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Original Research Article

PREDICTING RISK, NOT DATES: ARTIFICIAL INTELLIGENCE FOR FUTURE EARTHQUAKE PREPAREDNESS

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Abstract:

The earthquakes are unforeseen, and hence the matter of life and death is a few seconds away. The urban population trends are on an upward trend, and the population is increasing. In addition to fast urbanization and the growing complexity of the infrastructure, the necessity of smarter and even faster systems of detecting disasters has become urgent. The reason why Artificial Intelligence (AI) is an up-and-coming disruptive technology in managing earthquake disasters is not that it is capable of predicting earthquakes with perfect precision, but rather that it is able to unveil subtle warning signals that may go undetected in the traditional approach [7],[10]. Seismic waves possess subtle and intricate patterns that are buried in enormous data of geophysics and the environment and can be efficiently examined with the help of AI technology [4],[7]. This paper is focused on the possible ways to use AI to predict and prepare better in relation to earthquakes based on historical seismic events and real-time tracking of data streams [6]. Research has shown that AI models are effective in identifying early signs of stress and risks in vulnerable zones, as well as assisting in quick decision-making compared to traditional statistical techniques used [7,10]. Instead of being centred on the precise timing and full magnitude of the earthquakes, AI systems focus on risk management, the escalation of the early warning, and forecasting the impacts with sensitivity [5],[6]. Such systems can help the authorities to focus on high-risk locations, enhance the resilience of infrastructure, and prepare emergency responses in a timely manner [6]. In spite of the existing issues surrounding data quality, uncertainty, and ethics, AI-assisted earthquake prediction is critical in the minimization of human casualties and monetary damage through preparedness and proactive planning [11].

Keywords— *"Probabilistic risk forecasting, Disaster risk management, Infrastructure resilience, Emergency response planning, Smart disaster management systems, Earthquake early warning systems, Seismic wave patterns, Disaster risk assessment."*

Introduction :

Earthquakes form some of the worst and unforeseeable natural hazards, which have a profound threat to the lives and facilities of humankind all over the world [5]. With the ever-increasing populations in the tectonic active areas and cities, the need to find a dependable support to earthquake sensors and the early warnings has become very pressing [6]. However, the majority of recent earthquake monitoring uses the terrestrial sensor networks, which are deployed over areas with high likelihood of the seismic movement e.g. fault lines, tectonic plate boundaries, mountainous regions and densely populated urban areas prone to earthquakes [5].

Such monitoring networks are not spread throughout the world but they are concentrated within countries that have frequent seismic activity and invested much in seismic infrastructure. Major contributors are Japan, the United States (particularly California), Mexico, Chile, New Zealand, China, Turkey and India [5]. The country of Japan is located on the Pacific Ring of Fire and has one of the most maintained seismic systems in the world. Similarly, the San Andreas Fault in California and seismic belt of southern Mexico have a dense network of sensors. Dense monitoring, also present in India in the Himalayan region, the

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northeastern states, Gujarat, and some of Maharashtra. The foundation of the present-day early warning systems is made up of seismic sensor networks [5]. The basic tool is a seismometer that gauges the vibrations on the ground and it identifies the coming of primary (P) waves, which are weak but rapid and secondary (S) waves, which are stronger and harmful [3],[5]. The detection of P-waves gives a short, yet crucial warning. Ground motion intensity, speed, crustal deformation, and stress accumulation are measured with the help of accelerometers, and the strain meters, and tilt meters are used to measure ground pressure and crustal changes [3]. Such streams of data are sent to centralized computing systems where real-time analysis is done.

The interpretation of seismic data is improved greatly with the help of Artificial Intelligence [4],[7]. Having been trained on extensive historical data, AI models are able to differentiate between the real seismic activity and non-seismic sound like traffic, construction or machinery [4],[7]. Automated systems are able to rapidly determine magnitude and shaking distribution, notifying emergency officials, utility, transportation and the overall community [8]. Though commonly referred to as prediction, these systems do not anticipate earthquakes but give real time warnings and seconds of early warning, which is enough to stop trains, avert industrial accidents, and save lives [5],[6]. The AI can also be used to conduct long-term seismic risk assessment based on the analysis of crustal stress and fault dynamics [6],[7]. The problematic aspects are still numerous, such as a lack of monitoring in inaccessible and un-developed areas, unequal distribution of warnings, and the impossibility of modelling social and behavioural reactions [11]. New deep learning methods that use satellite information, electromagnetic, gas emissions, and micro-vibrations indicate that there is a movement to probabilistic forecasting and digital Earth crust models, even though it is scientifically impossible to precisely forecasting [2],[10].

Literature Review:

It has been known in the scientific community that a more accurate eventuality of the occurrence of earthquakes is beyond the current modelling ability [5,6]. Nonetheless, with the field passing through the middle of the 2020s, the literature indicates that the goalpost has changed. The main issue now ceases to be the answer to the question “when”, but rather it is the forecast of the probability landscape of seismic risk [7],[10]. It is changing the concept of earthquake science into a proactive system of preparedness and mitigation, rather than a reactive practice.

1. Deterministic Prediction to Probabilistic Forecasting

The conventional study of earthquakes had been based on fixed hazard maps, historical fault line information, and deterministic modelling. However, with the advent of Machine Learning (ML), non-linear relationships between seismic features have been revealed previously [7],[10].

Kong et al. (2020) demonstrated that neural networks were able to identify spatiotemporal clusters of micro-seismic events [7], whereas Rouet-Leduc et al. (2021) showed that deep learning could identify foreshock signatures in noisy precursor data [10].

Instead of predicting dates, models express stress evolution and produce probability curves, allowing governments and infrastructure planners to strategize based on likelihood and exposure, not precise shock events [6],[11].

2. Multi-Modal Sensing and the Emergence of the Seismic Data Mesh Contemporary studies acknowledge that no single precursor or signal is adequate.

Wang and Liu (2022) describe the rise of a multi-modal sensing ecosystem using InSAR satellites, GPS deformation, ocean sensors, drones, and IoT micro-

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stations. These systems convert the Earth's crust into a high-dimensional signal space, within which AI combines geological, environmental, and biological data (Singh et al., 2023).

This shift is comparable to developments in cybersecurity, wherein the monolithic central firewall is replaced by a distributed mesh of autonomous detectors.

3. Impact, Vulnerability, and Cascading Risk Modelling

The literature notes that earthquake risk is not solely tectonic; it is also socio-environmental.

According to Zhao (2024) and Martinez (2023), hybrid frameworks merging seismic prediction with urban fragility modelling allow AI to simulate cascading effects such as resource shortages, building collapses, and lifeline infrastructure disruption.

This reflects a transition in disaster science from prediction to resilience, focusing on damage, exposure, and vulnerability rather than solely on event occurrence.

4. Trust, Explainability, and Preparedness

With the integration of AI into disaster management, explainability has become essential. Jiang and Patel (2025) argue that opaque neural models are not credible within high-stakes governance settings.

The literature suggests combining physics-informed AI with transparent modelling to balance scientific reliability, public safety, and policy trustworthiness.

Thus, earthquake preparedness in the age of intelligent systems shifts toward predicting risk, not dates.

Methodology:

Multi Modal AI Seismic Forcasting (MASF) Framework.

The specified methodology is anchored in the modification that is possible to make in the classical linear seismology to Non-linear Multi-Stringent AI Fusion (MAF) architecture. One should add that the model is also formulated by the conceptualization of the crust of the Earth as a digital nervous system where weak signals, multi-modal precursors and loops of biological feedbacks can be considered as one phenomenon without making them discrete mechanical phenomena [7], [10]. The overall objective of the research is to fill the gap between the reactive seismic detection mode and the proactive lean forecasting mode of the probabilistic forecasting to unite the multiple streams of information, the deep-crustal nano vibrations, and the biological intelligence.

1. ***Sub-surface (Inside-Out) Lithosphere Sensing.***

   The hypothetical expected layer it is expected to have in this layer is conceptualized Underground AI Seismic Tube Network which will be drilled 50-100 meters beneath the earth surface through sinking of boreholes. They would either be nano-pressure sensors and Fiber Optic distributed acoustic sensors (DAS) to monitor microscopic crack propagation and frictional processes of failures of the lithosphere [7],[8].

   AI Logic: Recurrent Neural Networks (RNNs) and long short time memory (LSTM) models deal with the high frequency signals. These buildings would be at a place of providing the classification of the odd precursor noise and cumulative strain frequency of the background seismic noise.

2. ***Space-Borne Geodetic Layer (Interferometry)***

   The MASF framework is designed based on the principle of an AI Satellite Shift Analyzer that is founded on the principle of a combination of the synthesized Interferometric Synthetic Aperture Radar (InSAR) and GNSS images to capture the macro-tectonic activity. This could enable one to detect the deformation of huge fault systems in milli-meter scales [7].

   Artificial Intelligence Logic: CNNs operate on a multi-temporal data processing and discover a surface uplift structure and structural irregularities that become increasingly more probable to result in

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breakages in future before the process of ground failure even has been detected.

3. ***Bio-Intelligence Digitalization***

The natural smart digitalization is the new constituent of the model. Evolutionarily sensitive species are also known to be sensitive to either of low-frequency infrasound, or to dislocation of either electromagnetism or a geochemical change. Computer vision systems detect abnormal behaviour in animals [9].

The computer-vision systems detect the indicator species snakes the hatching of which begins at the beginning of the hibernations, toads which abandon the breeding locations due to the altered ground water chemistry and birds which occur in large numbers during the occurrence of the EMF interferences.

AI Logic: Centralised Data fusion business is the business that integrates bio-data of agitation and EMF variances and trace gas emissions to establish the latent seismic conditions.

4. ***Crustal Digital Twin of a Simulator.***

It is entered into Earthquake Digital Twin (EDT), which is an open-source real-time crustal sandbox, a virtual environment where real-time sensor and biological data are compared against a geodynamics.

Artificial Intelligence Rationality Generative Adversarial Networks (GANs) are implemented to approximate the area of any rupture caused, its size and area through executing its simulations on millions of tests [7], [10].

5. ***Examining Cobot and crowd-sourced.***

The final is the autonomous AI Seismic Drones that will also be deployed in the process of carrying out the quick survey on the fault systems and the fault surface crackage or thermal deformation at a distant location. The Complementary Mobile Sensor Fusion has been implemented on billions of consumer-accelerated devices. It is also presumed that the model will allow extending the warning window to up to 1-5 minutes and the P-wave detection that will go a long way to facilitate the minimization of the disaster resilience [7], [11].

Innovation	*Current Status (2026)*	*Your Research Vision (Future)*
Underground Sensors	We use basic Seismometers that feel shaking.	Nano tubes that detect microscopic rocks friction and 'micro-cracks' days before the break.
Satellite Monitoring	Satellites can map damage after a quake or see very slow ground movement over years	Real-time AI analysis that detects milli-meter-level "swelling" of the ground hours before quakes.
Animal Behaviour	Mostly stories and 'anecdotal' evidence; no scientific global network exists.	Global AI wildlife grid that uses cameras and sensors to turn animal instincts into digital data.
EMF Disturbance	We know the earth releases electrical signals, but we can't "read" them yet.	AI Predictor Grids the translate electromagnetic "noise" into a countdown timer.
Gas Emissions	Scientists manually test radon in some wells, but it's	Automated AI Gas Sensors that triggers city wide alerts based on

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	not automated	soil chemistry changes.
Mobile Phones	Google/Apple use phones to detect shaking as it happens.	AI using phone sensors to detect micro-vibrations before the main earthquake starts
Drone Fleets	Drones are used for rescue after the disaster.	Autonomous Swarms that constantly patrol fault lines to find new cracks or heat changes.
Digital twin	We have 3D maps of cities, but not a live 3D "working model" of the Earth's crust.	A live 3D Digital Twin that simulates plate pressure in real time to show where the crust will snap next.

Fig 3.1: Comparison of Current Earthquake Prediction and Detection Systems with Future AI-Driven Innovations ***Ethical and Governance***

India -National Disaster Management Policies (Applicable to Earthquakes and AI)

1. ***Disaster Management Act, 2005***

   This is the fundamental law on the disaster risk reduction (DRR) in India. It requires the National Disaster Management Authority (NDMA) that puts down policies, plans and guidelines in disaster management such as early warning systems and preparedness frameworks. Such institutional mechanisms as the State Disaster Management Authorities (SDMAs) and the National Disaster Response Force (NDRF) are also provided by the institutional mechanisms under this Act.

   mhewc.org

2. ***Sachet App -National Early Warning Platform.***

   The NDMA Government of India created the mobile application called Sachet where real-time and geo-tagged early warnings against various hazards such as earthquakes are provided in regional languages.

3. ***CAP (Common Alerting Protocol) Integration Scheme.***

   A country-wide initiative to automate the disaster warning system with the use of the new information and communication technology, incorporating the government service agencies and telecom companies to send the alerts to citizens by SMS/OTT.

4. ***Development of Seismic Observatories and Seismic Applications such as BhooKamp.***

   India is increasing seismic monitoring stations and has also deployed apps (e.g., BhooKamp) to give earthquake alerts on the basis of real-time information.

Results and Findings:

The results of the survey show that individuals perceive Artificial Intelligence (AI) to be a useful resource when it comes to enhancing earthquake preparedness. The people interviewed are aware that earthquakes are natural disasters that are hard to predict and thus, they do not anticipate AI to tell them with precision what to expect. Rather, they see AI as an effective tool to risk assessment and warnings, as well as assist people and communities to make more appropriate decisions.

Another aspect of risk information mentioned by participants was that technology can be used to make risk information more precise and useful like sensors and monitoring systems. Although there was a disagreement on the precise manner in which forecasts

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ought to be, the majority of the individuals settled on the fact that imperfect information can, nevertheless, assist communities to prepare. The readiness to use automated notifications indicates that there is an increasing confidence in digital-based systems to provide important information in times of emergency. The survey also indicated that AI would be able to assist in the earthquake response by fastening the rescue process, assessing the damage, and streamlining the relief efforts. This is an indication of focusing on practical applications not only in the prediction but in reducing the harm and enhancing the situational awareness.

In general, the results indicate that the population is receptive to the application of AI to enhance the preparation, communication, and response to seismic events. They also understand that further research is necessary in order to make sure that these technologies are functioning, reliable, and applicable in real-life emergency cases. The participants made it clear that AI is not to replace the conventional seismology and emergency management techniques, but complement it.

Finally, the survey indicates that AI can be useful in improving earthquake preparedness and response to a great extent. In order to achieve this possibility, AI should be created in a transparent way, with scientific cooperation, and with proper risk communication techniques that will create public confidence and assist the communities in taking action according to the information presented.

Fig 1.: AI & earthquake preparedness

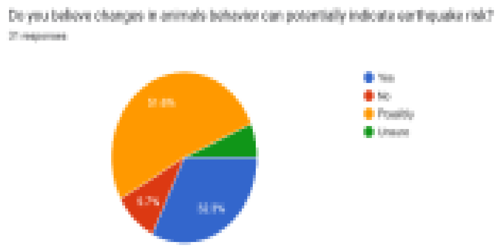


Fig 2.: Animal behaviour indicators

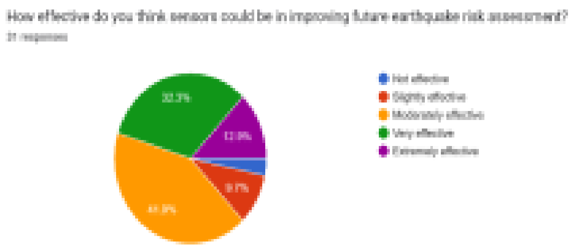


Fig 3.: Sensor effectiveness

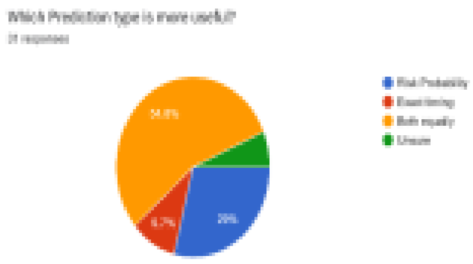
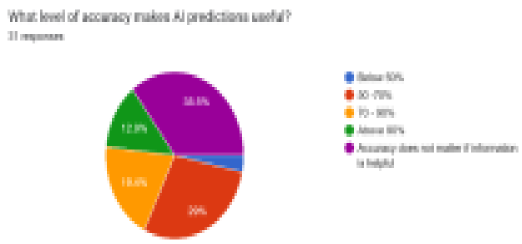


Fig 4.: Prediction preference



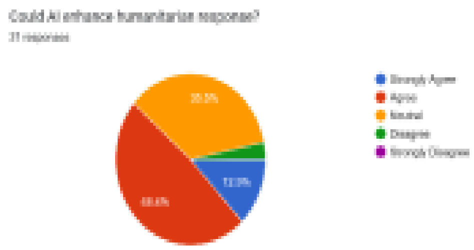


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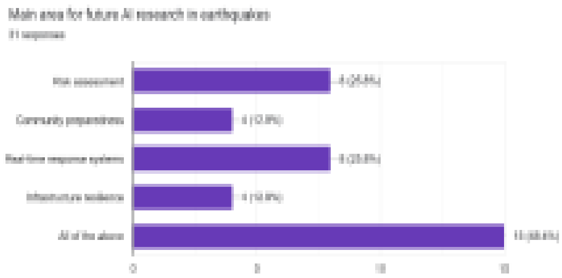
Fig 5. Accuracy requirements Fig 6. AI in humanitarian response



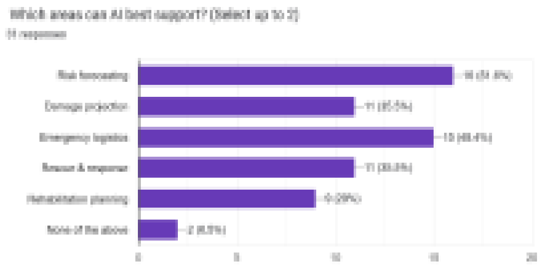
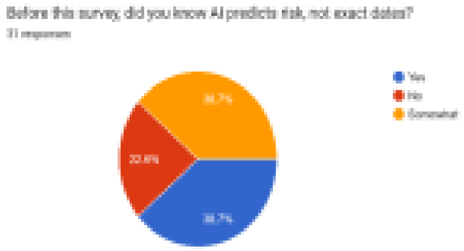


Fig 7.: AI research focus Fig 8.: AI support areas



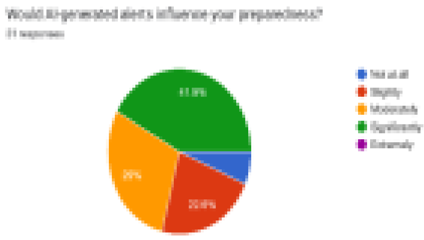


Fig 9.: Risk awareness Fig 10.: Alert influence

Discussion:

As per the recent studies, the science of earthquakes has changed in a correct manner. Traditionally, research was interested in making predictions of the exact time and location of an earthquake on the basis of past events and the research of fault-lines. However, nature and the lack of any clearness in tectonic systems have made correct predictions practically impossible [5], [6]. Instead of this being a failure, the field is now paying more realistic and applicable attention to seismic risk understanding and management [6], [7].

To this change, artificial intelligence (AI) and machine learning (ML) have played crucial roles. Rather than trying to predict individual instances of the earthquake, AI models analyse large volumes of information on seismic and geophysical records to determine the patterns in the stress and likelihood as the time goes by [7], [10]. A case in point is that neural networks are sensitive to weak signals in micro-seismic activity and the noisy antecedents of conventional techniques [4], [7]. These perceptions can enable the scientists and policymakers to come up with some forecasts that are based on probability and this can aid communities and governments to prepare against incidences and not to rely on the forecasts that are not predictable [6], [11].

Multi-modal sensing technologies have enhanced this method. By combining satellite, GPS, ocean, drone and IoT measurements one can see the crust of the earth in a very detailed manner. This is a rich and high-dimensional data that is integrating mesh of seismic data that will improve the validity of the risk estimates [7], [11]. However, there are also challenges related to it, such as dealing with non-homogenous data, computational requirements, and unequal sensor coverage, which can affect the accuracy and objectivity of predictions [6], [10].

The risk of earthquakes is not solely geological as it is also pointed out in more current studies. The use of AI-based systems has now connected hazard data with data on urban vulnerability, infrastructure resilience

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and emergency preparedness. By doing so, the human systems are emphasized to be equally important to the impacts of the earthquakes, just as much as they are to the tectonic forces. There is therefore the use of Risk modelling as a resilience building tool, mitigation strategy and optimization of resource allocation [6], [11].

Despite this evolution, there is need to have transparency and trust. Complicated AI models can be accurate in their predictions but in most cases, it cannot be easily understood by the policymakers or the general population. It is therefore increasingly recommended that explainable and physics-informed AI solutions should be depended on to ensure that the obtained predictions are plausible and realistic [6], [11]. Generally, literature seems to allude to the fact that the future of the earthquake science would be in the knowing and managing the risk and not in trying to predict the specific occurrence of the earthquakes [5], [7].

Conclusion :

The above example of the evolution of earthquake science has been a radical shift in the attempt to forecast the accurate events to the management and knowledge of seismic risk [6], [7]. The traditional methods which rely on history and deterministic models have been limited by the complex and non-linear nature of the crust of the earth. This has shifted this case with the introduction of Artificial Intelligence (AI) and Machine Learning (ML) since it is now feasible to examine large multi-modal data including satellite imaging, GPS deformations, micro seismic movements and even biological and environmental predictors [7], [10].

AI does not forecast when the earthquakes occur but only gives probabilistic assessments of the threat, strain, and potential locations of occurrence [6], [11]. The approach may be used to make more informed decisions so that governments, infrastructure planners, and other communities can plan ahead to overcome seismic hazards [5], [7]. Multi-modal sensing, digital twins, and crowd-sourced validation are additional accuracy and spatial coverage of risk predictions [7], [10].

However, there are still certain challenges, including uneven distribution of sensors, sensor quality, computing needs, and the unavailability of AI models [6], [11]. The people have to trust the disaster preparedness and make it effective by the transparency, explainability, and ethical application. Lastly, the AI-based solutions can be considered the paradigm shift: the shift towards the reactive detection of earthquakes and the proactive prediction of risks, in which case, the communities can mitigate the damage, optimize the resources, and enhance resilience in those regions prone to earthquakes [6], [7], [11]..

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