Time–Frequency Analysis of Strong Ground Motions from the 2011 Sikkim Earthquake

Shalin Mathew, Mohammed Ayub Ifan, Jayaprakash Vemuri, and K. V. L. Subramaniam

1 Introduction

The state of Sikkim in India lies in the Himalayan region and is bordered on three sides by Bhutan, Tibet, and Nepal. According to the Indian seismic zoning, Sikkim lies in the high-risk zone IV. Sikkim lies along the tectonic plate boundary where the Indian and the Eurasian plate are under collision. The Main Boundary Thrust (MBT) and Main Central Thrust (MCT) are the two major thrust faults passing through the state as shown in Fig. 1a. The region has recorded seismic activity in the past, and the distribution and damage pattern in the 2011 earthquake demonstrate attenuation features of the area [1–11] between the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). On 18th September 2011, Sikkim was struck by a Mw 6.9 earthquake which caused enormous structural damage to the built environment in the region. The earthquake exposing several structural defects and also highlighted the role of construction malpractices associated with non-engineered construction in the region. This paper analyses the ground motions of the 2011 Sikkim earthquake and describes the observed structural damage caused due to the severe ground shaking associated with this earthquake. Time–frequency analyses are performed on strong ground motion data recorded at six stations (Chungthang, Gangtok, Gezing, Melli, Mangan, and Singtam) as shown in Fig. 1b.

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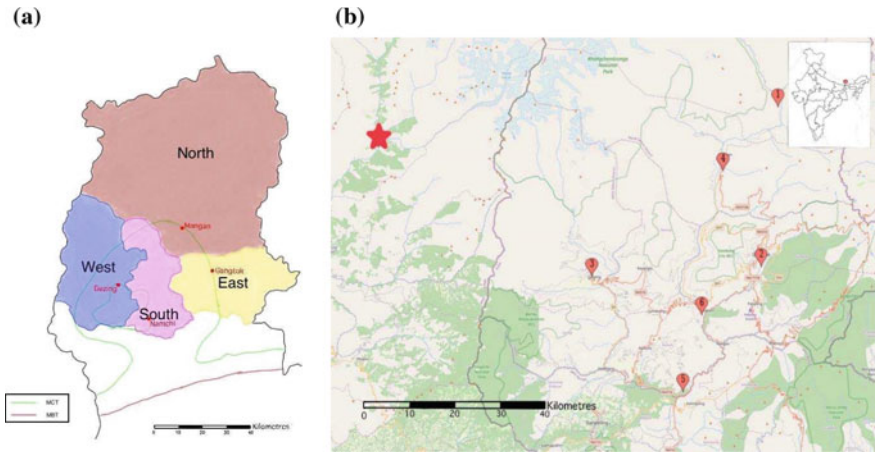

Fig. 1 **a** Location of MCT and MBT on the map of Sikkim, **b** Earthquake epicentre and recording stations. (1) Chungthang, (2) Gangtok, (3) Gezing, (4) Mangan, (5) Melli, (6) Singtam, *Epicentre

2 Observed Damage to Buildings

Several reconnaissance surveys by various researchers [12–16] were undertaken in the aftermath of the earthquake to assess structural damage. The surveys recorded the observed damage to the variety of structures prevalent in Sikkim. It was observed that damage was severe due to the non-engineered structures prevalent in the region (RC, unreinforced masonry (URM), and bamboo structures). In some towns, structural damage in engineered buildings was observed but was concentrated in low-rise buildings and the lower storeys of taller buildings. Table 1 describes the details of the wide variety in the observed structural damage due to the earthquake, as recorded in six towns of Sikkim from where strong ground motions are also available. Based on the severe damage observed in the town of Mangan, a damage intensity level of VIII+ (MMI scale) has been assigned [17]. Similarly, based on the high damage to structures in the towns of Chungthang, Gangtok, Mangan, and Singtam, the four towns were assigned a damage intensity level of VIII [17].

3 Features of Recorded Accelerograms

Table 2 shows the important characteristics of the seismic waves, namely peak ground acceleration (PGA), peak ground velocity (PGV), arias intensity (AI), mean period (T_m), and predominant time (T_p). The maximum PGA of 0.45 g was recorded at Gezing town (in the radial direction): the town was closest to the epicentre, at 50 km. The next highest PGA value of 0.39 g (in the radial direction) was recorded at Mangan town: the town is also situated at an epicentral distance of 50 km. Despite the distance

Table 1 Observed damage to buildings

S. No.	Station	Building material	Building use	Type of damage	References
1	Chungthang	Concrete	Residential, 1 storey	Damage to building due to a rolling boulder from landslides	[12]
2	Chungthang	RC framed	Storage facility building	Stiffness pattern was changed of various infill panel walls	[12]
3	Chungthang	Masonry	Chungthang Monastery, 1 storey	RRM masonry walls were damaged by collapsed by out-of-plane in corners of perimeter of the walls	[12]
4	Chungthang	RC framed	Communication structure on a 4	Damage observed in the lower storey of the building	[12]
5	Gangtok	Bamboo, mud, cement, stones	Residential, 2 storeys	Failure of load-bearing walls due to the poor transfer of earthquake inertial force	[14]
6	Gangtok	Bamboo, mud, cement, stones	Residential, 2 storeys	Shaking causing uneven settlement of the filled earth at the foundation of the house leading to tilting	[14]
7	Gangtok	Bamboo, mud, cement, stones	Residential, 2 storeys	Structures without any reinforcement or buttresses were damaged	[14]
8	Gangtok	Wooden frame, bamboo reeds, mud plaster	Residential, 1 storey	Damaged rubble masonry	[12]
9	Gangtok	RC framed	Police HQ, 3 storeys	RC elements and URM masonry infills damaged	[12]

(continued)

Table 1 (continued)

S. No.	Station	Building material	Building use	Type of damage	References
10	Gangtok	Undressed stones with mud, lime-based mortar	Enchey monastery,2 storeys	Damage in the upper storey, cracks below the windowsill, local spalling, and crushing of masonry pier	[12]
11	Gangtok	RC building with masonry infills	Rey Mindu monastery, 2 storeys	Exterior and interior brick masonry walls underwent severe cracking	[16]
12	Gangtok	RC building with masonry infills	Ranka lingdum monastery, 3 storeys	One RC column in the first storey of the new building suffered severe damage	[16]
13	Gangtok	RC framed	Serney school, 3 storeys	A portion of the first storey collapsed due to the absence of tie beams at the bottom of first storey columns	[16]
14	Mangan	Masonry	Ringin monastery, 2 storeys	Rubble masonry walls were found to have out-of-plane bulging and collapse	[12]
15	Mangan	Wooden frame, bamboo reeds, mud plaster	Residential, 1 storey	Undergone 15 cm of southward shift at the base	[15]
16	Singtam	RC framed	Residential, 3 storeys	In places of poor stiffness in the plan, structure observed torsion and collapsed	[12]
17	Singtam	RC	Commercial, residential; 4 storeys	Columns failed due to buckling in the first storey	[16]

Table 2 Characteristics of the accelerograms

S. No.	Town	Component	Distance (km)	PGA (g)	PGV (cm/s)	AI (m/s)	Tp (s)	Tm (s)
1	Chungthang	Radial	55	0.36	5.69	0.45	0.10	0.11
		Transverse		0.25	4.67	0.35	0.10	0.12
		Vertical		0.11	2.20	0.08	0.10	0.11
2	Gangtok	Radial	68	0.27	5.47	1.90	0.06	0.11
		Transverse		0.28	6.44	1.41	0.06	0.14
		Vertical		0.10	2.50	0.33	0.06	0.17
3	Gezing	Radial	50	0.43	8.42	0.76	0.12	0.12
		Transverse		0.38	5.35	0.57	0.06	0.11
		Vertical		0.18	3.98	0.17	0.08	0.12
4	Mangan	Radial	50	0.38	4.81	0.66	0.06	0.08
		Transverse		0.27	5.41	0.53	0.08	0.11
		Vertical		0.12	2.44	0.14	0.06	0.14
5	Melli	Radial	78	0.26	3.31	0.63	0.06	0.07
		Transverse		0.28	3.21	0.48	0.06	0.08
		Vertical		0.18	1.67	0.28	0.04	0.08
6	Singtam	Radial	67	0.21	4.68	1.30	0.06	0.16
		Transverse		0.10	2.66	0.38	0.08	0.14
		Vertical		0.26	6.40	1.88	0.06	0.13

being similar, the difference in peak accelerations is due to the soil properties and the propagation effects of the earthquake.

Chungthang town, situated at a distance of 55 km, experienced a PGA of 0.36 g. Gangtok and Melli which are located at distances of 68 km and 78 km, respectively, recorded the same PGA of 0.28 g. The town of Singtam, which is situated at a distance of 67 km, recorded a slightly lower horizontal PGA of 0.21 g. Velocity time series are derived from the accelerograms, after applying baseline filtering (Butterworth, Bandpass) of cut frequency 0.2–80 Hz and order 4 along with second-order baseline correction. The maximum PGV of 8.42 cm/s was observed at the Gezing station in the radial direction. PGVs (in the radial direction) for Chungthang, Gangtok, Mangan, Melli, and Singtam were 5.69 cm/s, 5.47 cm/s, 4.81 cm/s, 4.68 cm/s and 3.31 cm/s, respectively. Similarly, in the transverse direction, the maximum PGV of 6.44 cm/s was observed at Gangtok, followed by Mangan at 5.41 cm/s, Gezing at 5.35 cm/s, Chungthang at 4.67 cm/s, Melli at 3.21 cm/s, and Singtam at 2.66 cm/s.

4 Fast Fourier Transforms

Fast Fourier Transforms show the frequency content in a seismic wave. Figures 2, 3, 4, 5, 6, and 7 show the FFTs obtained for the accelerograms from the six stations. It is observed that the frequencies were primarily in the range of 0–20 Hz. The radial and transverse components are designated using the symbols, *R* and *T*, respectively.

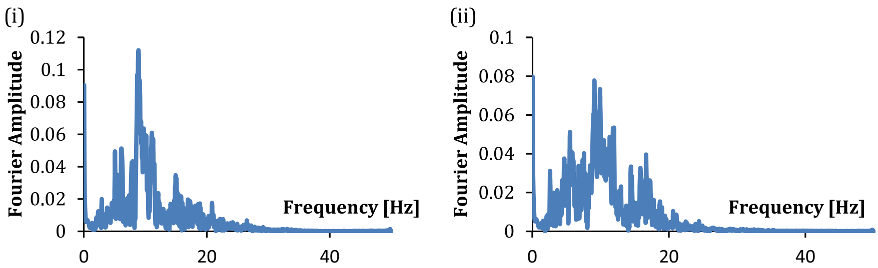

Fig. 2 FFT for Chungthang: (i) *R*, (ii) *T*

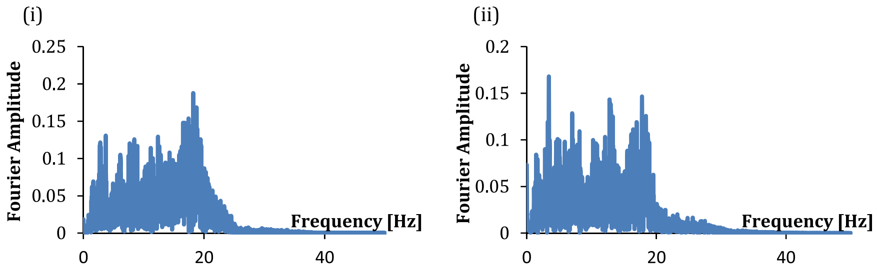

Fig. 3 FFT for Gangtok: (i) *R*, (ii) *T*

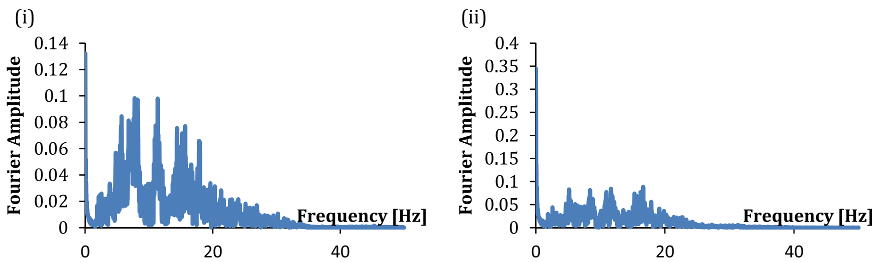

Fig. 4 FFT for Gezing: (i) *R*, (ii) *T*

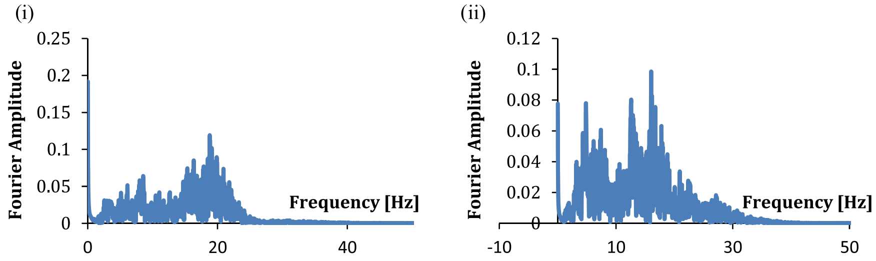

Fig. 5 FFT for Mangan: (i) *R*, (ii) *T*

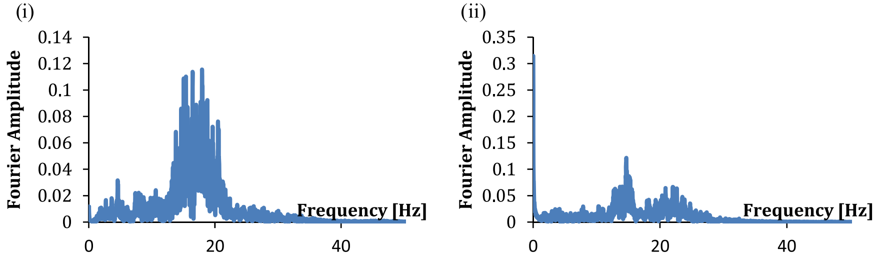

Fig. 6 FFT for Melli: (i) *R*, (ii) *T*

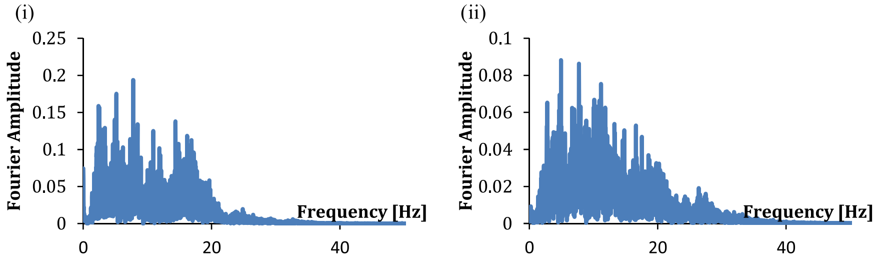

Fig. 7 FFT for Singtham: (i) *R*, (ii) *T*

5 Continuous Wavelet Transforms of Strong Ground Motions

Figures 8, 9, 10, 11, 12, and 13 (i, ii) show the CWTs for the six stations. In general, the CWT figures show the presence of high-frequency waves. In all the six towns, the high-amplitude waves contained high-frequency content of around 10 Hz, representing a low period of 0.1 s. However, in some towns, the high-amplitudes waves were observed at multiple frequency ranges. For example, the transverse record from Gezing town shows high-amplitude waves at multiple low periods, ranging from 0.04 to 0.2 s. Similarly, in the radial record from Singtam town, the high magnitude seismic waves are distributed over a low period range of 0.05–0.2 s. The damage

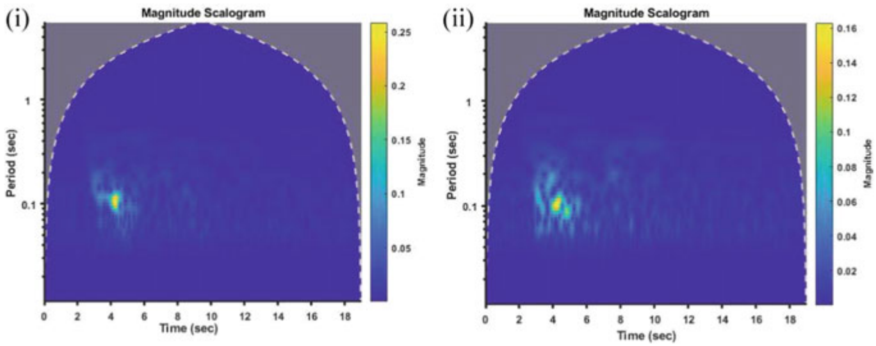

Fig. 8 CWT for Chungthang: (i) *R*, (ii) *T*

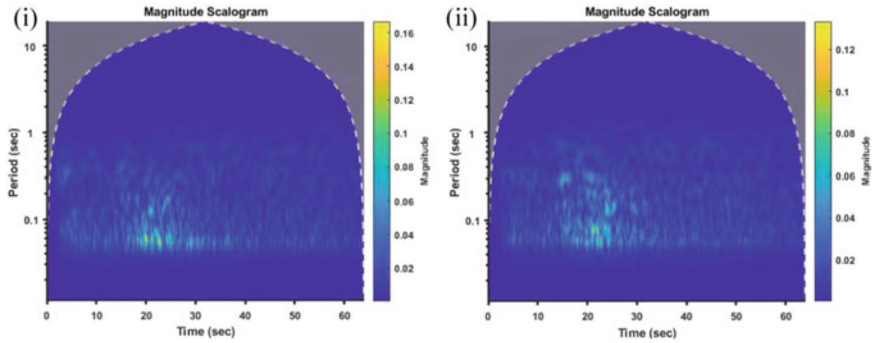

Fig. 9 CWT for Gangtok: (i) *R*, (ii) *T*

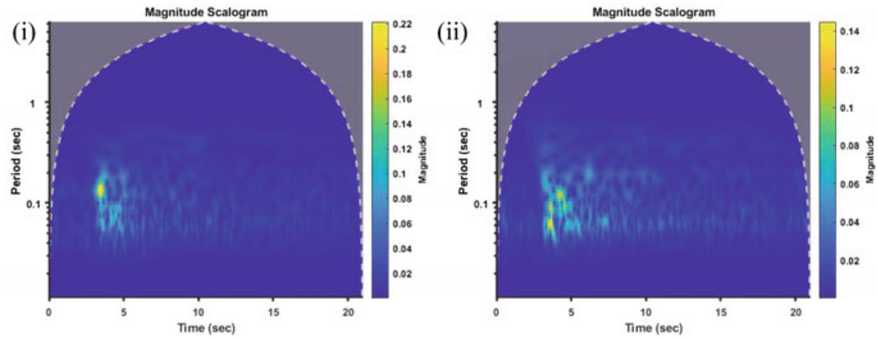

Fig. 10 CWT for Gezing: (i) *R*, (ii) *T*

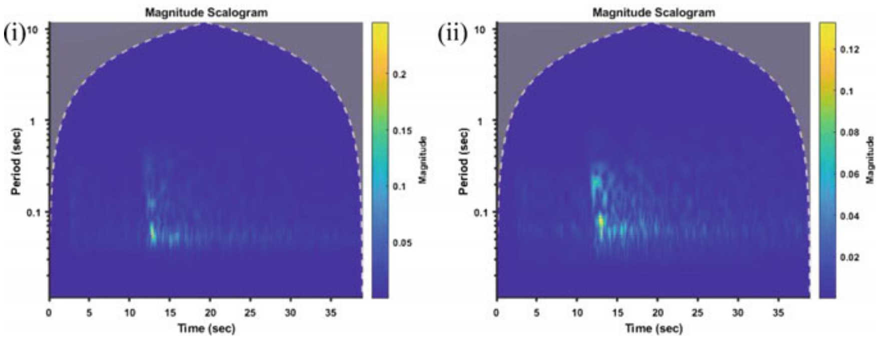

Fig. 11 CWT for Mangan: (i) *R*, (ii) *T*

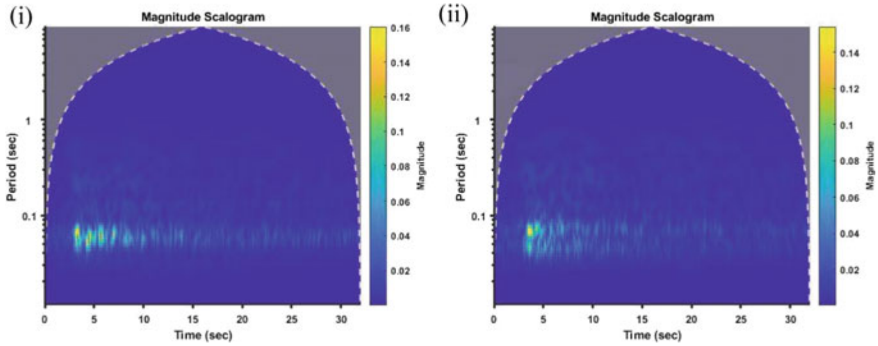

Fig. 12 CWT for Melli: (i) *R*, (ii) *T*

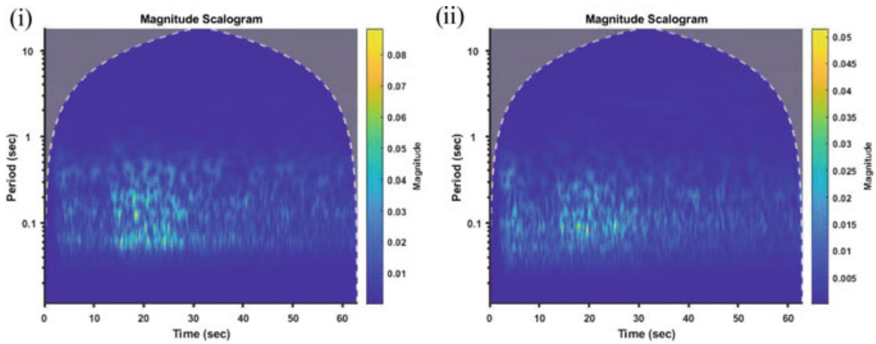

Fig. 13 CWT for Singtam: (i) *R*, (ii) *T*

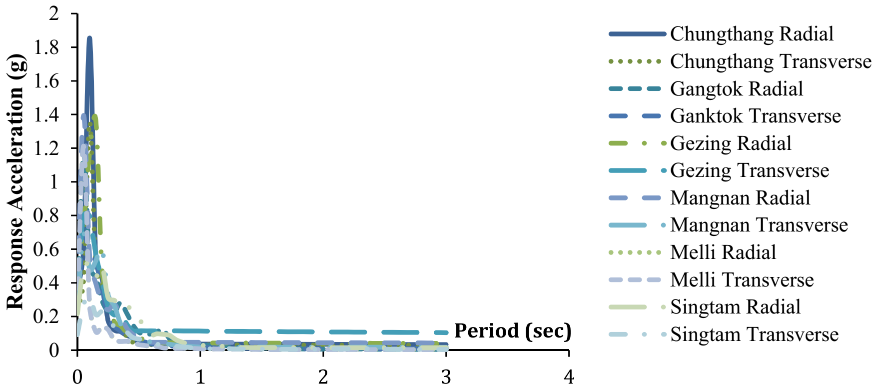

Fig. 14 Response spectra for six stations (*R* and *T* components)

due to this horizontal ground motion in Singtam town is also clearly corroborated with the observation from the reconnaissance surveys (rows 16, 17, Table 1). The CWTs of ground motions from Mangan town show high-amplitude waves having a period of 0.1–1.2 s. This is also clearly corroborated with the observed damage to 1 and 2 storey structures in Mangan town, as recorded in the reconnaissance survey (row 14–15, Table 1). Similarly, Gangtok town experienced multiple high-amplitude waves at various multiple frequencies causing damage to 1–4 storey structures (row 5–13, Table 1). In Chungthang town, the high-frequency–high-amplitude content was observed for a very short duration. Further, the response spectra as observed (Fig. 14) exhibit a peaky behaviour, corroborating the above observations. Overall, these observations indicate the high hazard to low-rise structures, prevalent in the region, which typically have low natural periods.

6 Summary and Conclusions

A massive Mw 6.9 earthquake struck the Himalayan state of Sikkim in India on 18th September 2011 causing severe damage to the built environment in several towns. In this paper, accelerograms recorded at six stations, which represent information in the time-domain, are analysed to obtain key characteristics, such as PGA, PGV, and AI of each ground motion. The response spectra of the horizontal ground motions from the six stations exhibit high peaks at very low periods and almost reduce to zero at a period of 1 sec. Fast Fourier Transforms (FFTs) of recorded ground motions from the six towns indicate that the frequency content mostly lay in the range of 0–20 Hz. The analysis of Continuous Wavelet Transforms (CWTs) correlates well with the observed damage to low-rise structures recorded in various reconnaissance surveys. It is observed that CWTs convey improved information about the destructive nature of earthquake waves as compared to the time domain or frequency domain representations.

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