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Urban Earthquake Early Warning for Aotearoa-New Zealand

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ABSTRACT

Earthquake Early Warning Systems (EEWS) should be part of any Earthquake Resilience toolkit due to their potential to save lives and reduce injuries. The Sendai Framework of disaster risk reduction 2015-2030 has 7 global targets including "Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030". Despite this New Zealand currently does not yet operate a national EEWS.

EEWS currently rely on three main pillars: earthquake science, sensor and communication technologies, and understanding of the end-users. The addition of a fourth pillar is considered essential - earthquake engineering. EEWS currently do not take into account the way shallow geology or tall buildings amplify earthquake shaking. These systems fail to consider complexities generated by the urban environment, which is a critical omission given:

- In New Zealand (NZ), over 85% of people live in urban areas,
- Shaking intensity at the top of a multi-storey building can be ten times stronger than at ground level.

The response of a building to ground shaking is a complex interaction of structural design, construction effects, site conditions, as well as the ground motion itself that is often characterized by shaking duration, intensity and frequency content. Seismic building monitoring is essential to better understand the full earthquake impact on building response for the purpose of EEWS.

NZ seismologists, social scientists, communication specialists and structural engineers in partnership with Māori, sensor companies and urban property developer-investor is developing a novel EEWS that is adaptable to national, regional, local, and building-level applications. The aim is to significantly reduce the cost to society of earthquake-related deaths and injuries and increase earthquake resilience for urban populations through increased education and awareness.

This next generation EEWS further considers the needs of a modern, socio-economic diverse population residing in different dwelling types in urban and rural area.

Keywords: earthquake-early-warning, seismology, social sciences, communication technologies, earthquake engineering.

BACKGROUND

Aotearoa-New Zealand (NZ) is a seismically active country with over 9,000 M2+ earthquakes recorded each year, including five M7+ since 2009 (GeoNet.org.nz). Earthquakes remain the costliest natural hazard events for New Zealand. The Canterbury earthquakes in 2011 remain as one of the most expensive insured, global natural disaster [1]. Earthquake Early Warning Systems (EEWS) work by detecting an earthquake event using sensors close to the earthquake epicentre from a wide field array. Then through rapid digital telemetry, an alert, in the order of seconds and up to minutes, can be delivered to end users before the strong shaking seismic wave arrive at the respective sites. EEWS have been implemented in several seismically active areas worldwide. Notable examples include the JMA system in Japan [2], the SASMEX system in Mexico [3], the CWB system in Taiwan [4] and the ShakeAlert system in California, USA [5]. Since 1991 ,when EEWS has been implemented, it has proven effective in providing warnings to a wide range of critical infrastructure operators and the public.

The Sendai Framework of disaster risk reduction 2015-2030 has 7 global targets including to "Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030" [6]. EEW should be part of an Earthquake Resilience toolkit due to their potential to save lives and reduce injuries. In NZ, reducing direct injuries from earthquakes can lead up to NZ$1M+ saving per significant earthquake event (based on cost of NZ$87K per 1 injury to NZ society [7]). Benefits also include a more resilient population through engagement and education [8]. There is not only a strong need to develop a national EEWS considering our level of seismic activity but also a strong appetite from the public [9]. Despite this New Zealand does not currently have an operational EEWS.

Current operational EEWS do not account for local shallow geology effects or possible building response amplification. Instead, they issue a "one size fits all" ergodic warning, leading to many missing a warning ahead of strong shaking [10] (Fig.1). The extent building response to ground shaking is amplified will depend on its structural design, construction effects, local site conditions. There is opportunity for seismic building monitoring to be integrated with EEWS to continuously assess and improve EEWS alerts. For NZ's upcoming EEWS, it is critical to tackle the challenges of variable soil and building shaking amplification and consider complexities generated by the urban environment, given:

- over 85% of people live in urban areas,
- Shaking intensity at the top of a multi-storey building can be ten times stronger than at ground level.

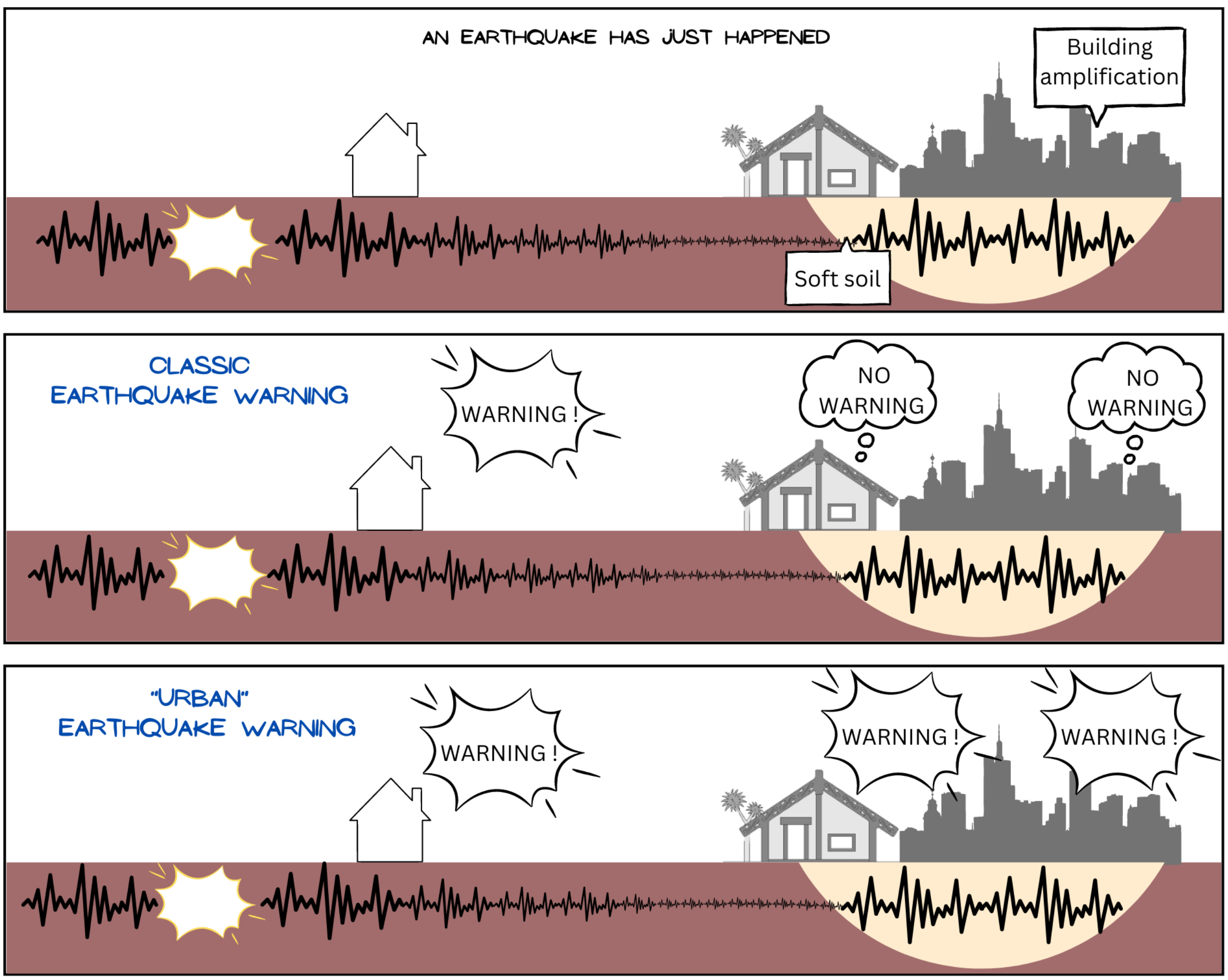

Figure 1: Top panel illustrates an earthquake occurring and site conditions and building amplification without an EQEWS warning. Middle panel illustrates the classic ergodic earthquake EQEWS that do not account for site conditions and building amplification. Bottom panel illustrates an urban EQEWS that integrates site conditions and building amplification for warnings.

There are current research effort examining the use of partially non-ergodic warnings by tailoring the expected amplitude of the S-wave to local site conditions [11]. More recent research concluded that ground motion intensities are not currently accurate enough to be applied toward intensities amplified by soil/basin conditions, and that building amplification functions should take into consideration the dynamic properties of the building, especially for tall structures and distant earthquakes [12]. An onsite EEWS do not require ground motion estimates, instead they predict shaking parameters based on P-wave characteristics. This is a particularly promising addition to provide non-ergodic warnings including structural drift estimates based on the first seconds of P-wave signals [13].

PROBLEM OR OPPORTUNITY

EEWS currently rely on three main pillars: earthquake science, sensor and communication technologies, and understanding of end-users. The addition of Earthquake Engineering as a fourth pillar is considered essential to support location specific EEWS. NZ seismologists, social scientists, communication specialists and structural engineers in partnership with Māori, sensor companies and urban property developer-investor are developing a novel EEWS that is adaptable to national, regional, local, and building-level applications. A NZ urban EEWS will also ensure better uptake of seismic building instrumentation in general, providing essential insights into structural performances and better understanding of earthquake impacts.

This collaboration centers around Wellington, NZ's capital city. Over the past decade, Wellington has benefited from the presence of instrumented buildings established by GeoNet [14], and numerous structures commercially equipped with instrumentations in the past five years. The Wellington region has encountered many moderate to strong earthquakes since 2013 with 70 earthquakes measuring magnitude 5 or higher (source GeoNet). This has enabled scientific discoveries [15,16,17] as well as heightening the interest of the local population [18,19] and citizen seismology [20,21]. This combination of factors creates an exceptionally suitable test bed for the project. It also currently benefits from enduring local and national end-users and industry technology partnerships.

PROPOSED URBAN EEWS FOR AOTEAROA-NEW ZEALAND

Can mobile phones be the solution?

A NZ study showed people preferred to receive EEW alerts primarily via mobile phones [22]. Typical EEWS are centralised and push the warning out via text or public media broadcasting. We propose to test an accompanying mobile app able to either:

a) receive a national or regional EEW alert, add the site amplification factor, and broadcast the warning if required,

b) receive a local alert from a nearby sensor (via instrumented buildings), and broadcast the warning if required, or

c) apply an EEW algorithm to the phone's own seismic data, and broadcast the warning if required.

The success of this project relies on the shaking amplification database needed by the app to estimate location specific shaking, data streams within sensors and phones, and user appetite for the app. Specifically the development of a minimum viable product (MVP) for the app will require:

- levels of details about the amplification database increasing with user needs and research advances,
- functionalities starting at a basic level (a) but ranging up to a sophisticated EEWS (b,c),
- warnings designed along with end-users.

Proposed methodology: Design science research approach

Our proposed framework is based on the design science approach [23] (Fig.2): "Design science or design thinking is an approach for structured and collaborative development of new solutions, knowledge about them, and their use and environment. " In particular:

- application of existing knowledge and increasing the knowledge base through rigour cycles,
- the needs of communities, national stakeholders and industries, which inform design through relevance cycles.

Within this overall concept, our project has 3 research objectives:

- construction of a dynamic database of amplification factors for sites and buildings in Wellington,

- understanding the needs, expectations and risks of the Wellington urban population and tailoring EEW to these individual levels,
- harnessing seismic and communication data streams within sensors and phones.

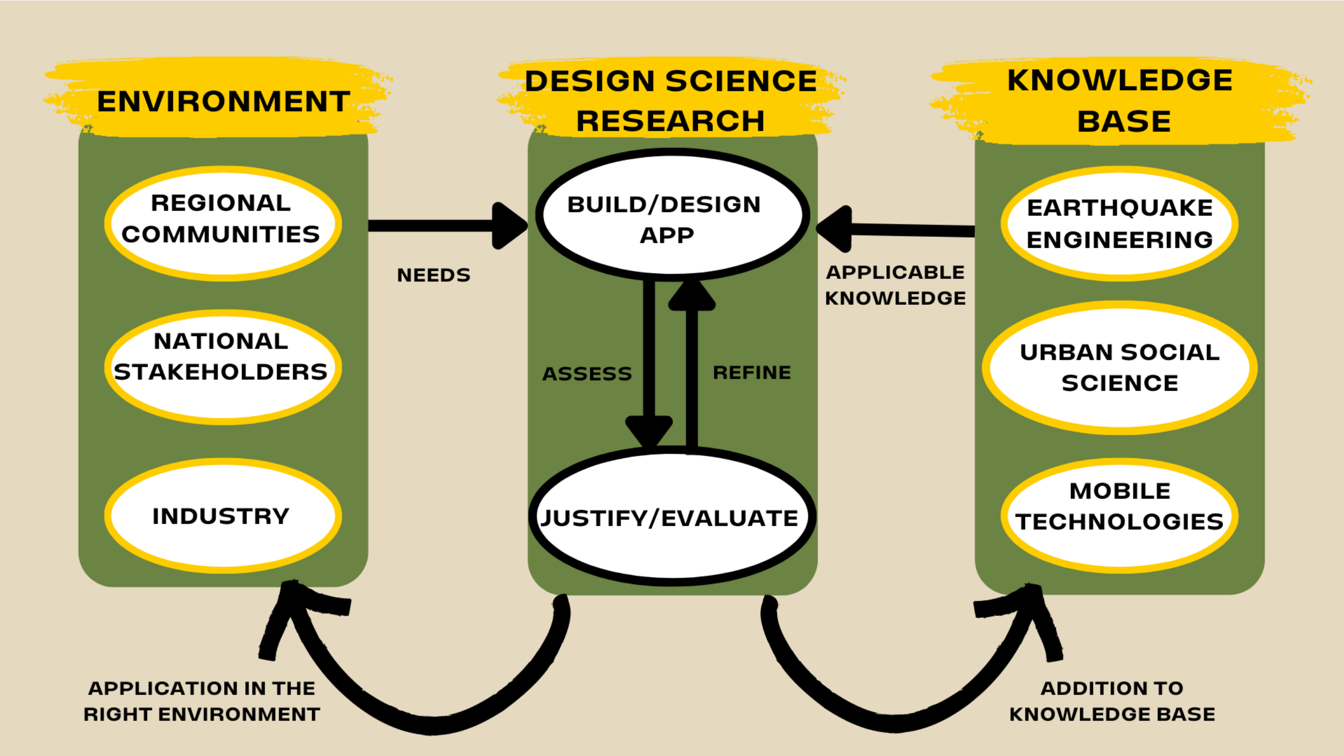

Figure 2: Diagram of the proposed "design science" research plan for our planned "Urban EEWS" project

This project is extremely timely.

NZ currently benefits from the success and failure of international EEWS and now has a chance to step up by including urban novel EEWS for the first time. This original work is complementary to ongoing research on the feasibility of EEWS for NZ [9] and Community based EEW [20].

We have a duty to work alongside Māori communities.

Māori communities are key contributors not only to the resilience to their communities but also have played significant roles to helping those in need following disasters (examples of 2010-2011 Canterbury and 2016 Kaikōura earthquakes). A proposed network of seismic sensors in Te Upoko o the Ika (NZ lower North Island) marae (meeting houses) will provide precious seconds of early warning, situation awareness, and science to communities. However, this cannot be achieved without regular meetings with a Māori advisory panel to facilitate the transfer of scientific findings to industry, tangata whenua, and local and national government organisations.

CONCLUSIONS

We propose to develop an enhanced urban earthquake early warning system (EEWS) suited to the urban set-up of Aotearoa New Zealand's cities, starting with Wellington. Our current approach is to develop a mobile app catered towards multi-storey building dwellers, owners, and managers. The app will leverage already existing, continuously recorded seismic data not only to directly derive site specific ground/building shaking but also to push site specific earthquake early warnings (EEW) directly through the app. Our project framework will be based on design science allowing to develop a Minimum Viable Product (MVP) that addresses practical problems experienced by communities and the seismic monitoring industry that is evolving in the NZ earthquake resilience space.

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REFERENCES

[1] https://www.icnz.org.nz/industry/canterbury-earthquakes/

[2] Kamigaichi, O. (2004). JMA earthquake early warning. Journal of JAEE, 4(3), 134–137. doi:10.5610/jaee.4.3_134

[3] Espinosa-Aranda J. M., A. Jimenez, O. Contreras, G. Ibarrola, and Ortega R. (1992). Mexico City Seismic Alert System, International Symposium on Earthquake Disaster Prevention, Proceedings CENAPRED-JICA, Vol. I, pag. 315-324, Mexico.

[4] Hsiao, N.-C., Wu, Y.-M., Shin, T.-C., Zhao, L., & Teng, T.-L. (2009). Development of earthquake early warning system in Taiwan. Geophysical Research Letters, 36(2). doi:10.1029/2008gl036596

[5] https://www.shakealert.org/

[6] Sendai Framework for Disaster Risk Reduction 2015-2030 (A/CONF.224/CRP.1) https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

[7] https://www.transport.govt.nz/about-us/news/social-cost-of-road-crashes-and-injuries-2019-update/

[8] Olds, S., Sumy, D., Crayne, J., Anderson, M., Pridmore, C., McBride, S., Jenkins M., Magura B., Johnson J. and DeGroot, R. (2021, December). Supporting Earthquake Early Warning Response and Learning through ShakeAlert Educational Resources. In AGU Fall Meeting Abstracts (Vol. 2021, pp. NH35B-0470).

[9] Becker, J.S., Potter, S.H., Prasanna, R., Tan, M.L., Payne, B.A., Holden, C., Horspool, N.A., Smith, R. and Johnston, D.M. (2020). *Scoping the potential for earthquake early warning in Aotearoa New Zealand : a sectoral analysis of perceived benefits and challenges.* International Journal of Disaster Risk Reduction, 51: article 101765; doi: 10.1016/j.ijdrr.2020.101765

[10] Saunders, J. K., Aagaard, B. T., Baltay, A. S. and Minson, S. E. (2020). "Optimizing earthquake early warning alert distance strategies using the July 2019 Mw 6.4 and Mw 7.1 Ridgecrest, California, earthquakes". Bulletin of the Seismological Society of America, 110(4), 1872–1886. https://doi.org/10.1785/0120200022

[11] Spallarossa D. and others (2019). "On-site earthquake early warning: a partially non-ergodic perspective from the site effects point of view", Geophysical Journal International, Volume 216, Issue 2, Pages 919–934, https://doi.org/10.1093/gji/ggy470.

[12] Farid Ghahari S., Baltay A., Çelebi M., Parker G. A., McGuire J.J. and Taciroglu E. (2022). *Earthquake Early Warning for Estimating Floor Shaking Levels of Tall Buildings.* Bulletin of the Seismological Society of America 2022;; 112 (2): 820–849. doi: https://doi.org/10.1785/0120210224

[13] Giovanni A., Gueguen P., Picozzi M. and Ghimire S. (2021). *Earthquake Early Warning System for Structural Drift Prediction Using Machine Learning and Linear Regressors*, Frontiers in Earth Science 9 DOI=10.3389/feart.2021.666444

[14] GeoNet Structural Array Data https://www.geonet.org.nz/data/types/structural_arrays https://doi.org/10.21420/5M59-SM97

[15] Chandramohan R., Ma Q., Wotherspoon LM., Bradley BA., Nayyerloo M., Uma SR. and Stephens MT. (2017) Response of instrumented buildings under the 2016 Kaikōura earthquake. Bulletin of the New Zealand Society for Earthquake Engineering 50(2): 237-252. http://dx.doi.org/10.5459/bnzsee.50.2.237-252.

[16] Simkin G, Beskhyroun S, Ma Q, Wotherspoon LM and Ingham J (2015). "Measured response of instrumented buildings during the 2013 Cook Strait Earthquake Sequence". Bulletin of the New Zealand Society for Earthquake Engineering, 48(4). DOI: https://doi.org/10.5459/bnzsee.48.4.223-234

[17] Skłodowska, A.M., Holden, C., Guéguen, P., Finnegan J. and Sidwell G. (2021). S*tructural change detection applying long-term seismic interferometry by deconvolution method to a modern civil engineering structure (New Zealand).* Bull Earthquake Eng 19, 3551–3569 (2021). https://doi.org/10.1007/s10518-021-01110-3

[18] Becker, JS., Blake, D., Thompson, J., Vinnell, LJ. and Doyle, EEH. (2022). *Communicating evacuation information to multi-storey apartment dwellers: a case study of the 2016 Kaikōura earthquake in Te Whanganui-a-Tara (Wellington), Aotearoa New Zealand*. New Zealand Journal of Geology and Geophysics

[19] Vinnell LJ, Inch P, Johnston DM. and Horspool N. *Behavioral responses to earthquake shaking: Video footage analysis of the 2016 Kaikōura earthquake in Wellington, Aotearoa New Zealand*. Earthquake Spectra. 38(3):1636-1660. doi:10.1177/87552930221086303

[20] Cui, A. (2021). College students shine in CRISiSLab Challenge 2021. CRISiSLab Blog. https://crisislab.org.nz/2021/08/college-students-shine-in-crisislab-challenge-2021/

[21] Prasanna, R., Chandrakumar, C., Nandana, R., Holden, C., Punchihewa, A., Becker, J.S., Jeong, S., Liyanage, N., Ravishan, D., Sampath, R. and Tan, M.L. (2022). "Saving Precious Seconds"—A Novel Approach to Implementing a Low-Cost Earthquake Early Warning System with Node-Level Detection and Alert Generation. Informatics, 9, 25. https://doi.org/10.3390/informatics9010025

[22] Becker, J. S., Potter, S. H., Vinnell, L. J., Nakayachi, K., McBride, S. K. and Johnston, D. M. (2020). *Earthquake early warning in Aotearoa New Zealand: a survey of public perspectives to guide warning system development*. Humanities and Social Sciences Communications, 7(138), 1–12. https://doi.org/10.1057/s41599-020-00613-9

[23] Peffers, T., Tuunanen, M. A., Rothenberger, and Chatterjee S. (2007). "A design science research methodology for information systems research," Journal of Management Information Systems, vol. 24, no. 3, pp. 45–77, 2007, doi:10.2753/MIS0742-1222240302