1.11   | 1.00   |
| Dangah                    | 2.08    | 2.51   | 1.43   | 1.29   |
| Chak Lalushah             | 1.70    | 2.66   | 1.10   | 1.13   |
| SIDCO Industries          | 1.88    | 2.95   | 1.41   | 7.83   |
| Sher-e-Kashmir University of Agricultural Sciences & Technology (SKAUST) | 1.82 | 4.21 | 1.16 | 1.23 |
| Geeta Nagar, Reasi        | 1.23    | 1.36   | 1.04   | 1.05   |
| Sidhra                    | 1.35    | 1.54   | 1.05   | 1.06   |
| Govt. Secondary School, Rehari Colony | 1.55 | 2.63 | 1.10 | 1.13 |
| Katli                     | 1.32    | 1.52   | 1.05   | 1.06   |
| Khandwali                 | 1.36    | 1.95   | 1.07   | 1.09   |
| St Xavier School, Barnai  | 1.93    | 2.21   | 1.34   | 1.26   |
| Patniyal                  | 1.70    | 2.69   | 1.10   | 1.13   |
| Stephens School, Sialkot Road | 1.36 | 2.97 | 1.38 | 7.82 |
| Raina Colony              | 1.60    | 2.85   | 1.11   | 1.14   |
| Transport Nagar           | 1.32    | 1.55   | 1.05   | 1.07   |
| Chak Lalushah             | 1.99    | 2.39   | 1.40   | 1.28   |
liquefaction-related damages in these areas. Significant building and structural damages were observed due to the Kashmir and Mirpur far-field earthquakes in 2005 and 2019, respectively, in these regions. Site locations of Laal Haveli and Punjaja with $f_0 < 1$ Hz present the vulnerability index ranging between 15 and 35. The majority of the sites in Poonch, Kishtwar, and the eastern part of Doda have extremely low $K_g$ values ($< 5$). For $K_g > 15$, the central portion of the JR displays H/V amplitudes between 4.5 and 6.8. Sites in the southwestern part of Jammu, Kathua, Samba, and central Rajouri where $V_{s30}$ ranges between 182 and 560 m/s. These sites exhibit very high amplification and are vulnerable to severe structural damages in case of any seismic activities.

Conclusions

The Jammu Region (JR) of Jammu and Kashmir is located in the NW Himalayas which is one of the most active tectonic regions. This area has witnessed damage during far-field earthquakes that occurred in 2005 and 2019. In this study, ten different bedrock motions from the Himalayan region were considered and a one-dimensional seismic response analysis for the equivalent linear case has been done. For short periods, amplification is higher at sites with rock outcrops in the north and north-west, and lower at alluvium sites in the south. For long periods, the amplification is greater at Simbal and Jatah-like alluvium sites near the banks of the Tawi, Ravi, and Chenab rivers. In Shareef Bagh, Banihal, and Bafalai, the PGA$_{surface}$ is more than 0.45 g. The factor of safety ($F_s$) against liquefaction is calculated using both SPT ($N$) value and shear wave velocity ($V_s$)-based field methods and results are superimposed to generate an integrated map of liquefaction zonation in the JR.

The majority of sites in southern Jammu, Samba, and Kathua have $V_s$ of less than 230 m/s. The results of local geology and field investigations were used to adjust the ranges for liquefaction zones. The projected liquefaction zones are labelled as very low, low, moderate, high, and very high, with $P_L$ of 0.2, 0.2–0.4, 0.41–0.5, 0.51–0.75,
and $>0.75$, respectively. The testing sites in the southern section have $P_L$ values more than 0.5. These locations are vulnerable to damage from either near-field or far-field earthquakes due to their fragile subsurface strata. The vulnerability indexing-based site grouping in JR was defined by means of resonance frequency ($f_0$) and $H/V$ amplitude. The findings concluded that more than half part of the JR is classified as moderate to high-risk zones. These

| $P_L$         | Zonation       |
|---------------|----------------|
| $P_L > 0.85$  | Very High      |
| $0.51-0.75$   | High           |
| $0.35 < P_L < 0.65$ | Moderate     |
| $0.21-0.40$   | Low            |
| $P_L < 0.15$  | Very Low       |

Fig. 11 Liquefaction zones for Jammu Region (Jammu and Kashmir)
findings can be used to analyse the seismic response of foundation soil and superstructures.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest associated with this publication.

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