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Harnessing the potential of digital twins in seismology

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Digital twins — virtual replicas of natural systems — are emerging as promising tools for assessing seismic hazard and for aiding disaster decision-making and earthquake rapid response. However, to truly harness their potential, the challenges of exascale computing must be tackled to create systems that are capable of adapting to ever-evolving earthquake dynamics.

Almost 60% of cities with >300,000 inhabitants are confronted with a heightened risk of exposure to multiple natural hazards, such as earthquakes, landslides, tsunamis or volcanic eruptions, intensifying their vulnerability to fatalities and economic damages related to disasters[1]. Digital twins are emerging as potentially powerful tools to address the challenges of geohazard response and management[2]. While still in development, these data-driven information systems show promise to provide users with a comprehensive digital reflection of the Earth system's state and its evolving nature, bounded by available observations and fundamental physical principles[3]. Yet, deciphering the complex, ever-evolving connections between physical assets of near-fault and on-fault observatories and their representation in digital twins remains a formidable task.

In this Comment, we outline the key challenges and strategies for the development of these virtual representations of Earth and discuss how they could best be harnessed to advance earthquake forecasting, seismic hazard assessment, risk mitigation and earthquake rapid response.

Earthquake complexity

Earthquakes remain one of the most complex phenomena in nature, spanning a large range of spatial, temporal and size scales. The study of earthquakes extends over 21 orders of moment magnitude (M_W), from M_W −12 in laboratory experiments to gigantic M_W 9 + events occurring on tectonic plate boundaries, with characteristic length scales varying from microns to >1000 km. Timescales for earthquake preparation and occurrence range from decades–centuries for major quakes to seconds–minutes during fault rupture, as illustrated in Fig. 1.

Understanding the intricate physical interactions across these spatial and temporal scales, and developing comprehensive approaches capable of modelling them, remains a major scientific challenge. For the development of digital twin components (DTCs) that cover seismic processes for risk and mitigation purposes, several requirements need to be met, including long-term earthquake occurrence and shaking probability, short-term forecasting, near real-time rupture propagation modelling and the synthesis of seismic waveform data.

Prototypes of DTCs that incorporate these requirements are under development[4,5]. Once fully developed, these DTCs will be deployed for real-time hazard, and eventually risk, applications, enabling continuous monitoring and modelling at relevant spatial and temporal scales (Fig. 1).

Data collection and management

For seismology's digital twins, one critical challenge is data collection and FAIR management[6]. At present, seismology uses global and regional deployments of thousands of seismic stations. Near-fault observatories integrate dense onsite networks of seismic sensors with satellite imagery, remote sensing, and geochemical and thermal modelling, essential to capture a comprehensive picture of the seismically active regions. Furthermore, the first on-fault observatories install sensors at depth on faults to acquire direct data on the rupture process. All these monitoring methods generate a massive influx of data. For example, seismic sequences can generate gigabytes of data within minutes to hours, and real-scale experiments on fault stimulation by fluid injection and earthquake nucleation produce >1 TB of waveforms daily, streamed from hundreds of sensors[7].

Handling these vast quantities of data presents its own challenge. Robust, high-resolution data collection methods must be paired with the development of computational systems capable of processing and interpreting the large volumes of data. To fully utilize these multi-scale and multi-physics Earth system modelling capabilities, digital twins must strive towards exascale computing power, performing a billion-billion (10^{18}) calculations per second. As well as the capacity to process billions of observations daily, this supercomputing infrastructure should support high computing throughput rates for physical models and concurrent execution of impact models. An innovative redesign is necessary to ensure maximum efficiency on future supercomputers, through integrating machine learning techniques for accelerated computing, data compression and sector-specific information extraction.

One key aspect of the digital twin would reside in its dynamic learning ability through user friendly interfaces, which aim to assimilate incoming real-time data while being continually refined through incorporation of physical principles and human interactions. A calibrated digital twin would operate in tandem with a physical twin, absorbing new data to refresh the digital subsystem models (Fig. 1). This challenge intensifies in the time-constrained phase preceding, during and immediately following an event, when all data streams need to be processed and assimilated in near real time.

While the challenges are substantial, there is notable progress being made. As these technologies evolve, we anticipate greater efficiency and efficacy in the responses to seismic events, and potentially also advances in earthquake predictability.

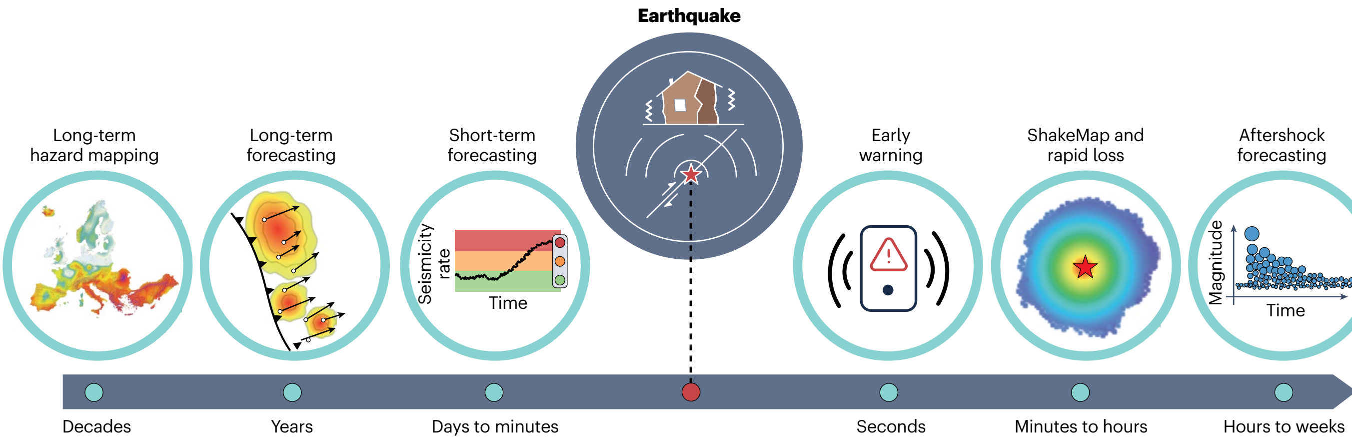

Fig. 1 | Digital Twin Components in seismology. Showcase of the multiscale approach to earthquake preparedness and response, with the diverse digital twin components (DTCs) before and during an earthquake, highlighting the varying timescales involved. Before an earthquake, DTCs would include information from long-term (decades to years) hazard mapping and geodetic and seismic data-based forecasting, to short-term (days to minutes) monitoring of small earthquakes. After an earthquake strikes, earthquake early warning (EEW) systems deliver advance notice within a few seconds, while ShakeMaps and rapid loss estimates guide emergency response within minutes to hours. Aftershock forecasting further supports ongoing monitoring and recovery efforts in the hours and weeks that follow.

Potential of a digital earthquake twin

As events like earthquakes and aftershocks transpire within seconds or minutes, uncertainties escalate and response times decrease. These quick, drastic changes call for real-time data to inform swift decision-making. Here, digital twins could become valuable as they would assimilate continuous streams of real-time data to capture and forecast changes in the real world (Fig. 1). In practical terms, this capability for rapid seismic risk assessment could enable time-dependent earthquake information and early warning systems. These systems hold the potential to speed up emergency responses and improve communication with affected communities.

To visualize the impact of fully realized digital twins, consider the real-world scenario of the M_W 7.8 earthquake that struck southern and central Turkey and northern and western Syria on 6 February 2023 (ref. 8). Approximately 9 hours later, a M_W 7.6 earthquake occurred north-northeast to the first quake, in the Kahramanmaraş Province. If implementation of digital twins had been realized, an ensemble of tools could have allowed for enhanced, physics-based time-dependent aftershock forecasting, swift generation of higher-resolution shake maps, and real-time modelling of fault ruptures and fault interactions. As such, harnessing the potential of digital earthquake twins could provide crucial information in a fraction of the current response time, guiding near-real-time decisions during hazardous events.

Future perspectives

Digital twins offer the potential to address the complex challenges of managing geophysical extreme events, such as earthquakes. To fully realize this potential, we must tackle the issues of high-dimensionality and diverse data frequencies and model resolution. Central to this endeavour is the exploration of computational methods that seamlessly integrate mixed-frequency, heterogeneous data to model the evolving dynamics of seismic activities.

To address these challenges, data and model standards must be unified. Manufacturing data should be standardized and delivered in common formats, and existing data standards should be adopted where possible. FAIR data and model principles must be upheld. Establishing a public database for digital twin sharing, managed by government funding agencies or a coalition of universities and enterprises, would enable researchers from industry to access digital twin data and models for research or business application development. Lastly, creation of digital forums and innovation hubs where researchers can discuss, develop and publish specifications would enable faster development by connecting data scientists and domain experts.

While extreme-scale computing entails extreme-scale data, utilizing machine learning as a bridge between data and information would help reduce the hardware footprint. Moving beyond the modelling to a digital twin framework, while ensuring seamless communication and collaboration between different stakeholders, is vital to develop and implement effective measures to mitigate seismic risk.

Alongside software development, human capacity training needs to be prioritized – establishing the next generation of seismologists and professionals to effectively use these advanced digital tools is paramount. Dedicated training programmes and curriculums that integrate the use of digital twins in seismology would foster a culture of continuous learning in this rapidly evolving field. Additionally, policies should be established to provide urgent access to high performance computing infrastructures.

Harnessing the potential of digital twins can reshape our approach to seismic hazard, providing a shift in understanding and mitigation of seismic risk. Digital earthquake twins show potential to foster proactive, data-driven decision-making, but also set the stage for a future where we could be better equipped to mitigate seismic hazards more effectively.

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