Wavelet Analysis of Far-Field Ground Motions from the M_w 7.6 2005 Kashmir Earthquake

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1 Introduction

The continuing collision of the Indian and Eurasian tectonic plates has caused high seismic activity across the entire Himalayan belt and lead to enormous damage to the built environment [1–4]. Kashmir lies in this region of collision and is known to be seismically active. The region has been previously struck by several earthquakes such as 1842 M_w 7.5 Kunnar earthquake, 1878 M_w 6.7 Abbottabad earthquake, 1885 M_w 6.3 Srinagar earthquake, and 1905 M_w 7.8 Kangra earthquake. In the year 2005, Kashmir was struck by a major earthquake having a moment magnitude of M_w 7.6 with a focal depth of 30 km [5]. The M_w 7.6 earthquake struck Kashmir on 8th October 2005 with its epicentre located at 34.45°N, 73.65°E, about 50 km from Abbottabad and a focal depth of 26 km. The earthquake was the result of reactivation of the northwest striking Balakot-Bagh fault, and the rupture on the surface extended from Bagh to Muzaffarabad till Balakot [6, 7]. Two aftershocks of magnitude 5.9 and 5.8 were also felt in Kashmir within 30 min of the earthquake. The fatalities were over 86,000, and the number of injured was over 1,00,000. The damage to lifelines and buildings was immense with over 6,00,000 buildings classified as "damaged or destroyed". Isoseismal maps for the earthquake have been drawn based on the reconnaissance studies [8] The earthquake triggered thousands of landslides, comprising of rockfalls and debris falls, over a large region spread over an area over 7,500 km^2 [9]. The earthquake damage exposed a lot of structural defaults and construction malpractices. The high fatalities and heavy destruction caused this earthquake to be the deadliest to ever strike the Indian subcontinent [10, 11].

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Himachal Pradesh is a state in north India, bordered by Jammu and Kashmir in the north, Tibet autonomous region of China and Uttarakhand in the east, Haryana in the south, and Punjab in the west. The geographic location of Himachal Pradesh is in the southern edge of the Himalayan mountain region. The state of Himachal Pradesh is located in the high-risk seismic zone IV and V of the Indian seismic zoning map. The state lies along the Himalayan mountain range with Himalayan Frontal Thrust (HFT), the Main Boundary Thrust (MBT), and the Krolm, the Giri, Jutogh, Nahan thrusts also lie in this region. This paper analyses the time–frequency effect of near and far-field ground motion data from the 2005 Kashmir earthquake recorded at eight stations (Abbottabad, Bhanjaru, Sundla, Dalhousie, Jawali, Dharmashala, Kangra, and Mandi). Figure 1 shows the locations of these eight stations.

Strong motion records were recorded at a few stations in Pakistan, namely, Abbottabad, Murree, and Nilore. The town of Abbottabad is a distance of 50 km from the epicentre and recorded a peak ground accelerations (PGA) of 0.231 g. The town of Murree lies at a distance of 34 km from the epicentre and recorded a PGA of 0.078 g. The town of Nilore is situated 54 km from the epicentre and recorded a PGA of 0.026 g. The vertical PGAs at these three towns were recorded as 0.087 g, 0.069 g, and 0.03 g, respectively [12]. Two ground motions were recorded at dam sites, Tarbela and Mangla. At Tarbela Dam, which is at an epicentral distance of 78 km, a horizontal PGA of 0.16 g was recorded at the crest and 0.1 g at the base. The Mangla dam is located at 90 km epicentral distance and recorded a PGA of 0.1 g

Fig. 1 The location of the Earthquake epicentre along with the locations where data was recorded. (1) Abbottabad, (2) Bhanjraru, (3) Sundla, (4) Dalhousie, (5) Jawali, (6) Dharmashala, (7) Kangra (8) Mandi *Earthquake

at the downstream toe of the Dam [10]. However, only the Abbottabad record was made available to the authors of the present paper. This strong ground motion record is analysed in this paper. On the Indian side, far-field ground motions are available from seven-station in Himachal Pradesh. Table 1 shows the details of these stations along with key characteristics of the ground motions. Figure 2 shows the response spectra derived from the ground motions recorded at the seven stations. It is observed that the spectra show peaks in the low period ranges indicating the possible damage to low rise structures. The spectra of ground motions from the Abbottabad town (relatively near field) are far greater than the spectra of ground motions from other far-field towns. Further, the response spectra of ground motions from the Abbottabad town exhibit a wide acceleration sensitive region indicating possible damage to a large range to structures with varying natural periods.

2 Observed Damage to Buildings

It has been estimated that 84% of the total building stock in Pakistan Administrated Kashmir were damaged [13]. It has also been estimated that 98% of the highly damaged area lies within a topographically amplified seismic response area [14]. The damage to non-engineered construction was the maximum. Housing in the region is primarily built using Unreinforced Masonry (URM) with heavy Reinforced Concrete Slabs (RC) as roofs. Stone masonry with mud mortar is a common building typology. Such structures are inherently weak under lateral forces resulting from a major seismic event. Often there is a lack of confinement leading to extensive cracking in the masonry walls. Although engineered construction such as reinforced concrete frames performed better, it was observed that there was poor steel detailing leading to a lack of moment resisting action. Overall, it can be remarked that the poor construction practices in the region along with non-adherence to code standards lead to the deficient response of all types of structures.

3 Key Characteristics of Recorded Ground Motions

All three components of the strong ground motions, i.e., radial, transverse and vertical were recorded at the eight stations. Table 1 lists the key characteristics of all these ground motions, namely, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Sustained Maximum Acceleration (SMA), Sustained Maximum Velocity (SMV), Arias Intensity (AI), Mean Period (T_m) and Predominant Period (T_p).

Table 1 Characteristics of recorded ground motions

Sr. No.	Station	Direction	Distance (km)	PGA (g)	PGV (cm/s)	SMA (cm/s^2)	SMV (cm/s)	AI (m/s)	T_p (s)	T_m (s)
1	Abbottabad (near-field)	Radial	50	0.26	45.05	0.20	32.60	2.44	0.78	0.99
		Transverse		0.18	31.02	0.16	22.79	1.66	0.98	0.86
		Vertical		0.08	9.89	0.08	8.46	0.36	0.64	0.50
2	Bhanjraru	Radial	293	0.03	2.96	0.02	2.83	0.01	0.32	0.76
		Transverse		0.03	2.62	0.02	2.08	0.01	0.36	0.67
		Vertical		0.01	2.05	0.01	1.61	0.003	0.30	0.88
3	Sundla	Radial	297	0.02	2.87	0.02	2.14	0.01	0.18	0.56
		Transverse		0.03	2.63	0.03	2.36	0.02	0.20	0.51
		Vertical		0.02	2.88	0.01	2.74	0.01	0.4	0.89
4	Dalhousie	Radial	302	0.02	5.33	0.01	4.19	0.03	1.08	1.59
		Transverse		0.02	4.86	0.02	4.84	0.03	1.70	1.72
		Vertical		0.01	4.42	0.01	3.71	0.01	0.26	1.95
5	Jawali	Radial	337	0.02	4.16	0.02	2.38	0.01	0.28	0.76
		Transverse		0.03	3.05	0.02	2.92	0.01	0.26	0.71
		Vertical		0.01	2.08	0.01	1.89	0.002	0.36	0.92
6	Dharmashala	Radial	351	0.02	5.82	0.02	4.57	0.05	0.64	1.11
		Transverse		0.02	6.79	0.02	4.95	0.05	0.48	1.07
		Vertical		0.01	3.09	0.01	2.30	0.01	2.46	1.24
7	Kangra	Radial	357	0.02	3.02	0.02	2.65	0.01	0.30	0.70
		Transverse		0.03	2.76	0.02	2.20	0.02	0.34	0.59
		Vertical		0.01	2.88	0.01	1.93	0.01	0.30	0.91

(continued)

Table 1 (continued)

Sr. No.	Station	Direction	Distance (km)	PGA (g)	PGV (cm/s)	SMA (cm/s^2)	SMV (cm/s)	AI (m/s)	T_p (s)	T_m (s)
8	Mandi	Radial	410	0.04	3.33	0.03	2.78	0.07	0.54	0.60
		Transverse		0.02	2.35	0.01	2.11	0.02	0.48	0.67
		Vertical		0.01	1.70	0.01	1.39	0.01	0.48	0.60

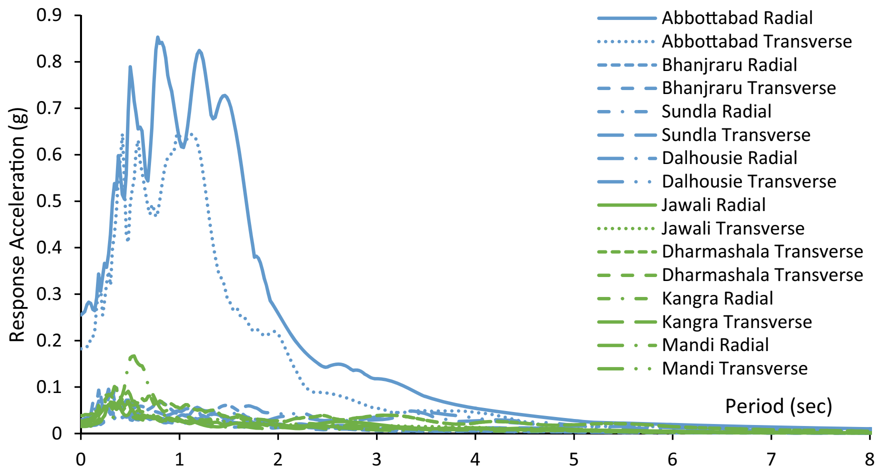

Fig. 2 Response spectra for eight stations (radial and transverse) directions

4 Frequency Estimation Using Fast Fourier Transforms

An earthquake wave consists of several frequencies. This frequency distribution is understood from observations of the frequency content obtained using Fast Fourier Transforms (FFTs). FFTs are used to transform seismic time history into the frequency domain. FFTs highlight the frequency ranges at which seismic energy is concentrated. Figures 3, 4, 5, 6, 7, 8, 9 and 10a, b show the FFT's derived for the recorded ground motions. It is observed that most ground motions had low-frequency content (0–10 Hz) with a few stations, i.e., Sundla, Jawali, and Kangra exhibiting slightly higher frequency content (0–20 Hz). The Fourier amplitude of ground motions from the Abbottabad town is 10–20 higher than the ground motions from the other far-field stations.

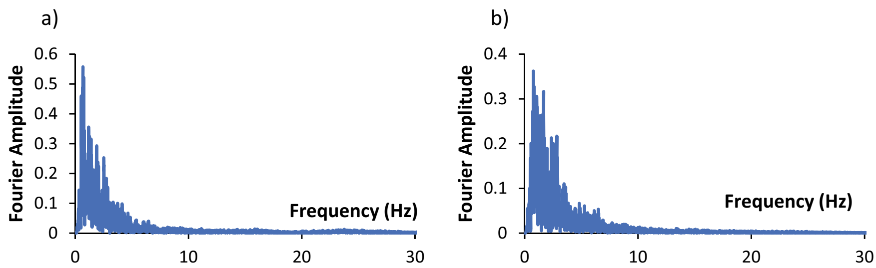

Fig. 3 FFT's of Abbottabad. **a** Radial. **b** Transverse

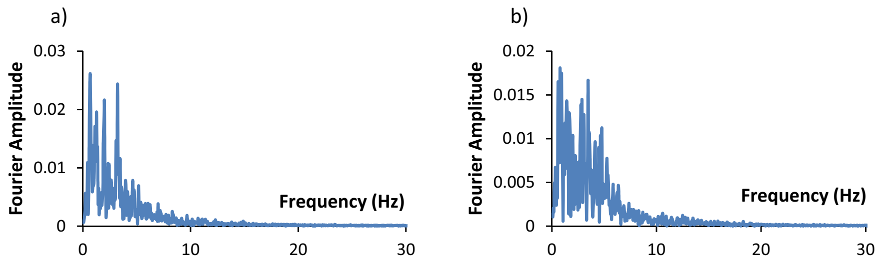

Fig. 4 FFT's of Bhanjraru. **a** Radial. **b** Transverse

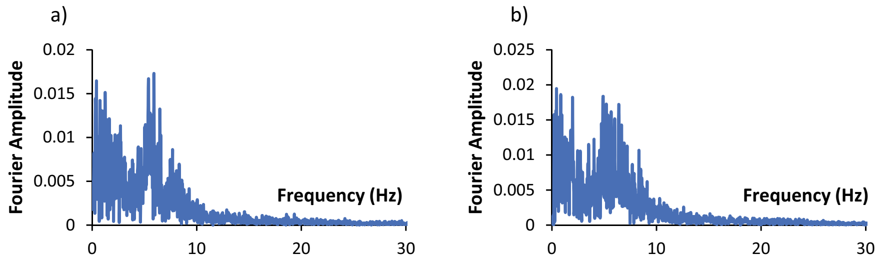

Fig. 5 FFT's of Sundla. **a** Radial. **b** Transverse

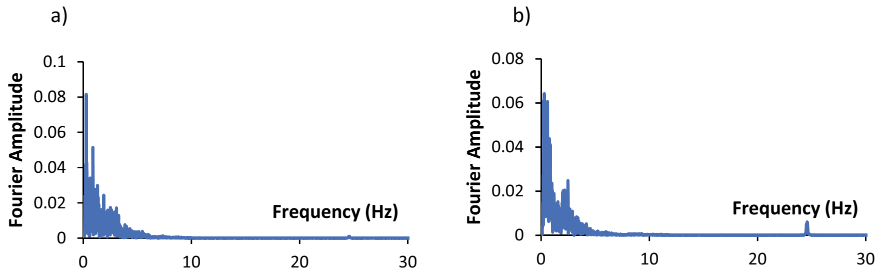

Fig. 6 FFT's of Dalhousie. **a** Radial. **b** Transverse

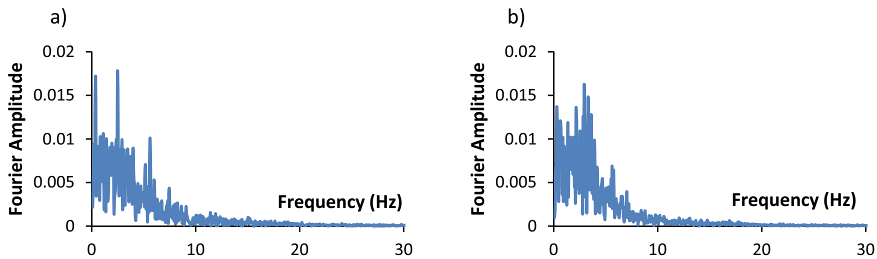

Fig. 7 FFT's of Jawali. **a** Radial. **b** Transverse

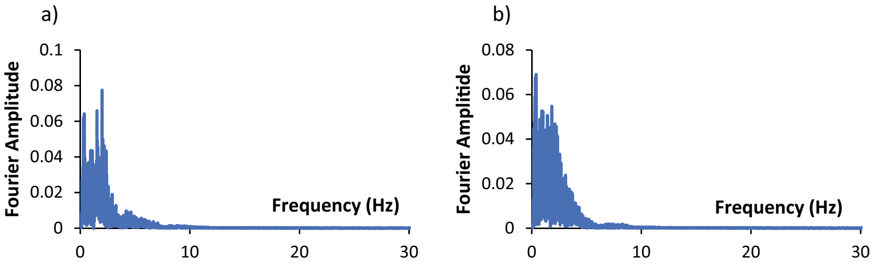

Fig. 8 FFT's of Dharmashala. **a** Radial. **b** Transverse

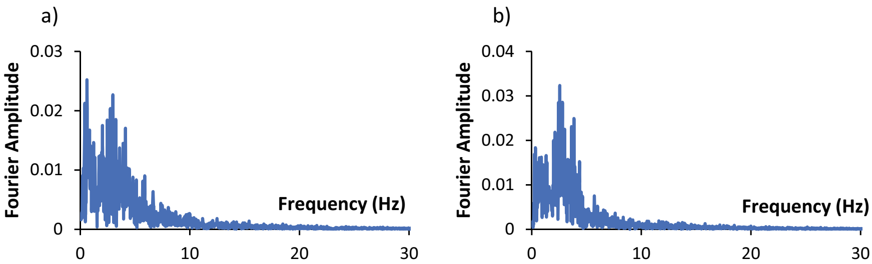

Fig. 9 FFT's of Kangra. **a** Radial. **b** Transverse

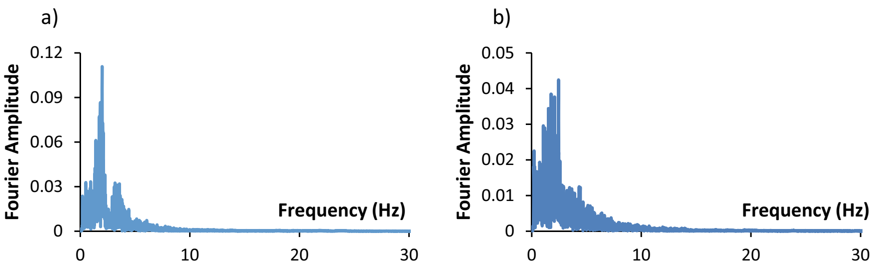

Fig. 10 FFT's of Mandi. **a** Radial. **b** Transverse

5 Continuous Wavelet Transforms of Recorded Ground Motions

As discussed previously, while the time-acceleration representation hides the information on the frequency content of the ground motion, the frequency-Fourier amplitude representation hides the time information of the ground motion. Since earthquake ground motions are non-stationary, i.e., their frequency content varies with time, both these representations convey partial information. Figures 3, 4, 5, 6, 7, 8, 9 and 10 indicate that the frequency content in the ground motions is primarily in the range of 0–10 Hz. However, from these figures, the true damage potential of the seismic wave is unclear since it is neither apparent if a single damaging frequency was sustained in time nor is it apparent if a damaging lower frequency arrived after a damaging higher frequency. In both such cases, there is a possibility of high damage to structures. A structure when subjected to a seismic wave with a resonant frequency over a sustained duration of time is prone to large displacements. Similarly, during an earthquake, it is well known that the stiffness of the structure degrades with time, thereby lowering its period, i.e., increasing its frequency. Hence, the structure may be damaged twice during an earthquake if there are waves of lower frequency followed by waves of higher frequency, especially if these frequencies are close to the original and changed natural period of the structure.

The wavelet transforms, e.g., the continuous wavelet transform (CWT), provide information on both the time and frequency content of non-stationary signals. In this section, the CWT is utilized to understand the changing time–frequency characteristics of the earthquake ground motion. Figures 11, 12, 13, 14, 15, 16, 17 and 18a, b show the continuous wavelet transforms for the eight stations.

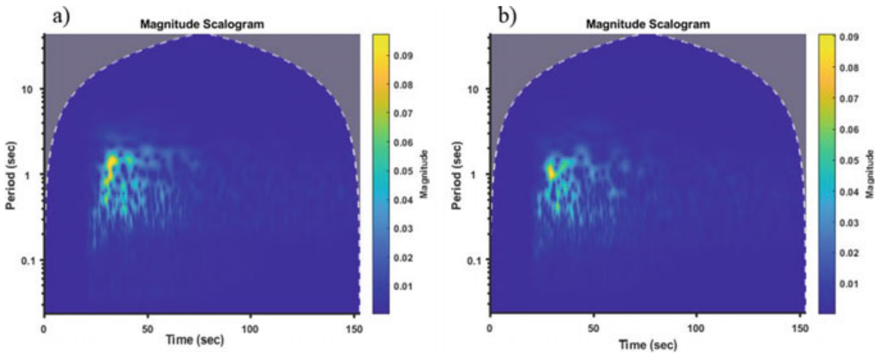

Fig. 11 CWT's of Abbottabad. **a** Radial. **b** Transverse

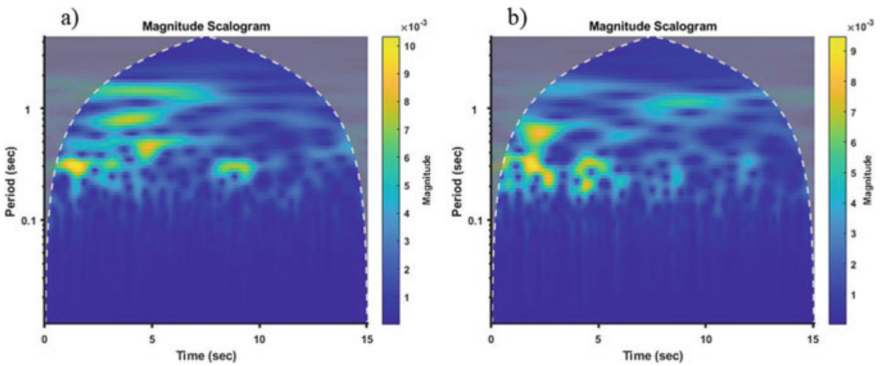

Fig. 12 CWT's of Bhanjraru. **a** Radial. **b** Transverse

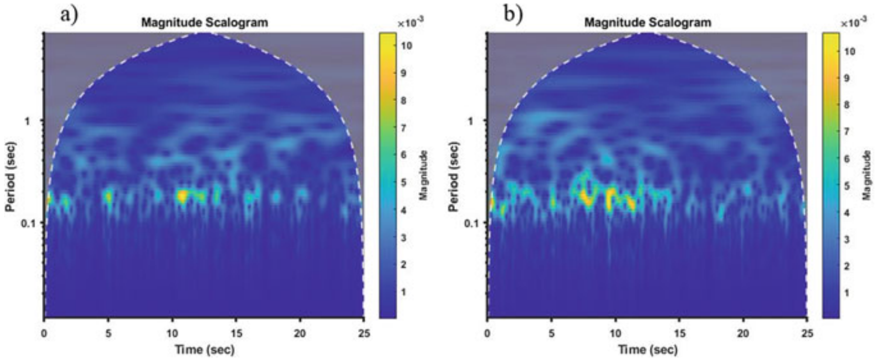

Fig. 13 CWT's of Sundla. **a** Radial. **b** Transverse

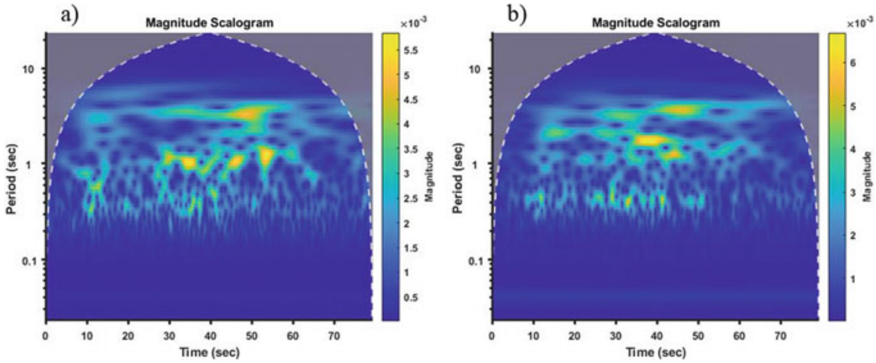

Fig. 14 CWT's of Dalhousie. **a** Radial. **b** Transverse

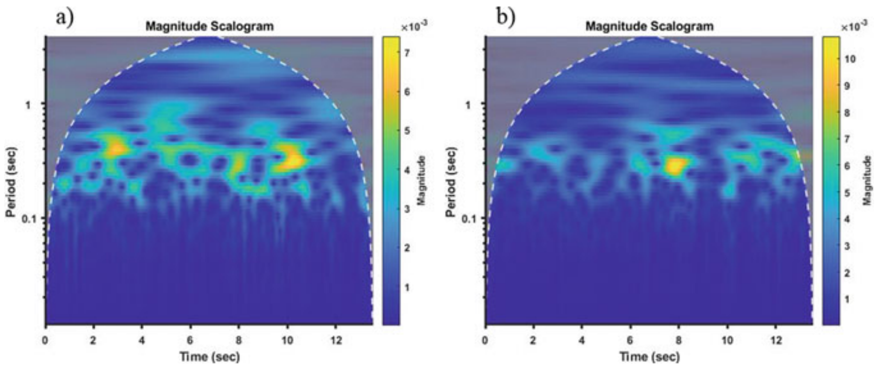

Fig. 15 CWT's of Jawali. **a** Radial. **b** Transverse

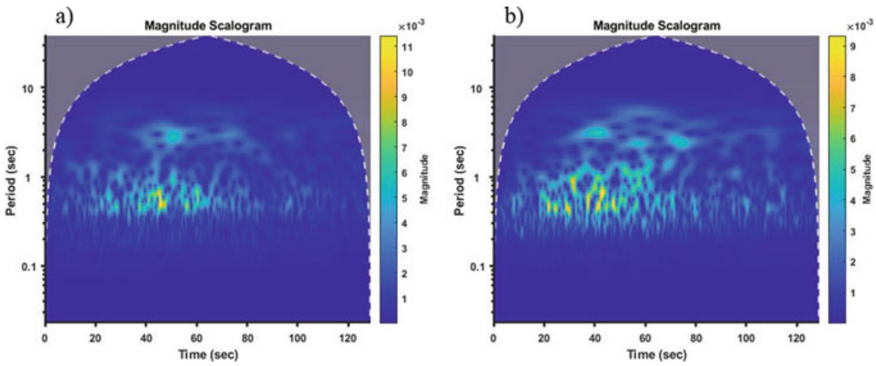

Fig. 16 CWT's of Dharmashala. **a** Radial. **b** Transverse

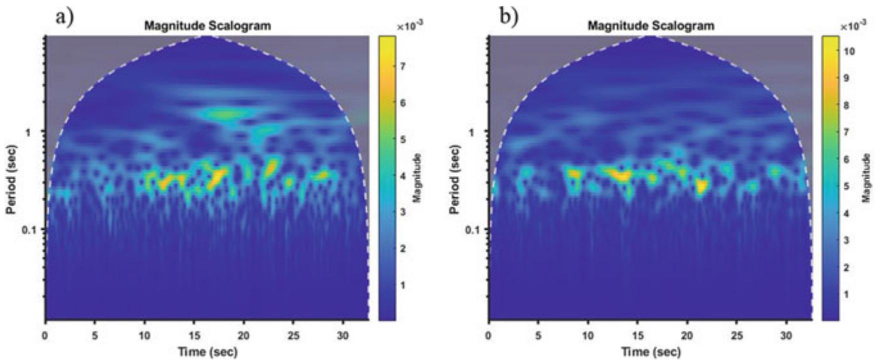

Fig. 17 CWT's of Kangra. **a** Radial. **b** Transverse

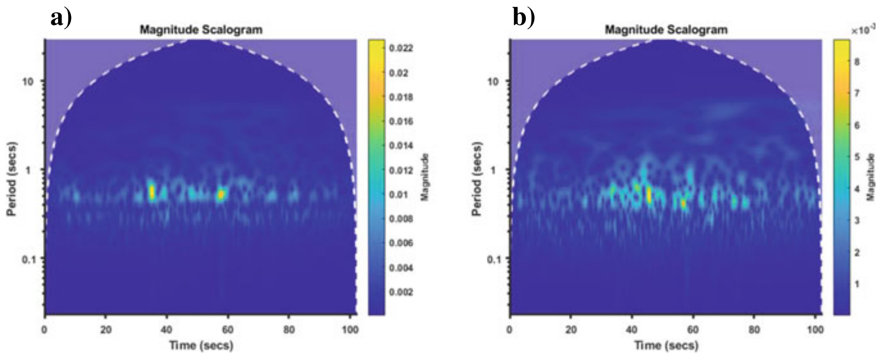

Fig. 18 CWT's of Mandi. **a** Radial. **b** Transverse

The strong ground motion recorded at Abbottabad primarily exhibits a single dominant frequency corresponding to a time period of 1 s. Apart from Abbottabad, the remaining ground motions were recorded in the far-field range. Bhanjraru has multiple frequencies primarily corresponding to a time period of 0.3–0.4 s. These dominant frequencies were observed at multiple instants of time. At Bhanjraru, the initial seismic waves display a high amplitude-low period and are followed by waves carrying a high amplitude-high period: such a sequence is especially damaging to structures since the natural period of the structure is also altered from a low period to a higher period due to change in its stiffness. The strong ground motion recorded at Sundla primarily exhibits a single dominant frequency corresponding to a time period of 0.2 s, recurring at multiple instants of time. Waves with such frequencies (corresponding to a time period of 0.2 s) may cause structural damage to low rise (1–2 storeyed) structures, especially since these damaging frequencies are sustained over a long duration of time. The strong ground motions at Dalhousie exhibit multiple frequencies, some of which are sustained in time. Jawali has frequencies primarily corresponding to a time period of 0.3–0.4 s. Dharmashala and Mandi primarily exhibit a single high amplitude frequency for short bursts of time. Kangra has frequencies primarily corresponding to a time period of 0.3–0.4 s and recurring at multiple time instants.

6 Summary and Conclusions

Ground motions recorded in earthquakes are time-domain signals. For nonlinear dynamic analyses of structures, analysts use accelerograms, which are the time-acceleration representations of the ground motions. The time-acceleration description hides the information on the frequency content of the ground motions. The fast Fourier transform (FFT) is used to obtain the Frequency-Fourier amplitude representation of the accelerograms. However, in this representation, the time information is lost, and it is not possible to discern if the peak amplitudes or energies of the ground motion are reached at single or multiple time instances. Since earthquake ground motions are non-stationary, i.e., their frequency content varies with time, both these representations convey incomplete information. Wavelet analysis provides information on both the time and frequency content of non-stationary signals. In this paper, the continuous wavelet transforms (CWT) are utilized to understand the changing time–frequency characteristics of the ground motions from the M_w 7.6 2005 Kashmir earthquake. The recorded ground motions were analysed to understand the influence of their critical characteristics on the observed damage to the building stock in the region. The observations from the CWT plots of ground motions recorded at various stations present a much-improved representation of the damage potential of strong ground motions. While some ground motions exhibit high amplitude waves at the same frequency content over a significant duration of time, other ground motions exhibit high amplitude waves in two to three frequency ranges. It is concluded that these observations correlate well with the observed non-uniform distribution of damage to reinforced concrete and unreinforced masonry structures in the region.

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