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India's Earthquake Early Warning Systems: A Review of Developments and Challenges

Himanshu Mittal[1] · Shanker Pal[1] · Rajiv Kumar[1] · Atul Saini[1] · Yih-Min Wu[2,3] · Ambikapathy Ammani[1] · R. C. Patel[4] · Sandeep[5] · O. P. Mishra[1]

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Abstract

The risk of earthquakes and their effects on both nature and infrastructure in seismically active regions of India require adaptable and scalable earthquake early warning (EEW) systems. Developing a robust EEW system is crucial to mitigate earthquake risks in the region, but it is a challenging task. Various institutes have attempted to develop EEW systems using different methods. Still, there is no common consensus, and issues remain with response time and reliability of disseminated information to the public. Efforts by institutions like the Indian Institute of Technology, Roorkee, have advanced EEW technologies, focusing on dense seismic sensor networks, real-time data processing algorithms, and effective dissemination mechanisms. Recent initiatives aim to improve sensor sensitivity and accuracy through fast communication systems for quicker earthquake detection. However, challenges persist in making EEW accessible and affordable, particularly in remote areas, due to the lack of a nationwide system. The National Centre for Seismology (NCS), under the Ministry of Earth Sciences (MoES), is piloting an EEW system in the NW Himalayas, which could lead to a nationwide implementation. Developing region-specific algorithms for rapid data analysis and nurturing collaboration between academic institutions, government agencies, and international partners are crucial steps. Public awareness campaigns and educational programs are essential for community resilience and timely response to earthquake alerts. Establishing a robust EEW system in India could significantly enhance earthquake risk mitigation efforts in earthquake-prone zones of the country and should be viewed within the context of a holistic risk reduction framework. EEW systems can enhance mitigation efforts, but they must be complemented by other essential measures, such as improving building resilience and promoting public awareness.

Keywords Earthquakes · Nationwide EEW · NCS-MoES · IIT Roorkee

✉ O. P. Mishra
opmishra2010.saarc@gmail.com

[1] National Centre for Seismology, Ministry of Earth Sciences, New Delhi 110003, India

[2] Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan

[3] Institute of Earth Sciences, Academia Sinica, Taipei 11529, Taiwan

[4] Department of Geology, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India

[5] Department of Geophysics, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India

Article Highlights

- Key challenges include the lack of public awareness, rapid urbanization, and the need for dense sensor networks with reliable real-time data processing for effective earthquake warnings
- National Centre for Seismology (NCS), Ministry of Earth Sciences plans to have a pilot on EEWS in the Himachal Himalayan region with a robust network of force-balanced accelerometers (FBAs) instruments
- Joint collaborative research among different institutions of India and overseas with NCS is a need of hour to develop a robust and reliable nationwide EEWS under the Earthquake risk resiliency program

1 Introduction

The fundamental principle of earthquake early warning (EEW) systems is that seismic waves from earthquakes travel slower than communication signals, allowing for alerts of impending ground shaking if detected near the source. This concept was first proposed in 1868 by J.D. Cooper, who suggested placing seismic sensors near Hollister, California, to send signals via telegraph to San Francisco, though it was never implemented (Nakamura and Tucker 1988). The first operational EEW system was established in Japan in 1965 to protect Shinkansen trains using mechanical sensors every 25 km that cut power if dangerous shaking was detected, providing a one-second warning (Nakamura and Saita 2007). In 1982, Japan upgraded this system with the coast-line detection system, deploying sensors along the East Coast to give a 10-s warning for offshore earthquakes (Nakamura and Saita 2007). Mexico followed with the Sistema de Alerta Sísmica of Mexico City (SASMEX), proposed after the devastating 1985 M8.1 Michoacan earthquake (Cuéllar et al. 2014). Operational since 1991, SASMEX initially warned the Mexico City subway and schools of earthquakes off the Guerrero coast using a network of 12 stations. It became the first system to issue public warnings in 1993 and provided a successful 72-s warning for the 1995 M7.3 Guerrero earthquake (Lee and Espinosa-Aranda 2003).

EEW systems are designed to detect the initial seismic waves (*P*-waves) that travel faster than the damaging waves (*S*-waves) and provide a warning before the occurrence of destructive shaking. EEW systems can be broadly categorized into on-site systems and regional systems (Cremen and Galasso 2020). On-site early earthquake warning systems use one seismic sensor near critical infrastructure, such as power plants and hospitals, to detect incoming seismic waves and issue alerts. While these systems may not include specific details on the location or magnitude of an earthquake, they work very well for localized use cases. The regional EEW systems employ many stations spread over a region to estimate the location and magnitude of an earthquake, thereby sending alerts to areas where it is needed. The regional EEW system consists of several steps. A network of sensors placed strategically in earthquake-prone zones is used to detect the earthquake. Based on the arrival times of *P*-waves from multiple sensors, the system estimates the earthquake epicenter. The more the number of sensors detecting the event, the more precise will be the location estimation (Satriano et al. 2011). After detecting the event at 5–6 stations, the system estimates the magnitude using the amplitude of the seismic waves. After estimating location and magnitude, the EEW system predicts the intensity of ground shaking at varying distances from the epicenter. The prediction models take into account various

factors such as soil type, topography, and historical seismic activity to enhance the accuracy (Wang et al. 2018). The system evaluates the predicted ground shaking against predefined thresholds to determine whether an alarm should be triggered. This decision-making process may include additional data analysis to confirm the characteristics of earthquakes and minimize false alarms. The system disseminates warnings through various channels, including radio, television, emails, websites, SMS messages, and smartphone applications, ensuring swift and comprehensive communication.

The EEW system can also generate shakemaps, which visually represent the distribution and intensity of ground shaking across the affected region (Wald et al. 1999; Legendre et al. 2017; Mittal et al. 2018, 2019a). These maps, continuously updated with data from seismic stations, are provided to emergency responders and disaster mitigation agencies to facilitate the organization and prioritization of relief efforts (Wu et al. 2016; Wu and Mittal 2021). Shakemaps also offer insights into the rupture direction, aiding agencies in anticipating the most severely affected areas (Wu et al. 2019; Mittal et al. 2021; Yang et al. 2023).

Lead time is one of the key features when talking about EEW systems, which defines the elapsed time between the warning issued and the arrival of damaging seismic waves. This warning time is the lead time available to taking steps such as slowing high-speed trains, shutting down industrial machines, or donning personal protective equipment. The lead time can take anywhere from a few seconds to a few minutes, depending on the distance from the earthquake epicenter. Locations farther away from the epicenter usually have more lead time in advance enabling them to adopt some measures before arrival but have less strong shaking. Similarly, there are regions close to the epicenter which get very short response time with more intense shaking. Lead times themselves do not directly ensure accuracy in EEW systems. Instead, they provide critical time for collecting additional seismic data from the propagating waves, enabling iterative refinements in calculations. This process allows for more precise estimates of earthquake parameters such as magnitude, location, and expected ground motion, thereby improving the overall reliability of the warning.

EEW systems face challenges, such as the blind zone near the epicenter, which refers to the area near the earthquake epicenter where no early warning can be provided due to the immediate arrival of damaging seismic waves. In these regions, the time between the detection of seismic activity and the arrival of destructive waves is too short to issue a useful alert. This zone grows with every additional second of transmission and processing time. This limitation underscores the importance of a dense seismic sensor network and rapid data processing capabilities to minimize the size of the blind zone. The on-site EEW systems are critical for handling the problem of blind zones, where the ground shaking is high (Wang et al. 2022). The on-site EEW systems issue the warning once the predefined thresholds are exceeded. Not all EEW systems are designed to estimate both location and magnitude, especially on-site systems, which primarily detect local seismic activity to trigger warnings without providing detailed information on location or magnitude. However, relying on a single fixed-threshold indicator can lead to significant inaccuracies.

In recent years, several comprehensive reviews have been published that summarize the progress and challenges in EEW systems worldwide. Allen and Melgar (2019) provide a detailed account of the latest developments in global EEW systems, emphasizing the importance of algorithmic advancements and real-time data transmission. Similarly, Cremen and Galasso (2020) critically reviewed the current approaches, advancements, and limitations of EEW systems worldwide. The paper highlights the importance of using engineering-based risk and resilience metrics to enhance decision-making in EEW systems and

discusses the potential improvements for future EEW systems, suggesting a shift toward more probabilistic and user-oriented frameworks to better address uncertainties and stakeholder needs. Wald (2020) detailed the challenges and practical limitations of implementing EEW systems. It emphasizes that while EEW can provide critical warnings to mitigate earthquake risks, there are inherent limitations in accuracy, lead time, and communication latency, especially for large, near-epicenter earthquakes.

In 1988, Japan introduced the Urgent Earthquake Detection and Alarm System (UrEDAS), the first with a P-wave detector, which could send a warning within three seconds of *P*-wave arrival (Nakamura and Saita 2007). Further advancements in estimating earthquake magnitude and location were made with methods such as the B-Δ method (Odaka et al. 2003), leading to more accurate early warnings. In 2007, Japan launched a comprehensive EEW system using over 1000 stations, capable of determining earthquake location and magnitude within seconds and delivering warnings through various media (Hoshiba et al. 2008). This system was significantly improved after the 2011 Tohoku earthquake (Kodera et al. 2021).

Following the success of Japan, Taiwan, South Korea, the USA and other countries developed similar systems. The EEW system of Taiwan evolved from email alerts within a minute to warnings within 10–20 s by 2013, using micro-electromechanical system (MEMS) sensors (Wu et al. 2013). South Korea and the USA have public EEW systems, while India, Romania, and Turkey have operational systems for specific users (Kumar et al. 2024; Sheen et al. 2017; Patel and Allen 2022; Ionescu et al. 2016; Erdik et al. 2003).

In Taiwan, the Central Weather Administration (CWA) is responsible for the official EEW. The first EEW system, VSN, was deployed in 2000 with 110 stations, including an ocean-bottom seismometer, providing alerts via mobile phones with a reporting time of 22 s (Wu and Teng 2002). Since 2012, the system has expanded to over 600 stations and now offers timely warnings to regions more than 40 km from an earthquake epicenter (Wu et al. 2021). The eBEAR system, based on Earthworm processing modules, uses peak *P*-wave displacement (Pd) for magnitude estimation and can locate epicenters using Geiger's method and an effective epicenter method to reduce warning times (Chen et al. 2019). For earthquakes over magnitude 5 since 2014, eBEAR has provided parameters with an average error of 4.1 km for epicenters and 0.27 magnitude units, with an average warning time of 17.3 s and no false alarms.

The P-Alert system of National Taiwan University features 751 MEMS accelerometers installed in elementary schools, providing on-site warnings if a 0.08 g threshold is exceeded. During the 2016 Meinong earthquake, on-site warnings ranged from 2 to 8 s in the epicentral region (Wu et al. 2016). Data are also sent to NTU for real-time shake mapping and dissemination (Wu et al. 2019). The real-time shake maps are plotted and sent once a minute to the National Science and Technology Center for Disaster Reduction (NCDR) for relief purposes and are distributed on social media (Yang et al. 2021, 2023; Mittal et al. 2022; Wu et al. 2023). The National Center for Research on Earthquake Engineering (NCREE) supplements the CWA system with on-site EEW at 3514 schools, using a satellite approach where alarms sound based on the fastest warning from either system (Hsu et al. 2021). Using the support vector machine method, it predicts peak ground acceleration (PGA) and significantly reduces blind zones, as demonstrated during the 2019 Hualien earthquake (Hsu et al. 2013).

Many countries have tested EEW systems, and new algorithms are continually being developed. Machine learning techniques, such as generative adversarial networks (GANs) and convolutional neural networks (CNNs), have improved real-time phase discrimination and are likely to be integrated into EEW systems soon (Li et al. 2018;

Meier et al. 2019). Advanced algorithms like PRESTo in Italy and Virtual Seismologist in Switzerland enhance point-source location speed and incorporate probabilistic approaches to account for location uncertainties (Satriano et al. 2010; Cua et al. 2009).

One challenge in magnitude estimation from the initial *P*-wave arrival is saturation for large earthquakes. The FinDer algorithm, used in the ShakeAlert system of the USA, matches early waveforms to synthetic models to estimate magnitude (Böse et al. 2018). Other methods use dynamic window lengths or Global Navigational Satellite System (GNSS) instruments for improved magnitude estimation (Crowell et al. 2018; Kawamoto et al. 2017; Minson et al. 2014).

The Earthquake Network project, launched in 2013, leverages smartphone accelerometers for a global, crowdsourced EEW system. Despite limited warning reach during the 2019 Peru earthquake, it shows great potential, especially with government support (Finazzi and Fassò 2017; Laure et al. 2022). Android Earthquake Alerts system of Google, introduced in 2020, uses smartphone sensors to detect and alert users of earthquakes, now covering regions like New Zealand, Greece, Turkey, and the Philippines (Allen and Stogaitis 2022).

Many facilities use autonomous, on-site systems, such as seismic switches, to activate alarms or control infrastructure during seismic events. These systems, widely used in lift control, gas shut-off, and electricity shut-off, generally do not feed data into regional EEW systems (e.g., Seismic Switch Inc., MBS Engineering). However, integrating on-site EEW systems with regional systems is possible, offering valuable supplementary coverage, especially in blind zones (Wu et al. 2021).

The entire Indian subcontinent, including the Himalayan belt extending from Jammu and Kashmir in the north to Arunachal Pradesh in the east, along with intraplate seismic regions and Andaman–Nicobar regions, stands to benefit greatly from EEW implementation. Northern India, in particular, is an ideal region for such an EEW system (Kumar et al. 2014). This is because the sources of large earthquakes are in the Himalayas, while many people and big industrial hubs, including the capital city, Delhi, are located in the nearby plains. The high population density and poor construction practices in these areas make them vulnerable to earthquakes. Various works (Khattri 1987; Kumar et al. 2006) have identified parts of Uttarakhand and Himachal Pradesh in the Central Himalayas as areas where large earthquakes (over magnitude 7) are likely to happen (Fig. 1). Studies (Joshi and Sharma 2011; Mittal et al. 2013, 2015) show that a major earthquake in this area would cause strong shaking in Delhi, about 300 kms away. Many densely populated cities and villages between Delhi and the Himalayas would also be heavily affected. If a large earthquake occurs in the Himalayas, these places could have a few to 90 s of warning before the damaging waves arrive (Bhardwaj and Sharma 2018). The areas receiving maximum warning time are likely to experience lesser ground shaking due to wave attenuation. For instance, in regions receiving a 90-s warning from the IIT Roorkee system during a magnitude M_w 6.5 event, the expected peak ground acceleration (PGA) might range between 0.05 and 0.1 g. This reduced level of shaking may disrupt sensitive systems and allow individuals to take precautionary measures. Using this real-time information effectively could greatly reduce injuries and damage. Therefore, a strong EEW system is essential for reducing the impact of earthquakes in northern India. Such a system could help minimize the devastating effects of large earthquakes in this vulnerable region, playing a key role in disaster mitigation.

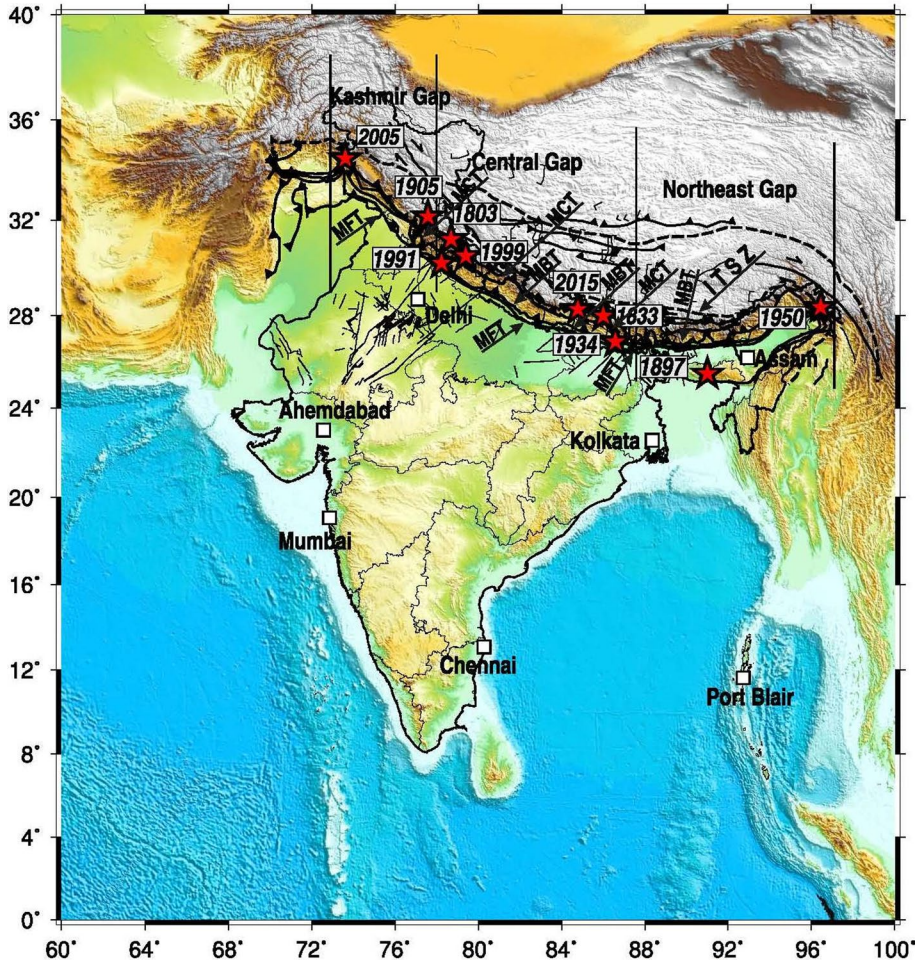

Fig. 1 The tectonic map of the Himalayas. Key tectonic features include the Main Frontal Thrust (MFT), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and the Indus-Tsangpo Suture Zone (ITSZ). The location of historical earthquakes along with seismic gaps is shown

2 Seismotectonics

The seismic activity in India is a direct consequence of its position at the crossroads of multiple tectonic processes. Understanding these complexities through seismic hazard assessments, robust monitoring networks, and proactive disaster preparedness efforts is vital to mitigate the impact of earthquakes and tsunamis on vulnerable populations and infrastructure across the nation Seismicity in India is influenced by various tectonic processes occurring across different regions of the country.

Himalayan Collision and Subduction: The Indian Himalayas are one of the seismically active regions of the world. Northern India, including the Himalayas and Indo-Burma, experiences frequent earthquakes due to the ongoing collision of the Indian and Eurasian

Plates. The collision of the Indian and Eurasian continental plates has caused the Indian plate to subduct beneath the Eurasian plate. Following this collision, the Indian plate has been moving northward at an average rate of about 50 mm per year (Bilham et al. 2003). As the Indian Plate pushes northward, it has driven the rise of the Himalayas and Tibetan Plateau. Key tectonic features include the Main Frontal Thrust (MFT), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and the Indus-Tsangpo Suture Zone (ITSZ) (Fig. 1). The ITSZ dips southward, while the MCT and MBT dip northward (Khattri and Tyagi 1983; Gupta and Gahalaut 2015). The MCT, the oldest thrust system, was active in earlier periods, whereas the MBT currently exhibits active thrusting. Simultaneously, the leading edge of the Indian Plate subducts beneath the Eurasian Plate along the MFT. The MFT is the southernmost and youngest thrust system (Kumar et al. 2001). These combined forces, collision, and subduction, generate frequent earthquakes, including high-magnitude events like the devastating 1905 Kangra and 2005 Kashmir earthquakes that caused extensive damage and loss of life. The recent Nepal earthquake on April 25, 2015, with a magnitude of 7.6, caused significant economic losses. Despite no major earthquakes (magnitude 8 or above) occurring in the Himalayas since the 1950 Assam earthquake, the region remains highly vulnerable. Researchers have identified various seismic gaps, regions where significant earthquakes are anticipated (Stevens and Avouac 2015). These include the Kashmir seismic gap, the central seismic gap, and the northeast seismic gap, among others.

Peninsular Intraplate Activity: While less frequent compared to the north, the peninsular region of India, situated within the stable interior of the Indian Plate, also experiences earthquakes. These intraplate events are primarily linked to faults and zones of inherent crustal weakness, such as the Central Indian Tectonic Zone (CITZ) and the Eastern Ghats Mobile Belt (Biswas and Chauhan 2022). Earthquakes in this region tend to be of lower magnitude but can still cause significant damage to infrastructure and communities.

Andaman–Nicobar Subduction Zone: The Andaman and Nicobar Islands, custodians in the Andaman Sea, lie close to the convergence zone between the Indo-Australian Plate and the Eurasian Plate. This region experiences frequent earthquakes due to subduction processes along the Andaman–Sumatran subduction zone (Kayal et al. 2004). The subduction generates both intraplate and interplate earthquakes. These earthquakes, particularly the interplate events, have the potential to trigger tsunamis that threaten coastal areas of the Andaman–Nicobar Islands and surrounding regions.

3 EEW System India

The Indian region, particularly the West Himachal Pradesh seismic gap and Uttarakhand–Dharchula seismic gap, parts of the central seismic gap (Fig. 1), have not experienced any major earthquake in recent recorded history (Kumar et al. 2023a). However, the region is undergoing rapid urbanization, settlement, and infrastructure development. According to the 2011 census, the Indian Himalayan region has a population of around 52.8 million, projected to exceed 260 million by 2061. A major earthquake in the central seismic gap could result in thousands of casualties and significant economic losses.

Recognizing the high seismic risk, a nationwide EEW system is needed for the India region. Indian Institute of Technology (IIT), Roorkee, is the first institute to establish EEW on a pilot basis in one of the parts of the Uttarakhand Himalayas, covered under the Uttarakhand–Dharchula gap (Kumar et al. 2024). Initially, a feasibility study was conducted to explore available solutions. This led to the establishment of the first Indian regional EEW

system, the Uttarakhand Earthquake Early Warning System (UEEWS). Recognizing the need for EEW, the other institutes are also participating in developing the EEW for different regions.

3.1 EEW System by IIT Roorkee

The establishment and maintenance of a 300-strong-motion network across the Himalayas from 2005 to 2015, spanning from Jammu and Kashmir in the north to Arunachal Pradesh in the east, laid the groundwork for EEW in India. India is divided into four seismic zones, Zone II, III, IV, and V, based on the level of seismic risk, with Zone-V being the most seismically active. The Himalayan region, parts of the Northeast, Gujarat, and the Andaman and Nicobar Islands fall under Zones IV and V, indicating high vulnerability to earthquakes, while other regions face moderate-to-low risk (BIS 2016). The network of 300 instruments, which covered seismic zones IV and V, as well as some densely populated areas of Zone III, has provided invaluable data (Mittal et al. 2006; Kumar and Mittal 2018). This datum has been instrumental in developing ground motion prediction equations (GMPEs), strong ground motion simulations, and hazard scenarios. By analyzing the recorded data, it was conceptualized that if sensors are densely placed along the Himalayan belt and a strong earthquake occurs, the recorded data could be used to issue warnings to the highly populated areas in the plains. Depending on the distance between the source zone and the target region, these warnings could provide lead times ranging from a few seconds to 90 s.

To leverage the extended warning times for the plains from earthquakes originating in the Himalayas, the Ministry of Earth Sciences (MoES), Government of India, approved a project titled "Development of Earthquake Early Warning System for Northern India" for the Centre for Excellence in Disaster Mitigation and Management at the Indian Institute of Technology, Roorkee (Kumar et al. 2014). As part of this project, approximately 100 sensors were to be installed in the Garhwal Himalayas of Uttarakhand, with an interstation spacing of 15–20 km. The primary objective of this instrumentation, covering an area of 100 by 40 km, was to provide warnings to the plainer regions located hundreds of kilometers away from earthquakes occurring between the Main Boundary Thrust and the Main Central Thrust, situated in the central seismic gap. Initially, after beginning the installation in 2014, around 80 instruments were installed at various locations and connected to the central receiving station at Roorkee (Kumar et al. 2022a, b). This was accomplished using the State Wide Area Network (SWAN) and the state-owned telecommunication network, Bharat Sanchar Nigam Limited (BSNL). Testing showed that neither network introduces more than 1.5 s of latency (Chamoli et al. 2021) (Fig. 2).

The project received a significant boost when the Uttarakhand Government provided additional funding, allowing for further installations. With this funding, it was proposed to instrument the entire Uttarakhand region, including both the Garhwal and Kumaon Himalayas. Currently, the system consists of 170 accelerometers, known as P-Alert MEMS instruments, sourced from the National Taiwan University (NTU), Taiwan (Kumar et al. 2024). Most of these instruments are installed in government-owned buildings, preferably one or two-story structures, belonging to BSNL and SWAN. The government of Uttarakhand officially launched this fully operational system for public use on August 4, 2021(Kumar et al. 2024).

Receiving real-time data from field instruments at the central receiving station in Roorkee, estimating source parameters, and issuing warnings based on magnitude or intensity

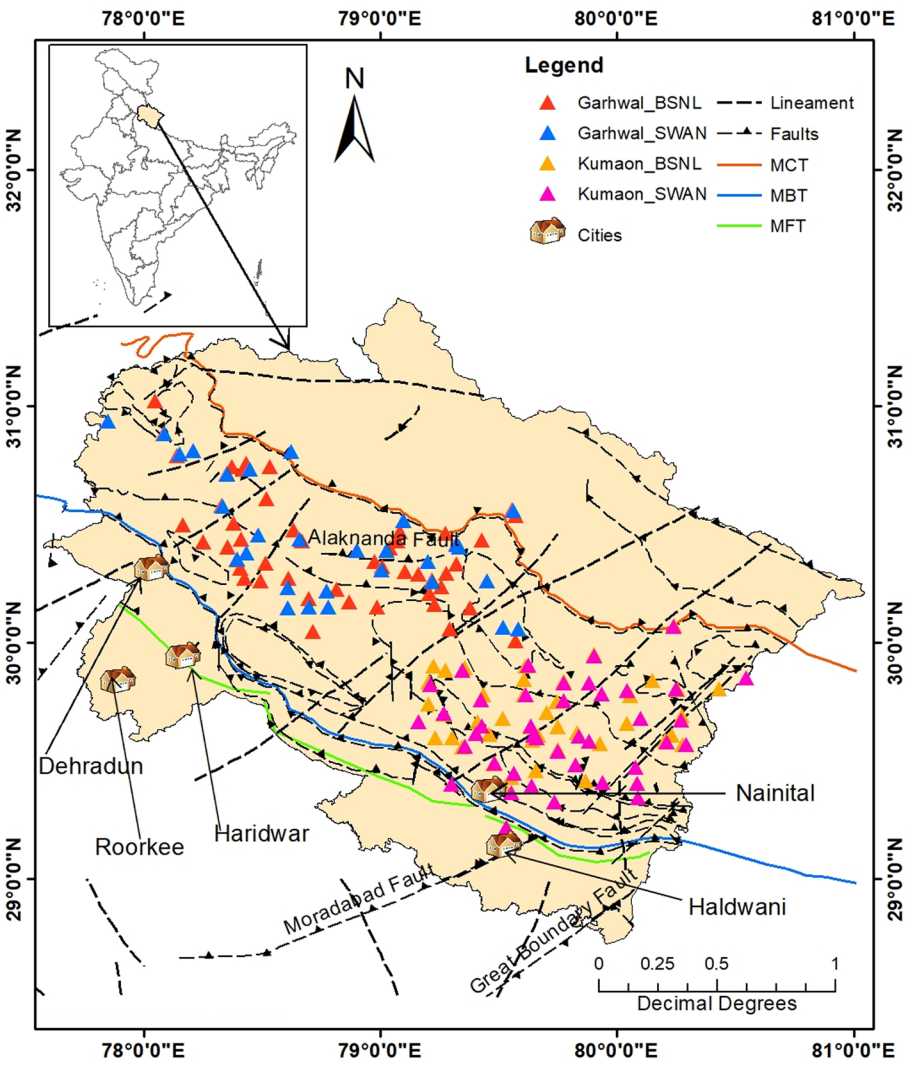

Fig. 2 The EEW network of IIT Roorkee. The network consists of around 170 sensors placed in the Uttarakhand region of the Himalayas (Kumar et al. 2024)

will help distant areas benefit from the EEW network. However, this process takes time, and by that time the damaging S-waves may have already reached a distance, where no warning is possible (blind zone). To address this issue and fully utilize the instrumentation in both the source region and farther areas, it was decided to procure instruments capable of serving both regional and on-site warning purposes. For this purpose, *P*-Alert MEMS instruments were acquired, which not only transmit acceleration data but also continuously perform double integration, enabling the use of peak displacement (Pd) and peak ground acceleration (PGA) as local trigger parameters (Wu 2015). The *P*-Alert sensor records three-component acceleration data at a 16-bit resolution and a sampling rate of 100 Hz,

spanning a full dynamic range of ± 2 g. It comes equipped with a pre-installed 10 or 20-Hz low-pass filter to lessen high-frequency noise interference originating from the sensor itself. Data processing at Roorkee is managed using Earthworm, with specific modules developed in Taiwan for the eBEAR system (Chen et al. 2015, 2019). Magnitudes are estimated based on Pd over the first three seconds of data (Hsiao et al. 2011). However, magnitudes estimated for the significant earthquakes recorded thus far have been lower than expected, indicating that the empirical relationship developed for Taiwan requires adjustment for local conditions (Chamoli et al. 2021).

Currently, the system is designed to issue warnings for any earthquake with a magnitude greater than M5.5. These warnings are disseminated via a smartphone app. Sirens are installed at field stations and within the IIT Roorkee campus, which provided a 25-s warning for the M5.5 Rudraprayag earthquake in 2017. Since becoming fully operational, the system has successfully detected and issued notifications and warnings for 10 earthquakes between September 2021 and January 2023, utilizing mobile app notifications and siren alerts (Kumar et al. 2023b). At present, the system relies solely on the algorithm developed by IIT Roorkee by modifying the algorithms designed for the *P*-Alert system of Taiwan. However, limited research has been conducted to explore other potential parameters and algorithms that might be more suitable for specific geological conditions of India. The accuracy of the EEW system is directly tied to the algorithms used for early detection. In the case of the Taiwan P-Alert system, the performance of the algorithm was evaluated based on how well it predicted ground shaking, with a specific focus on minimizing false negatives (failing to issue a warning) and false positives (issuing a warning when one is not needed). The current testing of EEW systems in India has shown some promising results, with early warnings successfully issued for four moderate-magnitude earthquakes over the past year. However, to further enhance accuracy, comprehensive testing will be conducted, utilizing data from historical seismic events and future occurrences to refine the models continuously.

3.2 NCS-MoES Instrumentation and Planned EEW

India has a comprehensive seismological network to monitor and study seismic activity across the country. This network plays a crucial role in earthquake detection, seismic research, and public safety. The National Centre for Seismology (NCS), under the Ministry of Earth Sciences (MoES), serves as the primary authority for continuous earthquake monitoring in India and its surrounding regions, operating on a 24/7 basis (Bansal et al. 2021). Initially equipped with 84 continuous stations in 2014, NCS has expanded its network to include 160 permanent seismological observatories (Fig. 3). While officially tasked with tracking earthquakes within a 4000-km range, the advanced equipment of NCS boasts the potential to detect moderate and strong earthquakes even further. This enhanced reach provides valuable insights into regional seismic activity and contributes to global earthquake monitoring efforts. A denser network increases the number of sensors, allowing for more precise detection and location of earthquakes, even smaller ones. This leads to faster and more accurate warnings, giving people crucial seconds to prepare for tremors. More data translates to a better understanding of earthquake sources, including fault characteristics, rupture patterns, and wave propagation. This information is vital for refining earthquake prediction models and hazard maps, ultimately leading to better preparedness. NCS collaborates with international organizations and neighboring countries for seismic monitoring and research. This cooperation includes sharing seismic data, participating in regional and

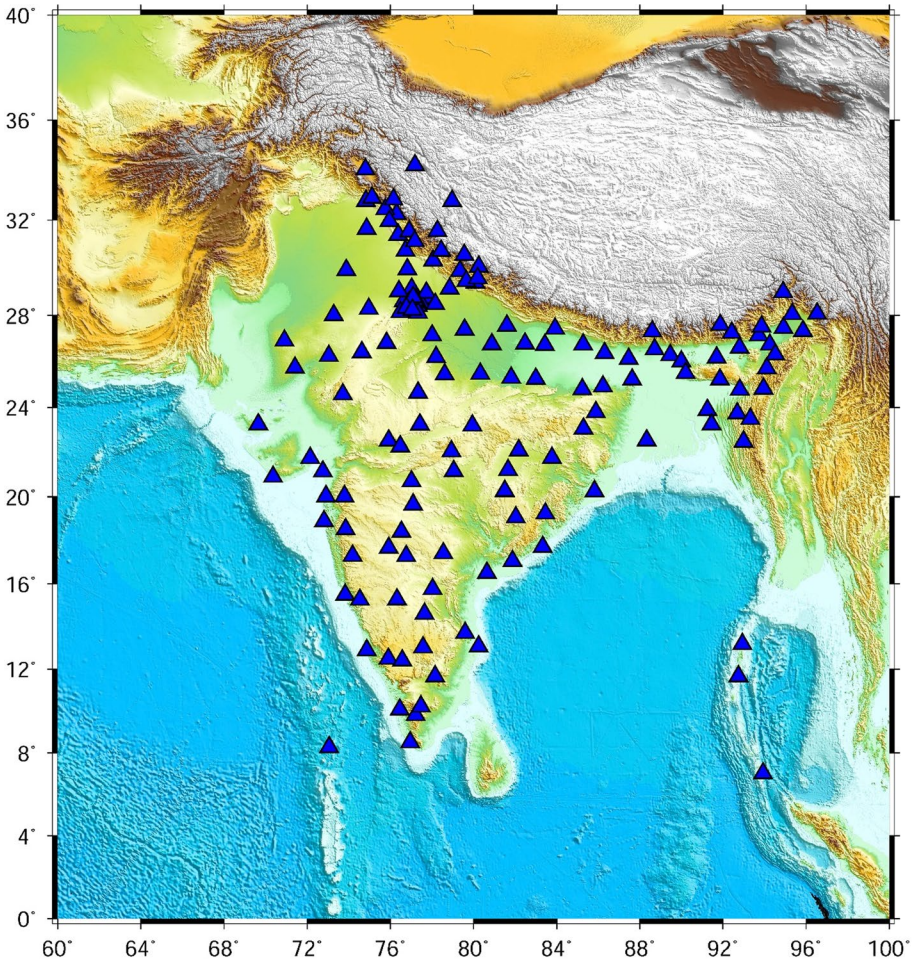

Fig. 3 The NCS network consists of 160 co-located broadband and strong-motion instruments

global seismic networks, and contributing to international efforts for earthquake research and hazard mitigation. Over the years, the increased number of instruments has drastically reduced the time required to estimate earthquake parameters such as the epicenter, origin time, and magnitude. What once took over an hour to inform the public about the source parameters of an earthquake can now be determined in an average of less than 8 min. This improvement is a significant rise in the ability of NCS to quickly and accurately detect seismic events. The first message is received by the authorities within one to two minutes; however, it takes approximately 8 min to estimate the source parameters and inform the public about the location and magnitude of the event. This 8-min timeframe is not aligned with the requirements of an EEW system, which necessitates rapid and real-time dissemination of information to minimize potential impacts.

To better protect lives and infrastructure, NCS plans to develop an EEW system. This system is supposed to consider various factors, including earthquake magnitude, depth, location, and potential ground effects. Initially, the system will be tested in a pilot region of

the northwest Himalayas, and based on the success, the system will be expanded to other locations.

The NCS evaluated regions for piloting the EEW system, observing the operational EEW in Uttarakhand, managed by IIT Roorkee, with about 170 MEMS sensors covering the Seismic Zone-V area. Based on research indicating strain energy accumulation in the Central and Western Himalayas, the NCS identified Himachal Pradesh as a key region due to its geological features and seismic risk, including the MCT, MBT, and neo-tectonic faults. The high-risk seismic Zone-V and Zone-IV status of Himachal Pradesh, historical seismicity, and seismic gap further supported this choice. To optimize detection, 15-km interstation spacing was decided considering factors like PGA decay, seismic activity, and a magnitude 5.0 threshold. This setup, assuming significant earthquakes have a focal depth of less than 15 km and a blind zone radius under 20 km, requires around 150 stations (Fig. 4) within 31°N to 33°N latitude and 76°E to 78°E longitude, subject to consultation with Himachal Pradesh State Government authorities. NCS plans to begin the project with the installation of force-balanced accelerometer (FBA)-based strong-motion accelerographs (SMA) initially. In a later stage, MEMS sensors, postholes, boreholes, displacement, and GNSS instruments will be added.

The warning times depend on various factors like earthquake location, network configuration, and station density. Engagement with the highest authorities of the Himachal Pradesh State Government is crucial for securing support and suitable sites. Communication for data transmission must have minimum latency (0.01 ms), excluding satellite options. Involvement of BSNL, or other agencies, is recommended to ensure robust, high-speed connectivity. Reviewing global EEW System software including the PLUM model of Japan, the Shake Alert of USGS, τ_c, and the P_d approach of Taiwan revealed no

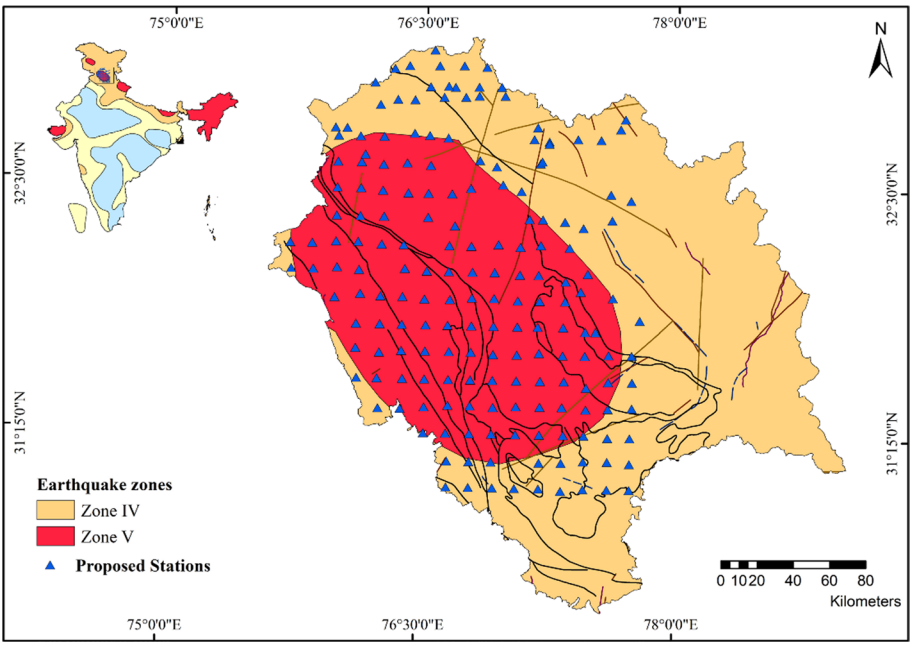

Fig. 4 The proposed locations of the NCS network in Himachal Pradesh. The locations will be reduced to approximately 150 based on the logistics

off-the-shelf EEW software. The 24 × 7 Operational Centre of NCS employs SeisComP for rapid earthquake parameter analysis. Any software should be able to handle real-time location, magnitude, expected intensity, and projected damage, leveraging the Virtual Seismologist (Bayesian approach), and the Finite-Fault Rupture Detector but requires customization for India. In the pilot phase, the warning will be disseminated to the authorities using controlled SMS, mobile apps, or sirens. In the later phase, the warning will be issued to the general public after the system becomes robust.

Ground motion prediction equations (GMPEs) are fundamental to the accuracy of EEW systems, as they are used to estimate the expected ground shaking intensity based on the earthquake magnitude, depth, and distance from the epicenter (Kumar et al. 2017; Vandana et al. 2024). In the proposed EEW system for India, the GMPEs are being developed based on data from several regional seismic events, but the accuracy of these equations is a critical factor in the reliability of the warnings. Testing and validation of these GMPEs are currently underway, using data from recent earthquakes to ensure they provide accurate predictions of ground motion. Specifically, in cases where warnings have been successfully issued by the IIT Roorkee network, we are analyzing the predicted versus observed shaking to improve the model. For example, during recent field tests of the Taiwan P-Alert system, instances of magnitude underestimation within the range of 0.3 to 0.5 were observed. To address this, we are refining the real-time magnitude estimation algorithm by optimizing its parameters. Additionally, we are adjusting the GMPEs to account for potential biases introduced by the initial magnitude estimates, ensuring accurate ground motion predictions.

3.3 Planned EEW by ISR

The industrialization and urbanization of Gujarat, combined with its seismic history and geographical location, emphasize the importance of comprehensive risk mitigation strategies to enhance resilience against earthquakes and other natural disasters. Efforts to integrate urban planning, infrastructure development, and disaster management are essential for safeguarding lives, livelihoods, and economic assets in the region. The Kachchh region, in particular, has a significant seismic history, with two major destructive earthquakes occurring over nearly two centuries. The 1819 Allah Bund earthquake, with a magnitude of Mw 7.8, and the 2001 Bhuj earthquake, with a magnitude of Mw 7.7, caused extensive damage to life, property, and infrastructure in the region (Rastogi 2001). The Institute of Seismological Research (ISR) plays a pivotal role in advancing seismological science, monitoring seismic activity, and promoting earthquake resilience in the earthquake-prone region of Gujarat. The institute is equipped with state-of-the-art seismological instruments, including seismometers, accelerometers, GPS stations, and other geophysical equipment (Chopra et al. 2008). These instruments are deployed across the Gujarat region to monitor seismic activity continuously. The institute provides crucial support to the disaster management authorities of Gujarat by offering timely and accurate information on seismic activity, conducting risk assessments, and helping formulate strategies for disaster preparedness and response. The ISR is running some EEW instruments including FBA-based SMAs on a test basis. In the future, ISR aims to introduce an EEW system designed for urban areas, particularly Ahmedabad, with a specialized focus on earthquakes originating from the Kachchh region of Gujarat. The data collected from the existing network of SMAs and Broadband sensors is used for fine-tuning the algorithms. Initially, the network will use the existing network for designing the network and later it will be densified. In addition to regular algorithms involving τ_c and the P_d approach, the researchers are exploring the use

of machine learning algorithms for magnitude estimation. The warning is supposed to be disseminated using mobile apps, SMS, and sirens. The new EEW system can be a big help during earthquakes by giving people in cities like Ahmedabad a few seconds to a couple of minutes before shaking starts. While the level of shaking at farther distances may not cause significant structural damage, it can still disrupt sensitive systems and allow individuals to take precautionary measures. This is super important because cities are getting bigger and more crowded, especially Ahmedabad, which means earthquakes can be even more dangerous. So, having this warning system can make a difference in keeping people safe.

3.4 Few EEW Instruments by NDRF

The National Disaster Response Force (NDRF) in New Delhi is involved in monitoring three on-site earthquake alert systems installed in 2018 in association with real-time data provided by NCS-MoES, India. These systems are located at the NDRF Headquarters in New Delhi; 08 Bn-NDRF in Ghaziabad; and the RCC in Dehradun. Each system consists of three integral components: a master detector, a redundant sub-master detector, and a siren for issuing alerts and shutting off utilities that are made to be robust. The master detector includes an electronic 3-axis sensor and is configured to trigger at an earthquake intensity threshold of V. The main unit is also equipped with an SMS/email alert module. Since these three systems contribute to on-site alerts at different locations, they sense ground motion, and once the intensity (obtained from recorded ground motion) exceeds the predefined threshold of V, the alert gets activated.

3.5 Metro EEW System by CSIR-CSIO

In 2015, the CSIR-Central Scientific Instruments Organisation (CSIO) installed five accelerometers at strategic locations within the Delhi Metro system: Mundka, Metro Bhawan, Botanical Garden, Huda City, and Faridabad. These accelerometers are connected via a local area network (LAN) to a central control point, which monitors seismic activity. When acceleration thresholds are exceeded, the system triggers a range of responses, from sending SMS alerts to staff to generating audio-visual alarms. Each node detects seismic events and sends signals to the central control, which then issues an alert based on the combined data from all nodes. This setup enhances the safety and preparedness of the Delhi Metro system against earthquakes (https://www.csio.res.in/upload/PDF/earthquakewarning.pdf).

3.6 EEW by Other Organizations

Several organizations, including the Haryana Institute of Public Administration (HIPA) in Gurugram and the Disaster Mitigation and Management Centre (DMMC) in Dehradun, have implemented on-site early warning systems within buildings by installing FBA or MEMS sensors. However, standardized specifications, technical expertise, and validation through peer-reviewed studies or real earthquake case studies for such systems in India remain unavailable in the public domain.

3.7 Indian Tsunami Early Warning Centre (ITEWC)

Apart from the EEW system, there is also the Indian Tsunami Early Warning Centre (ITEWC), which operates under the Indian National Centre for Ocean Information Services (INCOIS) in Hyderabad (Srinivasa Kumar and Manneela 2021). This center keeps an eye on the Indian Ocean using data from 400 stations contributed by different countries, including 17 stations in India from the NCS network. When an earthquake happens, ITEWC can detect it within 10 min and send out alerts, especially focusing on how close it is to the coast. If the earthquake is far away, they wait for data from buoys to confirm if there is a tsunami before they sound any alarms. They spread these alerts using SMS, email, mobile apps, and social media. There is also good progress in making communities ready for tsunamis. Noliasahi village in Jagatsinghpur district, and Venkatraipur village in Ganjam district, both located along the coast of Odisha, have achieved a significant milestone. They have been recognized as the first two 'Tsunami Ready' villages in the entire Indian Ocean Region. This recognition comes from the Intergovernmental Oceanographic Commission (IOC) of UNESCO, acknowledging the high level of preparedness demonstrated by the local communities in these villages to deal with tsunamis. They have sirens installed, and people there are well-prepared and know what to do in case of a tsunami. (https://india.mongabay.com/2020/08/indias-first-two-tsunami-ready-villages/).

4 EEW Research in the Indian Scenario

EEW studies started around 2009 at IIT Roorkee and other institutes. To ensure that the algorithms used in the planned EEW systems are sufficiently accurate, extensive testing is essential. This testing will involve running simulations using both synthetic and real seismic data, as well as testing the ability of the system to predict ground motion for both small and large earthquakes. During these tests, the algorithm precision will be evaluated in estimating magnitude, location, and intensity, comparing the predictions against observed data. A particular focus will be placed on minimizing the underestimation of magnitudes, which can lead to insufficient warnings. Data from regional seismic networks, including strong-motion records from past earthquakes, will be used to calibrate and validate the algorithms before full deployment. Some of the works have been carried out using data from past earthquakes in India and data from other regions of the world. Here is a description of some of the works.

Bhardwaj et al. (2010) developed a simple and robust algorithm for detecting the *P*-wave onset of earthquakes using a time-domain cumulative absolute velocity (CAV) threshold. CAV, defined as the integral of absolute acceleration, was calculated using a three-second sliding window. The algorithm was tested on 546 earthquake records from the K-Net database of Japan and 43 records from the strong-motion network of India. The study found that a difference in CAV of 0.1 cm/sec between adjacent windows could effectively identify the P-onset. The algorithm achieved an error margin of less than 0.1 s for about 70% of the Indian data set and 90% of the Japanese data set. Post P-onset detection, the algorithm evaluated a 5-s CAV window to issue earthquake warnings. Kumar et al. (2014) discussed the initial phase of the EEW system of IIT Roorkee. Bhardwaj et al. (2016) focused on developing a multi-parameter-based EEW algorithm to enhance the accuracy and reliability of real-time earthquake warnings. This algorithm uses multiple parameters, including

maximum predominant period (Tmax), average period (τc), peak displacement (Pd), CAV, and root sum of squares cumulative velocity. Various combinations of these parameters were tested to optimize the alarm issuance, which refers to minimizing both false positives and false negatives. A false positive occurs when a warning is issued without an actual earthquake, causing unnecessary alarm, while a false negative is when no warning is issued despite the occurrence of a significant earthquake.

In the absence of too much recorded data, Mittal et al. (2019b) evaluated the effectiveness of an EEW system in India using data from the extensive P-Alert network in Taiwan. The P-Alert network has proven successful in issuing on-site warnings and generating shakemaps. In contrast, the IITR network of India, with 170 P-Alert systems in the northern Himalayas, has not yet recorded any significant earthquakes. To test the EEW system, Mittal et al. (2019b) mapped the coordinates of the P-Alert systems of Taiwan onto the Indian coordinate system and transformed the locations of Taiwanese earthquakes (magnitude > 5.5) to fit the Indian context. They used Earthworm software to play concatenated pre-recorded earthquake data and tested the algorithm. Parameters such as peak displacement (Pd) and characteristic period (tc) were calculated from 3 to 5 s time windows following P-wave arrivals, applying a high-pass 0.075-Hz Butterworth filter to remove low-frequency noise. The initial tests used the Taiwan velocity model, which gave reasonable results. Further experiments used the Taiwan, Indian (Kumar et al. 2009), and Global (Kennett and Engdahl 1991) velocity models to assess the applicability of EEW in India. Testing three-magnitude 6 earthquakes for regional EEW purposes showed commendable performance in detection, P-wave picking, magnitude estimation, and location accuracy. The lead time ranged from 10 to 90 s for various locations (Fig. 5). Peak displacement proved to be a more reliable magnitude estimator than the characteristic period. In the current testing of EEW systems in India, we achieved a commendable performance by reducing false negatives to below 10% for earthquakes above magnitude 5.0, lying in the instrumented window. This means that the system was able to issue timely and accurate warnings for most significant seismic events. Simulations of historical Indian earthquakes, such as the Chamoli (1999) and Uttarkashi (1991) events, were conducted to refine the performance of the system under Indian conditions. These simulations indicated that the EEW system could accurately pinpoint earthquake locations and magnitudes, providing effective warning times for various cities based on the NW Himalaya earthquake scenarios. However, we are continuously refining the system to improve this accuracy as more data becomes available.

Kumar et al. (2020) from ISR Gandhinagar examined the feasibility of implementing EEW in the Kutch region of India. Their study used broadband data from the GSNet network, focusing on earthquakes with magnitudes ranging from 3 to 5.2. They estimated relationships between various parameters such as PGA, peak ground velocity (PGV), peak ground displacement (PGD), and parameters Pa, Pv, and Pd to assess the shaking strength. Chamoli et al. (2021) evaluated the performance of the IITR EEW system using data from the May 12, 2015 Nepal earthquake, the October 26, 2015 earthquake, and the December 6, 2017 earthquake. Their results confirmed that the system has the potential to provide early warnings for large or major earthquakes. The IITR EEW system has undergone continuous testing and performance monitoring and synthesized ground motion records have been used to further evaluate its effectiveness. Kumar et al. (2022b) discussed the challenges involved in EEW around the globe. Additionally, they established regression relationships by using data from Japan.

Kumar et al. (2023b) evaluated the IITR EEW network during three moderate earthquakes in the Western Nepal region on November 9, 2022, November 12, 2022,

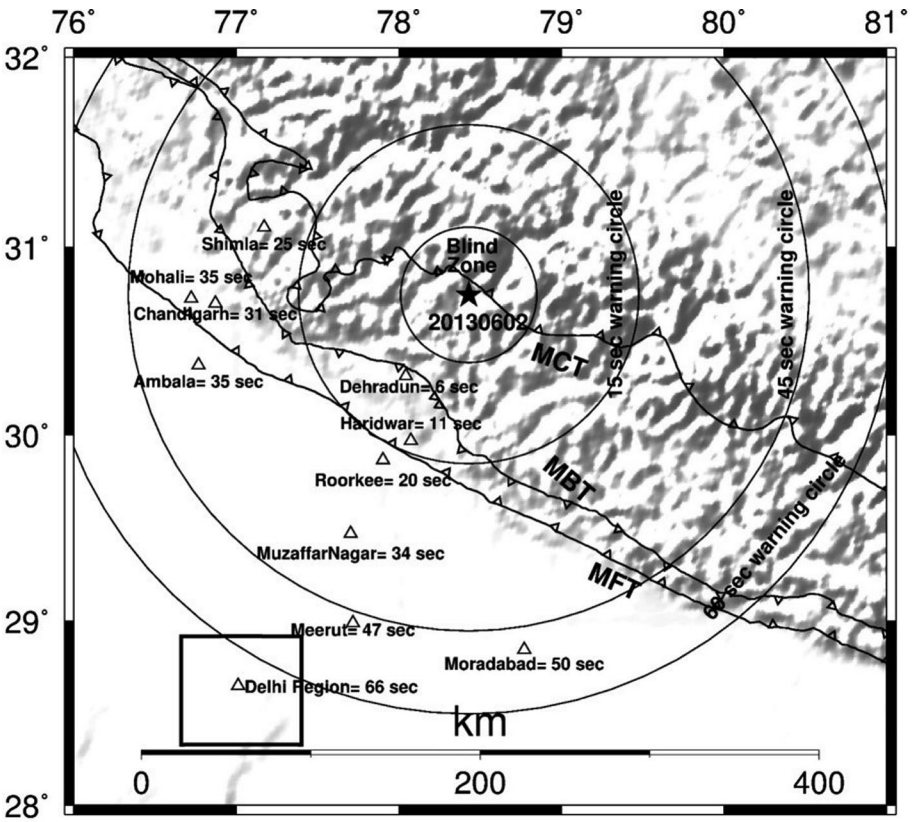

Fig. 5 The lead time for various cities in the Northern Himalayas from the earthquakes originating between Main Boundary Thrust (MBT) and Main Central Thrust (MCT). The maximum lead time of 66 s was achieved at Delhi (Mittal et al. 2019b)

and January 24, 2023, with magnitudes of 5.8, 5.4, and 5.8, respectively. Despite the epicenters being approximately 100 km away from the instrumented array, real-time ground motion data were received at the central station in Roorkee, and warnings were issued. Due to the distances involved, there were significant variations in the reported magnitudes during the initial phase. Pal et al. (2024) proposed magnitude scaling relations for EEW in the Garhwal region of India. These relations, derived from P-wave onset data from both observed and simulated records, have important implications for the IIT Roorkee EEW network in the region. The study involved simulating 14 earthquake scenarios based on the 1991 Uttarkashi and 1999 Chamoli earthquakes. By combining data from 170 observed and 63 simulated records, τc–Mw and Pd–Mw relations specific to the Garhwal region were established. These relations were used to determine lead times for potential future earthquakes, ranging from 4 to 60 s for sites located 56–200 km from the Uttarkashi and Chamoli epicenters.

5 Summary and Recommendations

Countries around the world have adopted EEW systems personalized to their specific needs and environments, serving a variety of purposes. This highlights that developing an EEW system is a gradual process (Allen et al. 2009). It requires consistent funding, a long-term vision, and collaboration between various parties. The path to a reliable EEW system is never the same, as the best approach depends heavily on how earthquakes occur in a specific region (Galasso et al. 2023). Factors like how people react to warnings, the direction faults run, the underlying tectonic plates, and how close communities are to earthquake epicenters all play a crucial role in how much warning time an EEW system can provide and its effectiveness (Suárez 2022). While EEW systems are valuable tools in reducing the impact of earthquakes, it is important to recognize their limitations. EEW systems are not a panacea for earthquake risk, particularly in areas with highly vulnerable buildings that are prone to collapse. The warning provided by EEW systems can give individuals time to take protective measures and allow critical infrastructure to implement automated safety protocols, but they cannot prevent injuries or damage caused by structurally weak buildings (Strauss and Allen 2016; Allen and Melgar 2019). As such, EEW systems should be seen as part of a broader earthquake risk mitigation strategy, which includes enforcing earthquake-resistant building codes, retrofitting vulnerable structures, and public preparedness initiatives (Wald 2020).

The diverse and active seismic regions of India, including the Himalayas, Andaman and Nicobar Islands, and Bhuj in Gujarat, emphasize the critical need for a comprehensive EEW system. The Himalayas, formed by the ongoing collision of the Indian and Eurasian plates, are among the most earthquake-prone areas globally, experiencing frequent and often severe earthquakes. The Andaman and Nicobar Islands, situated near the boundary of the Indo-Australian and Eurasian plates, are similarly vulnerable to both earthquakes and tsunamis. Bhuj, Gujarat, the site of a catastrophic earthquake in 2001, continues to face significant seismic risk due to the tectonic activity of the region. Implementing a nationwide EEW system in these areas is essential for minimizing damage, reducing casualties, and enhancing the overall resilience of communities against earthquakes. A nationwide EEW system for India would require a coordinated approach that integrates the ongoing efforts of institutions across different regions. The current systems being developed by IIT Roorkee in the northwest Himalayan region, the planned system by ISR in Gujarat, and NCS at a national level demonstrate the potential to protect large populations. However, each of these systems operates or plans to operate independently, with their algorithms, instrumentation, and modes of dissemination. To create a cohesive national framework, it is essential to establish a central coordinating body, potentially under the MoES that would oversee the integration of these systems. This would involve standardizing EEW algorithms across regions, sharing real-time data between seismic networks, and creating a uniform dissemination strategy to ensure that warnings reach all relevant stakeholders promptly. The nationwide system could benefit from lessons learned in other countries with national EEW frameworks, such as Japan (Nakamura and Tucker 1988) and Mexico (Espinosa-Aranda et al. 2009), where centralized data coordination and standardized protocols have been crucial to successful early warning operations. By adopting a similar approach, India can enhance the efficiency and effectiveness of its EEW efforts, ultimately increasing public safety and disaster preparedness.

The first step in developing an EEW system is a detailed stakeholder mapping exercise. This can be done through workshops at both national and state levels, bringing together

various groups (WMO 2018). These workshops will ensure a comprehensive mapping by including multiple sectors and viewpoints and also help stakeholders understand the EEWS objectives and their roles, promoting the necessary coordination for an effective system. The surveys should be conducted among different stakeholder groups, including community members. These surveys will help gather their preferences on warning features, communication methods for delivering warnings, and their views on false alarms. This feedback is crucial to ensure the EEWS meets user needs.

One of the major challenges in implementing an EEW system in India is the lack of public awareness and knowledge about earthquakes. Many people, especially in rural and newly urbanized areas, are not well-informed about earthquake risks or the appropriate safety measures to take during an earthquake (NDMA 2019). This lack of awareness can significantly delay the effectiveness of an EEW system, as individuals may not respond promptly or correctly to warnings. Also, the Himalayan region has seen rapid urbanization, leading to increased population density and infrastructure that may not be built to withstand strong earthquakes. This urbanization amplifies the risk of extensive damage and casualties in the event of a major earthquake. The National Disaster Management Authority (NDMA) leads disaster-related activities in India, coordinating with State Disaster Management Authorities (SDMAs) and District Disaster Management Authorities (DDMAs). The National Centre for Seismology (NCS), the Ministry of Earth Sciences (MOES), and other national research and technical institutes handle earthquake detection and information dissemination. State and district agencies share and implement this information locally. The National Disaster Management Plan (NDMP) outlines the roles of various central and state agencies in capacity building and public awareness. Training programs for seismic safety are provided by MoES, the National Institute of Disaster Management (NIDM), and other bodies. Mock drills and exercises involve a wide range of government ministries and agencies to ensure preparedness. Community-based disaster management is supported by NDMA, the Ministry of Rural Development (MORD), the Ministry of Housing and Rural Affairs (MHUA), and others, emphasizing the importance of local involvement and regular drills to enhance resilience.

Technical and logistical challenges also pose significant difficulties to the implementation of a nationwide EEW system. Establishing a dense network of seismic sensors across the vast and varied geography of India requires substantial investment and coordination. Moreover, ensuring real-time data processing and maintaining reliable communication channels to disseminate warnings effectively are complex tasks that demand advanced technology and robust infrastructure. An EEW system primarily concentrates on quickly detecting and identifying hazardous earthquakes. This requires a network of seismic sensors, along with telemetry and data acquisition software, similar to those used for regular seismic monitoring. The main differences for an EEW system are the need for speed and additional software to determine if warnings are necessary and where they should be issued. The speed of earthquake detection is heavily influenced by the density of the monitoring network. The closer the seismic stations are to the earthquake source, the faster the detection. Transmission time between the stations and the processing center is also crucial, along with the time taken by the software to calculate the location and magnitude of earthquakes and then translate these into expected ground motions.

To ensure effective earthquake detection, the network of seismic sensors should be as dense as possible. The network coverage should be adjusted based on the estimated earthquake hazard in different parts of the country. In areas with moderate seismic hazard, an interstation spacing of 40 to 50 km is recommended. In high-hazard and high-risk areas like the Himalayas, where the potential for damage is greater, this spacing should be

reduced by half to provide more accurate and quicker detection. The most crucial feature of a sensor is its ability to accurately record the amplitude of large, nearby earthquakes. This depends on the sensitivity and dynamic range of the sensor, the dynamic range of the digitizer, and the self-noise of the instruments. Accelerometers are particularly useful for EEW because they can handle the high amplitudes of even very large earthquakes without saturating. Also, having more sensitive seismometers at some locations can help in testing and fine-tuning the system more efficiently.

The availability of reliable and low-latency data transmission is crucial. Latency, the delay between data recording and transmission affects warning time directly; a 1-s delay in data from any of the nearest four stations to an epicenter means the warning will also be delayed by 1 s. However, reliability is even more critical because if any of these stations fails to transmit data, the warning delay could be much longer. Modern dataloggers use internet protocols for data transmission, requiring reliable internet connectivity. Some EEW systems, like those in the USA and Turkey, use dual connectivity to ensure both reliability and low latency. This approach is recommended for robustness. Ideally, a VSAT link can provide reliable connectivity, while a WAN connection offers speed. WAN connections can be established through local state-wide area network (SWAN) hubs for cost-effectiveness, with Ethernet radio links allowing remote stations to connect to these hubs.

Warnings from the EEW system should primarily be sent out using cell broadcasts and public sirens. Additionally, a smartphone app, similar to the one used in the Uttarakhand EEW system, should be linked to the EEW system and promoted extensively. Broadcasting warnings over television and radio should also be considered. Third-party organizations should be encouraged to register to receive warning messages to use them for private sirens and to implement user-specific, risk-reducing actions.

To maximize the efficiency of an EEW system, regular drills and training programs are desired. These initiatives can educate the public on how to respond to earthquake warnings, such as the "Drop, Cover, and Hold On" procedure. Drills help familiarize people with the warning signals and protocols, reducing panic and improving coordinated responses during actual seismic events. Regular training sessions for emergency response teams and community leaders can further enhance preparedness, ensuring that responses are swift and effective. By rooting these practices in the community, the overall resilience against earthquakes can be significantly bolstered.

Each step in the EEW process involves rapid real-time calculations, which can introduce uncertainties due to the speed and complexity of data processing. Traditional challenges in earthquake prediction, such as variations in seismic wave propagation and variable geological conditions, further contribute to these uncertainties. By identifying and mitigating these factors, EEW systems can enhance their accuracy and reliability, thereby improving their effectiveness in protecting lives and property during earthquakes.

The progress made in developing EEW systems across various regions in India, including significant advancements by institutions such as IIT Roorkee, NCS-MoES, and ISR Gandhinagar, is outlined. Each of these efforts contributes valuable insights into the development of a nationwide system, yet they face specific regional challenges. For instance, the system of IIT Roorkee has demonstrated the capability of providing up to 90 s of warning for earthquakes originating in the Himalayan region, but further refinement of GMPEs is needed to reduce false alerts and improve accuracy for local populations. Similarly, NCS-MoES and ISR Gandhinagar have made strides in early warning systems for Himalaya and Gujarat, but the challenges of optimizing warning dissemination to rural communities remain. By synthesizing these individual efforts, we recognize the potential for a unified EEW framework in India, which could leverage the strengths of regional systems while

addressing shared challenges such as algorithm performance, sensor network density, and real-time communication reliability. However, to achieve this, collaboration between institutions and coordinated data sharing will be necessary.

Given the high seismic risk in various parts of India, a nationwide EEW system is crucial. The challenges of public awareness, rapid urbanization, and technical implementation must be addressed through concerted efforts by government agencies, educational institutions, and community organizations. Public education campaigns and regular drills are essential to ensure that individuals know how to respond effectively to earthquake warnings, thereby enhancing the capacity of the system to save lives and protect property. A well-implemented EEW system, supported by an informed and prepared population, can help mitigating the impact of earthquakes in India.

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