Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 58, No. 3, September 2025

TECHNICAL NOTE

INSTALLATION METHODS FOR GROUND MOTION SENSORS IN COMMUNITY-ENGAGED EARTHQUAKE EARLY WARNING SYSTEM

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(Submitted *July 2024*; Reviewed *August 2024*; Accepted *October 2024*)

ABSTRACT

This research investigates installation methods for ground motion accelerometers within a community-engaged Earthquake Early Warning (EEW) network, where untrained volunteers install sensors in their homes. Four installation methods were evaluated on plush wool-type carpets using a two-dimensional horizontal axis shake table with sinusoidal waveforms within the expected frequency range of earthquake ground motions and real-world earthquake acceleration data from historical events. The performance of these methods in accurately capturing key characteristics of ground motions was assessed through statistical and frequency analysis relative to a reference accelerometer fixed to the shake table. The initial findings with two-dimensional horizontal shake table testing indicate that both the loosely placed sensor and the anti-slip sticker method provide effective solutions, with the loosely placed sensor offering optimal accuracy and ease of installation and the anti-slip sticker method providing greater stability. The study highlights the need for future research to explore additional installation methods and floor types using three-dimensional shake tables to enhance broader applicability.

https://doi.org/10.5459/bnzsee.1708

INTRODUCTION

New Zealand (NZ), prone to frequent seismic activity due to its geographical position, currently needs a comprehensive national Earthquake Early Warning System (EEWS). Although the GeoNet program provides valuable seismic data, it does not offer real-time earthquake warning capabilities. In response, the CRISiSLab research group at Massey University has launched a pioneering project to develop a community-engaged EEWS utilising low-cost Raspberry Shake 4D (RS4D) ground motion sensors equipped with MEMS-based accelerometers [1]. These sensors represent an innovative step towards enhancing seismic preparedness through a decentralised, community-driven strategy. This technical note focuses on a series of shake table tests to evaluate various installation methods for RS4D sensors. The aim is to identify a balance between accurate seismic data collection and practical installation by untrained volunteers in residential settings, which is crucial for successfully deploying a community-engaged EEWS.

SHAKE TABLE TESTS

Test Setup

The experimental setup was designed to replicate residential conditions closely, focusing on plush wool carpet flooring due to its prevalence in NZ homes. The evaluation considered five distinct installation methods for the RS4D sensors, with a comprehensive test plan developed to assess each method's impact on data accuracy and sensor stability.

Figure 1 illustrates the two-dimensional horizontal axis shake table implementation for the plush wool carpet floor type. Five sensors were installed on the shake table, with each sensor employing a different installation method including one reference sensor fixed directly to the shake table, and four sensors installed using ‘simple’ methods:

1. Reference Sensor: Served as a control, directly screwed onto the shake table to ensure maximum fidelity in recorded seismic data.
2. Loosely Placed Sensor: Positioned freely on the plush wool carpet to assess performance without any securing mechanism.
3. Loosely Placed Sensor with Anti-Slip Sticker: Employed an anti-slip sticker affixed to the base of the sensor to gauge the effect of minimal stabilisation on data accuracy.
4. Sensor with Steel Base: A steel plate was attached to the sensor's base, adding weight and stability to examine if increased inertia benefits data integrity.
5. Sensor Fixed with Tape: Utilised double-sided tape for attachment.

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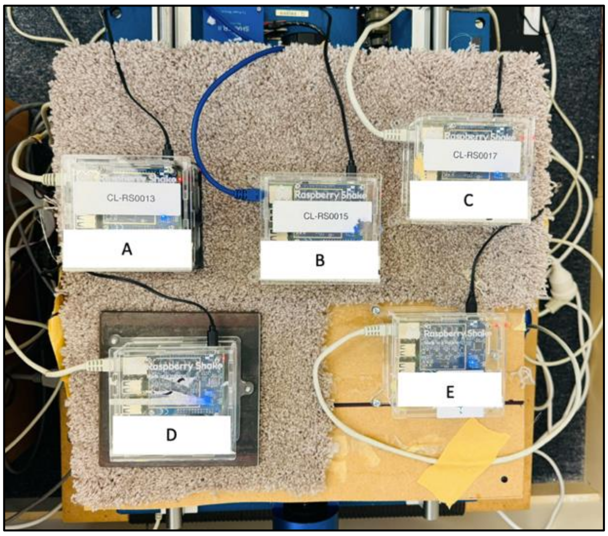


Figure 1: Shake table test setup for plush wool carpet flooring with the four different installation methods along with the reference sensor: (a) a sensor with an anti-slip sticker, (b) a sensor stuck to the floor, (c) a sensor placed loosely, (d) a sensor with a steel plate, and (e) a sensor screwed to the shake table (reference sensor).

Ground Motion Series

The tests were carried out in two phases to provide a range of performance data. First, the sensors were subjected to sinusoidal waves across selected frequencies (0.1 Hz to 20 Hz) in both east-west and north-south directions horizontal directions, reflecting typical seismic activity ranges. This phase of the work aimed to assess sensor responses to a spectrum of the inputs, using frequencies of 0.5, 1, 5, 10, and 15 Hz for a targeted examination of sensor performance in varying seismic scenarios.

Next, the study expanded its focus to evaluate the performance of seismic sensor installation methods using recorded data from three historically significant earthquakes: the 1992 Cape Mendocino earthquake (EQ1), the 1940 El Centro earthquake (EQ2), and the 1994 Northridge earthquake (EQ3). These events were chosen for their notable impacts on seismic research, providing a broad spectrum of data for realistic sensor performance assessment.

For EQ1, 84 strong motion sensors recorded data from the 1992 Cape Mendocino earthquake, which affected the North Coast of California, United States. The specific station from which the ground motion data was used in this study is Cape Mendocino. The 1940 El Centro earthquake (EQ2) affected both the United States and Mexico, with data from the El Centro Array station used in this analysis. The 1994 Northridge earthquake (EQ3) impacted the Greater Los Angeles Area in Southern California, United States, with over 200 stations recording the event; the ground motion data in this study was taken from the Sylmar - Olive View Med FF station.

Factors influencing selection included each earthquake's area intensity, duration spread (D5-95), and spectral acceleration at approximately 0.1 seconds. EQ1's high intensity and broad duration spread are ideal for assessing sensors in intense seismic conditions. EQ2 offers a range of motion intensities for understanding sensor behaviour in variable conditions. Lastly, EQ3, with its moderate intensity and significant spectral acceleration, is apt for testing sensor accuracy in intermediate yet significant seismic events. As summarised in Table 1, the characteristics of these earthquakes are instrumental in evaluating the effectiveness of different sensor installation methods. The ground motion data simulated with the shake table was scaled to the maximum allowable motion, following the specifications of the shake table.

SINUSOIDAL MOTION RESULTS

The study utilised Fourier Spectral Analysis (FSA) to examine ground motion data from sensors compared to a reference sensor (Table 2), with the Root Mean Square Error (RMSE) serving as the quantifiable metric for accuracy in seismic signal capture. Results from Table 3 show that the loosely placed sensor installation method consistently yielded the lowest RMSE values across a wide range of frequencies. For instance, at 0.1 Hz, the RMSE was just 0.00008, and even at higher frequencies like 20 Hz, the value increased only to 0.02707. The anti-slip sticker installation method also performed well, showing minor deviations compared to the loosely placed sensor, with an RMSE of 0.00009 at 0.1 Hz and 0.02887 at 20 Hz. In contrast, other methods, such as sticking to the floor and steel plate installations, exhibited higher RMSE values, indicating a more significant deviation from the reference sensor data. These findings highlight the loosely placed sensor as the most accurate, followed closely by the anti-slip sticker method.

Table 1: Area intensity, duration spread (D5-95), and spectral acceleration at approximately 0.1 seconds for the chosen earthquakes in the North-South direction.

EQs	Areas Intensity (m/s)			Peak Ground Acceleration (PGA) (m/s^{-2})			Duration (s)			Spectral Acceleration at ~0.1s (m/s^{-2})		
	East-West	North-South	Vertical	East-West	North-South	Vertical	East-West	North-South	Vertical	East-West	North-South	Vertical
EQ1	5.96	2.39	1.33	14.65	10.19	7.25	6.2	9.68	6.28	15.4	5.35	5.88
EQ2	1.69	1.72	1.34	5.19	3.76	5.83	8.3	9.55	4.19	9.57	9.49	4.06
EQ3	2.60	5.01	1.14	5.93	8.27	5.26	6.8	5.32	8.44	13.1	18.3	2.4

Table 2: Ground motion recordings and Fourier spectra for five sensors across selected frequencies (0.1 to 20 Hz).

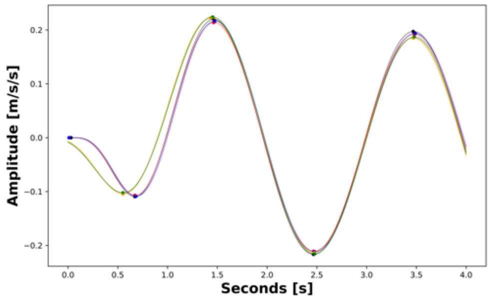
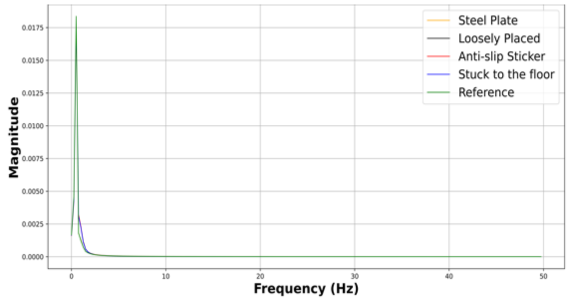
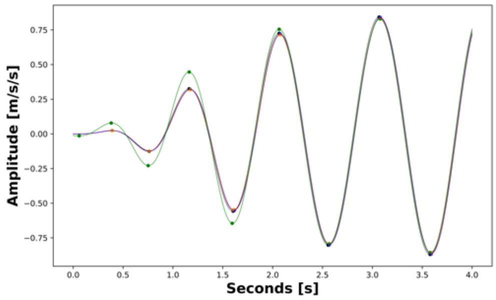
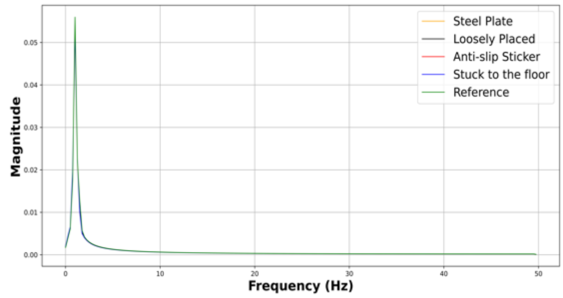
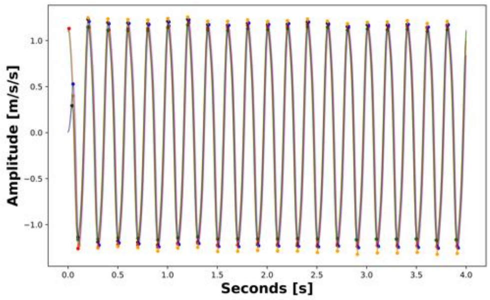
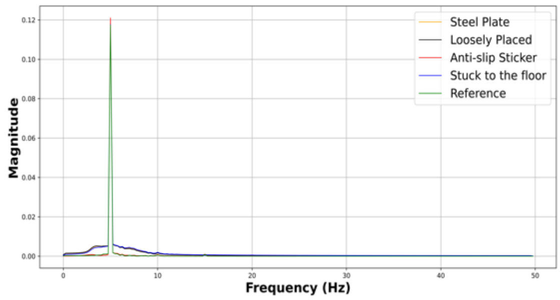
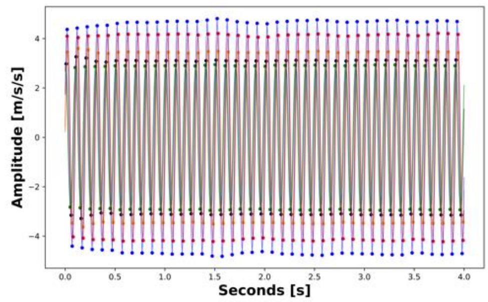
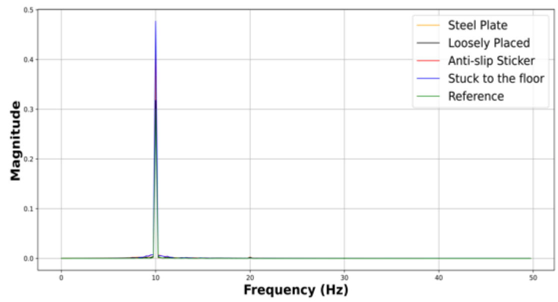
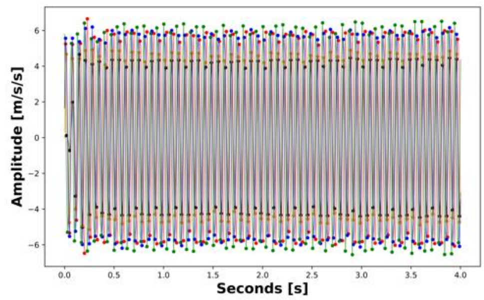
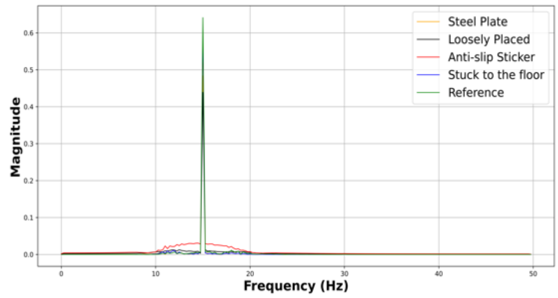
Frequency	Ground motion recordings	Fourier spectrum
0.5 Hz		
1 Hz		
5Hz		
10Hz		
15Hz		

Table 3: RMSE values for FS across different installation types compared to the reference sensor.

Method	0.1 Hz	0.3 Hz	0.5 Hz	1 Hz	3 Hz	5 Hz	7 Hz	10Hz	13 Hz	15 Hz	17 Hz	20 Hz
Loosely placed	0.00008	0.00015	0.00023	0.00057	0.00029	0.00064	0.00307	0.00368	0.00546	0.01315	0.00544	0.02707
Anti-slip Sticker	0.00009	0.0001	0.00024	0.0006	0.0003	0.00099	0.00432	0.01063	0.00497	0.02049	0.0045	0.02887
Stuck to the floor	0.00012	0.00012	0.00028	0.00068	0.00031	0.00087	0.0043	0.0106	0.00544	0.0056	0.0034	0.02413
Steel plate	0.00015	0.00018	0.00027	0.0008	0.00046	0.00144	0.00803	0.00829	0.00852	0.01128	0.0053	0.02658

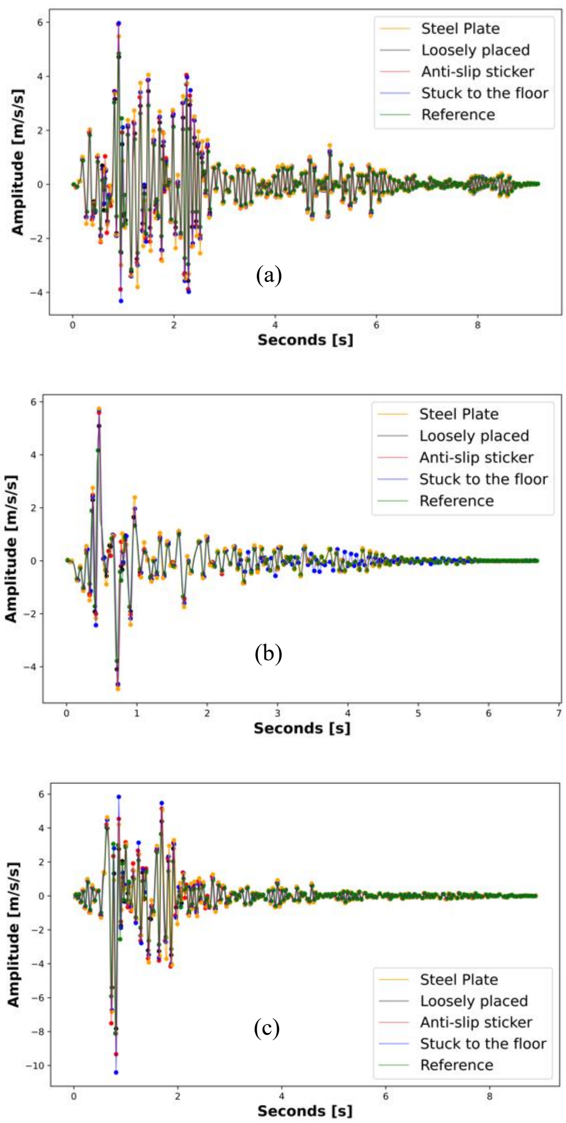


Figure 2: Displays the waveforms captured for the chosen three earthquakes in both east-west and north-south horizontal directions using the four sensor installation methods mentioned above alongside the reference sensor.

EARTHQUAKE GROUND MOTION RESULTS

The study conducted shake table simulations in both *in east-west and north-south* horizontal directions (Figure 2) of three significant earthquakes to evaluate how various RS4D sensor installation methods on plush wool carpet flooring capture seismic data. The comparative analysis, which included visual and statistical evaluations of waveform data, revealed significant deviations for sensors installed using a steel plate method compared to a reference sensor's recordings. In contrast, the loosely placed sensor on the plush wool carpet demonstrated a closer match to the reference sensor, indicating high accuracy in ground motion detection. RMSE values from Table 4 further support this, with the loosely placed method consistently showing the lowest deviations across all earthquake scenarios. For instance, during EQ1, the RMSE for the loosely placed sensor was 0.0027, while the anti-slip sticker method, which performed second best, had an RMSE of 0.0046. Sticking to the floor and using a steel plate showed higher RMSE values across the three earthquakes, indicating notable deviations from the reference sensor. This pattern persisted across EQ2 and EQ3, confirming the precision of the loosely placed method, followed by the anti-slip sticker method's reliability in accurately capturing seismic signals.

Table 4: RMSE values in comparison to the reference sensor.

Earthquake	Loosely placed	Anti-slip Sticker	Stuck to the floor	Steel plate
EQ1	0.0027	0.0046	0.0048	0.0051
EQ2	0.003	0.0041	0.0051	0.0047
EQ3	0.004	0.0048	0.0061	0.0077

The Acceleration Response Spectrum (ARS) analysis aligned with these results, showing that the loosely placed sensors' acceleration spectra closely tracked the reference sensor in all three simulations, particularly in the mid-period range, as depicted in Figure 3.

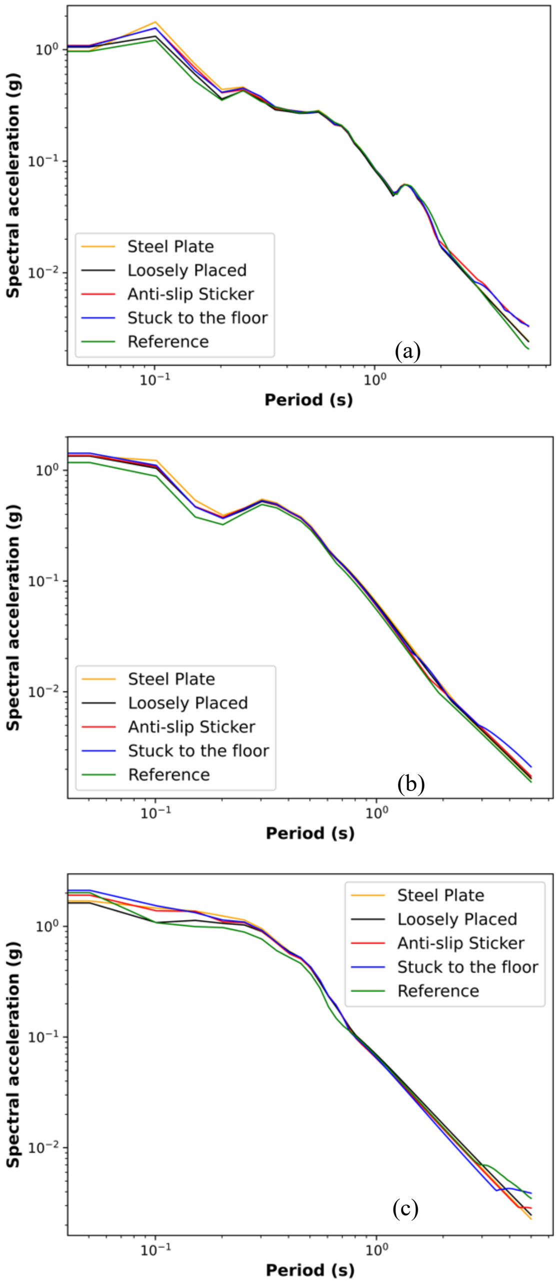


Figure 3: Displays spectral acceleration comparison captured for the chosen three earthquakes in both east-west and north-south horizontal directions using the mentioned four sensor installation methods alongside the reference sensor.

RMSE values from Table 5, such as 0.0017 for EQ1, underscore the method's reliability. The anti-slip sticker-based sensor installation method showed the second-best performance, closely following the loosely placed sensor with minimal deviations.

Peak Ground Acceleration (PGA) analysis provided additional insights into installation method performance, highlighting the loosely placed method's consistency with the reference sensor (Table 6). Notably, the loosely placed sensors deviated by just 2.7% for EQ1, far less than the deviations for other methods. For EQ2 and EQ3, deviations of 22.18% and 3.42% were observed. The anti-slip sticker-based sensor installation method showed the second-best performance compared to the reference sensor, with deviations of 22.41% for EQ1, 34.26% for EQ2, and 15.16% for EQ3.

Table 5: RMSE values for acceleration response spectrum analysis.

Earthquake	Loosely placed	Anti-slip Sticker	Stuck to the floor	Steel plate
EQ1	0.0017	0.0043	0.0062	0.0042
EQ2	0.0029	0.0034	0.0048	0.004
EQ3	0.005	0.006	0.0079	0.0073

Table 6: Displays PGA percentage difference with reference to the reference sensor computed for the chosen three earthquakes using the mentioned four sensor installation methods.

Earthquake	Loosely placed (%)	Anti-slip Sticker (%)	Stuck to the floor (%)	Steel plate (%)
EQ1	2.7	22.41	23.14	23.09
EQ2	22.18	34.26	36.85	37.89
EQ3	3.42	15.16	28.46	15

A COMMENT ON VERTICAL ACCELERATION

The shake table's limitation to only horizontal two directional movements required an assessment of sensor installation slip without explicitly applying vertical acceleration. The potential for slip was evaluated by comparing the horizontal shear force applied by the earthquake to the static frictional force at the sensor installation interface, with a frictional force greater than the seismic shear force indicating that no slip would occur.

Vertical ground motion data from the PEER Ground Motion Database[2] were used to analyse the vertical ground reaction force applied to sensors during three earthquake scenarios for each installation method. The ratio of seismic shear force to frictional force was plotted over the time series for each earthquake, establishing a no-slip threshold at a ratio value of 1 (Figure 4). Results indicated that installations with anti-slip stickers had the least potential for slip, followed by steel-plated installations. The loosely placed sensor exhibited the highest probability of slip among the methods tested.

Despite the lower stability of the loosely placed sensor, it demonstrated the highest accuracy in seismic signal replication, as evidenced by consistently lower RMSE values across a broad frequency range. This accuracy, combined with the simplicity of the installation process and the absence of a need for additional securing mechanisms, highlights the effectiveness of the loosely placed method for RS4D sensor installation on plush wool carpeting. On the other hand, the anti-slip sticker method also showed strong performance, with minimal deviations compared to the loosely placed sensor and greater stability against slip. Given these initial findings with two-dimensional shake table testing, this study recommends both the loosely placed and anti-slip sticker installation methods, acknowledging that each has advantages and disadvantages.

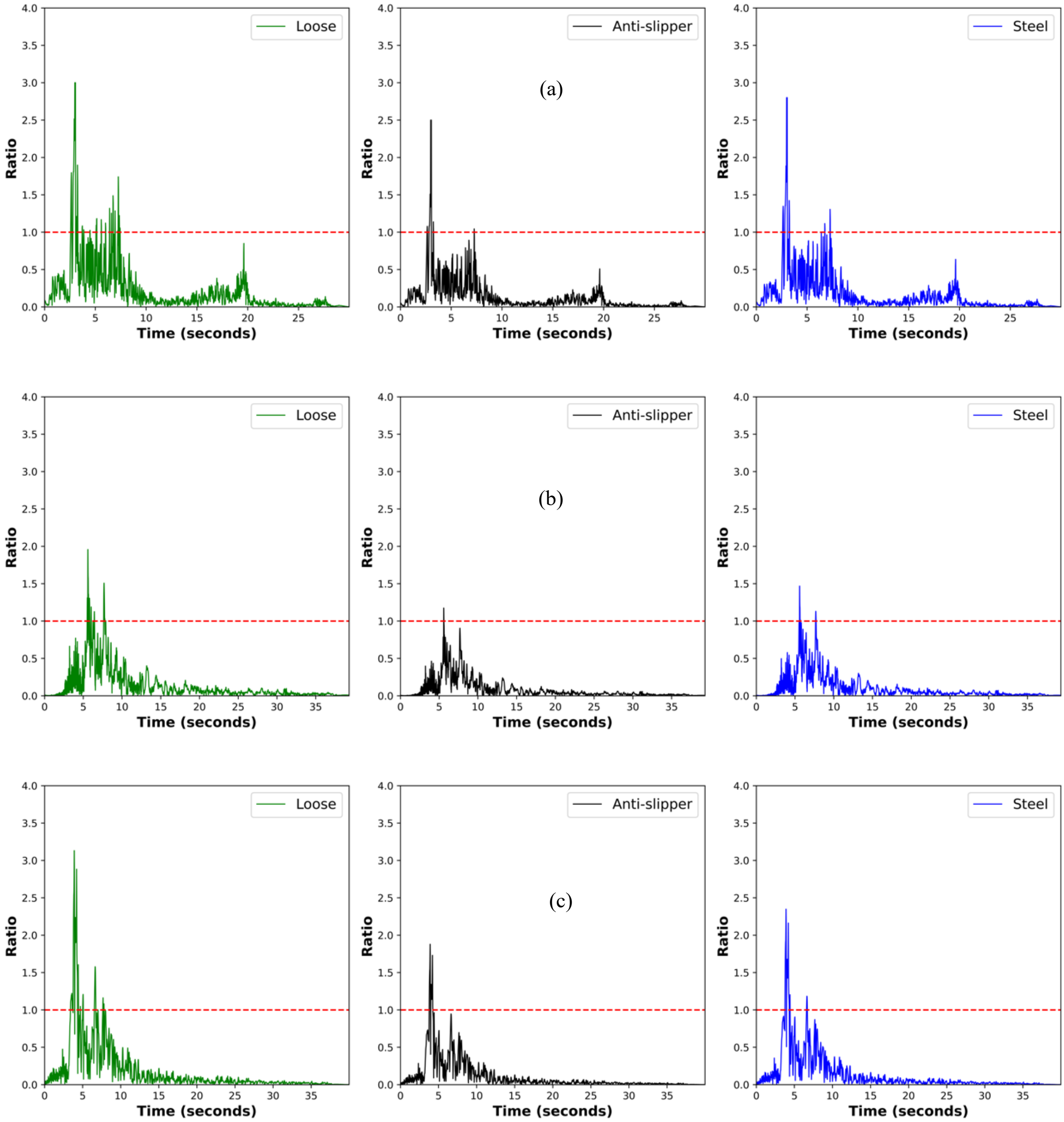


Figure 4: (a), (b) and (C) show the ratio of horizontal force to frictional force at the wool carpet interface for EQ1, EQ2 and EQ3, respectively, along with their installation methods (loosely placed, anti-slip stickered and steel plated). The red horizontal line represents the stability threshold ratio value of 1.

To identify the most suitable installation method, further research using a three-dimensional shake table is required. Also in future tests, multiple sensors with the same installation method will also be explored on a larger shake table floor. This will enable a more comprehensive sensor performance evaluation under realistic seismic conditions, providing deeper insights into the optimal installation techniques.

CONCLUSIONS

This research evaluated four RS4D sensor installation methods on plush wool carpets in NZ homes. It identified using two-demensional shake table testing that both the loosely placed and anti-slip sticker methods as effective, with the loosely placed method demonstrating high accuracy in seismic data replication and the anti-slip sticker method providing greater stability against slip. Despite the shake table's limitation to simulating only horizontal ground motion, the developed methodology is adaptable and robust, suitable for advanced, three-dimensional shake tables and applicable for broader testing across various flooring types. Future studies will expand this research to include a broader range of flooring materials in residential and commercial settings. They aim to develop guidelines for optimal sensor installation using three-dimensional shake tables to analyse vertical movements closely. This work significantly enhances the effectiveness of community-engaged EEW networks by recommending the most suitable sensor installation methods for community households.

REFERENCES

1 Prasanna R, Chandrakumar C, Nandana R, Holden C, Punchihewa A, Becker JS, Jeong S, Liyanage N, Ravishan D, Sampath R and Tan ML (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**(1): 25. https://doi.org/10.3390/informatics9010025

2 Goulet CA, Kishida T, Ancheta TD, Cramer CH, Darragh RB, Silva WJ, Hashash YMA, Harmon J, Parker GA, Stewart JP and Youngs RR (2021). "PEER NGA-East database". *Earthquake Spectra*, **37**(1_suppl). https://doi.org/10.1177/87552930211015695