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Assessment of seismic vulnerability in reinforced concrete buildings in Tawau, Sabah: A study on damage potential

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ABSTRACT Tawau located in Sabah is deemed to possess a moderate level of seismic activity, primarily because previous earthquakes were concentrated in the Lahad Datu-Tawau region due to the existence of an active fault. Regrettably, a significant number of reinforced concrete (RC) buildings in this area lack awareness and comprehension of earthquake-resistant construction practices, which necessitate the evaluation of building vulnerability in high-seismic-hazard zones. The goals of this study are to conduct fieldwork for the evaluation of the damage potential on 105 existing RC buildings and develop a building damage map in the Tawau area. This entails employing Rapid Visual Screening (RVS) surveys in accordance with the FEMA P-154 guidelines, employing a scoring system to assess the potential for damage in buildings, and subsequently presenting the results on a map. The results of this survey reveal that most buildings in this study exhibit plan irregularities and vertical irregularities in their beams do not align with columns and weak or/and soft story, respectively. This survey concludes that the most prevalent damage potential among the surveyed buildings in this area is Grade 3, followed by Grade 4, with the least prevalent being buildings with a Grade 2 damage potential.

KEYWORDS: RC buildings, RVS, Damage evaluation, Moderate seismicity, Tawau
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Original Article

INTRODUCTION

Sabah is susceptible to both regional and local earthquakes, which are occasionally felt as minor tremors in the area. Regarding regional earthquakes dating back to 1900, there have been 90 shallow earthquakes with focal depths of less than 70 kilometres with magnitudes exceeding 7.0 (Mw) within 1000 km of Sabah's coastline, based on data from earthquake databases maintained by the United States Geological Survey (USGS). Simultaneously, data from the USGS earthquake database shows that since 1973, there have been 221 earthquakes with a magnitude greater than 6.0 (Mw) occurring within 1000 km of Kota Kinabalu. Figure 1 illustrates the origins of these earthquakes, which typically stem from active subduction zones, including the Philippine Trench, Manila Trench, Negros Trench, Sulu Trench, Cotabato Trench, and North Sulawesi Trench. Consequently, the seismotectonic environment in Sabah reveals that the occurrence of earthquakes is closely linked to plate tectonic movements in the region, as detailed in a study by Tongkul *et al.* (2020).

In Tawau, the seismic activity is characterized as moderate, as defined by Mansor *et al.* (2017). This classification is based on a macrozonation map that utilizes two-thirds of the values from a 2,475-year average return period, which corresponds to ground motions having a 2% probability of exceedance in 50 years. The USGS earthquake database records approximately 18 low to moderate earthquakes with a magnitude greater than 4.0 Mw, both onshore and offshore, between the years 1900 and 2019, as detailed in Table 1. Tongkul (2020) indicates that most of the earthquakes in this region have a magnitude of less than 5.0 Mw. However, there have been two notable exceptions, with earthquakes of magnitude 6.0 Mw or higher, namely the 1976 Lahad Datu earthquake (6.2 Mw) and the 1923 Lahad Datu earthquake (6.3 Mw). For instance, the Lahad Datu earthquake in July 1976 resulted in significant property damage, particularly in the epicentral area of Lahad Datu. The ground floor walls of the new Lahad Datu police complex sustained significant damage, and nearby structures such as the Fire Department flat, Telecom building, and low-cost houses were also affected.

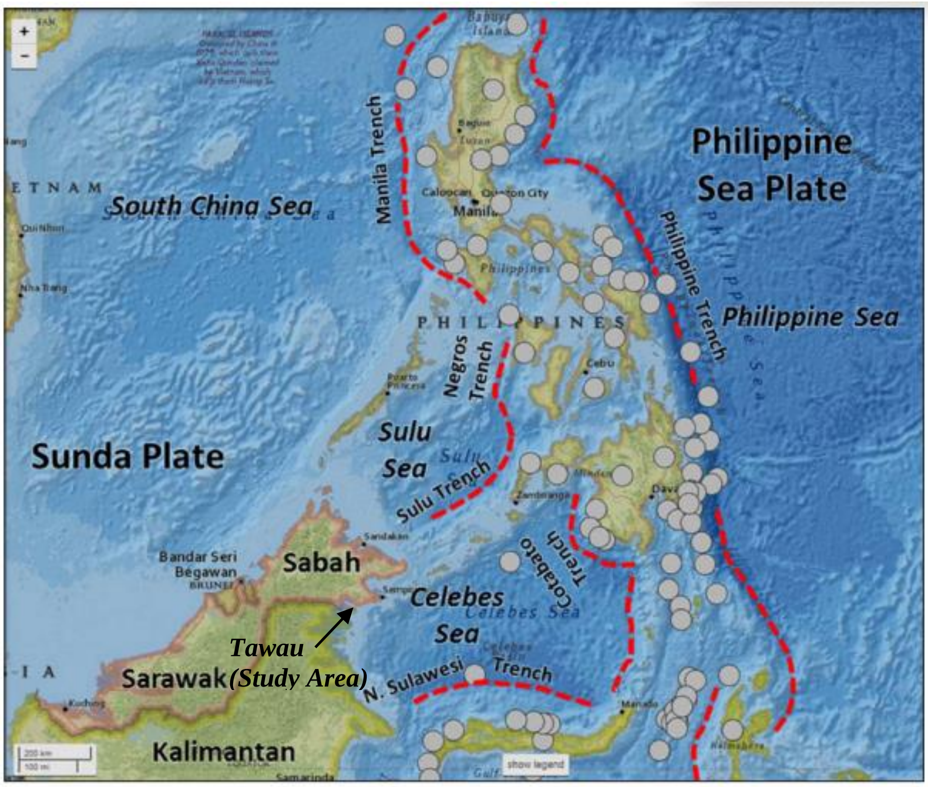

Figure 1. Seismotectonic setting in Sabah (Tongkul *et al.*, 2020) and study region (Tawau) shown on the map

Table 1. Earthquake distribution near to Tawau based on USGS (Tongkul, 2020)

Event date	Time	Depth (km)	Magnitude (M)
11-08-1923	00:54	35	6.3
25-07-1976	14:03	33	5.3
26-07-1976	02:56	33	6.2
26-07-1976	03:03	33	5.3
26-07-1976	05:35	33	5.2
26-07-1976	08:36	33	5.3
26-07-1976	09:43	33	5.1
26-11-1982	19:29	33	4.5
14-03-1984	00:39	50	5.7
13-02-1989	20:24	33	4.4
04-07-1992	22:33	10	4.6
02-11-1994	01:43	55	5.7
11-08-1995	06:21	33	4.1
06-12-1996	12:42	33	4.4
09-04-2008	00:51	28	4.5
05-09-2014	01:15	12	4.3
04-03-2016	00:43	35	4.1
26-03-2017	09:30	34	4.6

The limited earthquake focal mechanism solutions provided by the USGS suggest that the local earthquakes in Sabah result from extensional stress regimes (associated with normal faults) and compressional stress regimes (involving thrust faults and strike-slip faults). Active faults are defined as linear areas where significant earth movement occurs systematically and continuously, and if there is evidence of movement or seismic activity within the last 10,000 years, the fault is typically considered active, as explained by Tongkul (2017). Consequently, the seismic activity in Sabah strongly indicates the presence of active faults, including thrust faults, strike-slip faults, and normal faults, according to research by Tongkul (2021).

A previous study conducted by Tongkul (2017) discovered that most of the thrust faults and strike-slip faults are located in Tawau with numerous fault scarps, damaged roads, mud volcanoes, and hot springs. Furthermore, historical earthquakes in Tawau, such as the 1976 magnitude 6.2 Lahad Datu earthquake, have been associated with strike-slip faults, whereas the 1984 magnitude 5.7 Tabin earthquake was linked to thrust faults. Figure 2 illustrates numerous linear features, typically ranging from 20 to 40 kilometers in length, in the Lahad Datu-Tawau region. These linear features are mostly attributed to earthquakes caused by thrust faults as depicted by the red line and strike-slip faults as indicated by the purple line.

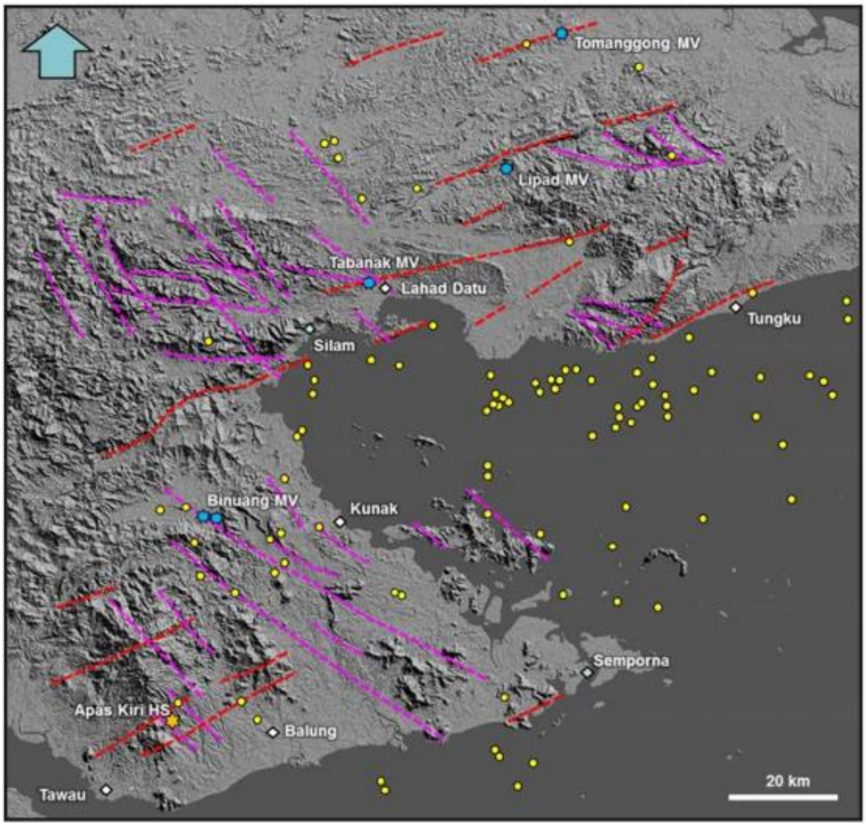

Figure 2. Thrust faults and strike-slip faults in Tawau (Tongkul, 2017)

Given that most of the reinforced concrete (RC) buildings in the study area lack earthquake-resistant construction practices, it is imperative to assess the vulnerability of these buildings in high seismic-risk zones. Tawau is particularly vulnerable due to its high exposure to seismic hazards. Therefore, it is crucial to identify effective ways to mitigate the potentially catastrophic effects of earthquakes in this region. In order to address this need, a field-based methodology known as the Rapid Visual Screening (RVS) survey has been selected as an appropriate approach. This choice is influenced by the insufficient availability of building inventory data for conducting a comprehensive seismic vulnerability assessment. The outcomes of this survey will be utilized to create a building damage map that highlights specific indicators. This map serves as a valuable communication tool in the decision-making process for disaster management. The primary objective of this research is to conduct fieldwork to assess the damage potential of 105 existing RC buildings and to generate a building damage map for Tawau. This effort is a crucial step towards understanding and addressing the seismic vulnerability of the region's building stock, ultimately contributing to better disaster preparedness and mitigation efforts.

This research has the same aims as the previous study by Harith *et al.* (2023) that related to the seismic vulnerability study for analysis of potential damage to buildings in Sabah using the same approach of RVS method to develop the building damage map. However, the current research focused on one part of Sabah only located in Tawau, meanwhile, the previous study concentrated on several parts of Sabah, including Kota Kinabalu, Ranau, Kota Marudu, Kudat, Lahad Datu, Semporna, and Tawau. The seismic vulnerability study in southeast Sabah, specifically Tawau area is to be extended due to a lack of research in comparison to Northeast Sabah, where such studies have been more frequent.

METHODOLOGY

The methodology employed in this study, as depicted in Figure 3, encompasses three distinct phases: the preliminary study, field survey, and building vulnerability assessment. During the initial phase, which focuses on earthquake and seismic hazard conditions, a preliminary study was conducted in accordance with the MSEN1998-1:2015 (2017) guidelines. This phase aimed to evaluate the hazard risk associated with earthquakes and seismic activity in Tawau, specifically in the area of Tawau. The preliminary study serves as the foundation for the subsequent phases of the research, providing essential information about the seismic hazard landscape in the region.

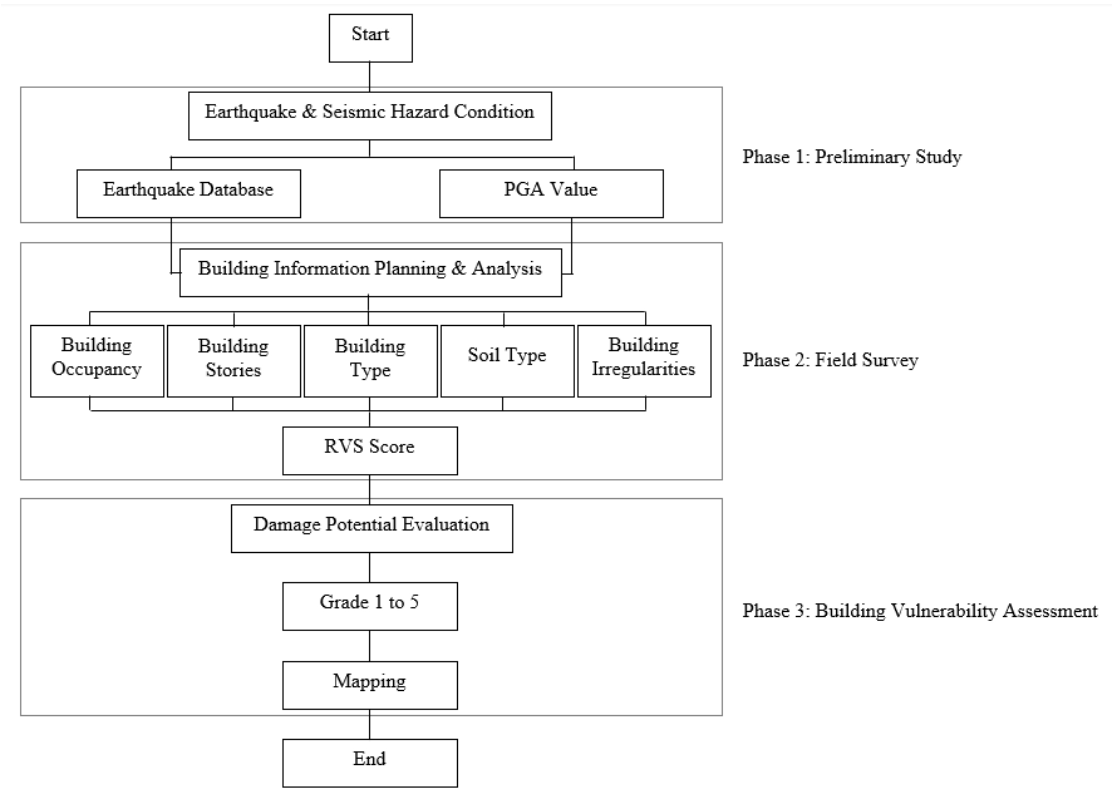

Figure 3. Flowchart of methodology for vulnerability assessment on Tawau RC buildings

In the second phase of the field survey, the research began by collecting information on 105 existing RC buildings and proceeded with their analysis to quantify their overall seismic performance in the study areas. To conduct this survey, a RVS method was employed. This approach involved gathering information about each building and recording it in a data collection form. The choice of using RVS is based on its suitability for assessing building damage without the need for structural calculations. It is considered a more straightforward and practical approach compared to analytical methods that involve detailed calculations and multiple scenarios. This method was recommended by Shah *et al.* (2018) and has also been utilized in previous studies by Jainih & Harith (2020) and Ghafar *et al.* (2015) for assessing the potential for building damage in other areas of moderate seismicity within Sabah.

RVS is a valuable tool for quickly evaluating the condition and potential vulnerability of buildings in a seismic context, making it a suitable choice for the current research in Tawau. In this study, the primary tool used for the RVS survey was the FEMA P-154 Data Collection Form. These forms are categorized into three types based on the relative intensity of seismic risk in the area, namely low, moderate, and high seismicity. Since Tawau falls into the category of moderate seismicity, the RVS forms specific to moderate seismicity, as per the FEMA P-154 (2015) guidelines, were employed. The FEMA P-154 Data Collection Form includes various criteria that are reviewed for each building, and these criteria are used to determine the RVS score. The key parameters considered in the form include occupancy, number of stories, building type, soil type, and irregularities. These criteria help in assessing the seismic vulnerability and performance of each building surveyed.

The occupancy classification is based on the use of the building, and seven distinct occupancy classifications have been identified and recognized in the investigated area, as summarized in Table 2. This classification provides important information for the seismic assessment and risk evaluation of the buildings in the study area.

Table 2. Classification of building occupancy according to FEMA P-154

Building occupancy	Number of buildings
Assembly	2
Commercial	43
Emergency services	2
Industrial	2
Office	21
Residential	21
School	14

Furthermore, the surveyed buildings were categorized based on the number of stories they had, dividing them into three distinct categories: 1 to 3 stories (low-rise) relatively shorter buildings, 4 to 6 stories (mid-rise) with medium height buildings, and more than 7 stories (high-rise) where the tall buildings with multiple stories. Table 3 provides a data tabulation of the distribution of building stories in Tawau. The tabulated data reveals that the majority of buildings in the area fall into the low-rise category, followed by mid-rise buildings, and finally, high-rise buildings are the least common. This categorization by building stories is essential for understanding the building stock in the region and its potential seismic vulnerability, as different types of buildings may respond differently to seismic activity.

Table 3. Classification of building stories

Building stories	Number of buildings
1 to 3	53
4 to 6	43
More than 7	9

Additionally, according to FEMA P-154 (2015), the RVS method is built on the assumption that the buildings being assessed belong to one of the 17 FEMA building types, each identified by alpha-numeric reference codes used in the data collection form. In the context of this study, the focus was specifically on RC buildings. As a result, the surveyed buildings were classified into three distinct types, including C1, C2, and C3 represent concrete moment-resisting frame buildings (MRF), concrete shear wall buildings (SW), and concrete frame buildings with unreinforced masonry infill (URM INF), respectively. The C1 type (MRF) are buildings constructed with concrete frames designed to resist lateral forces, such as those generated by earthquakes. The C2 type (SW) are buildings characterized by the use of concrete shear walls, which provide lateral stability and resistance to seismic forces. The C3 type (URM INF) is categorized as concrete frame buildings that incorporate unreinforced masonry infill. The data pertaining to building types in Tawau, as summarized in Table 4, indicates that the majority of surveyed buildings belong to the C1 and C3 categories. These findings are important for assessing the seismic vulnerability of different building types in the region and for tailoring mitigation strategies accordingly.

Table 4. Classification of building type according to FEMA P-154

Building type	Number of buildings
C1 (MRF)	82
C2 (SW)	4
C3 (URM INF)	19

The soil type, or site class, is a critical factor in determining the amplitude and duration of ground shaking during an earthquake, which, in turn, influences structural damage as mentioned in FEMA P-154 (2015). However, visual methods in the field may not always provide a clear identification of soil types. To address this, the soil type is categorized and represented in a readily usable map format during the RVS survey, usually denoted by letters A through F in the data collection form. For this study, the identification of soil types for the surveyed buildings was facilitated using the European Digital Archive of Soil Maps (EuDasm) website. This approach is consistent with a previous study conducted by Harith *et al.* (2018). Table 5 summarizes the findings related to the soil type of the surveyed buildings in Tawau. The data reveals that the majority of surveyed buildings are situated on dense soil (soil type C) and a smaller proportion on stiff soil (soil type D).

Table 5. Classification of soil type according to FEMA P-154

Soil type	Number of buildings
Dense Soil (C)	103
Stiff Soil (D)	2

After completing the building information section in the data collection form, the final phase of building vulnerability assessment was carried out. This assessment phase aimed to evaluate the potential damage to the existing buildings based on the RVS score calculated for each building. According to FEMA P-154 guidelines, the RVS score is computed by combining the basic score with circled score modifiers specific to the building. The RVS score modifiers come in three types such as basic score, positive score modifiers, and negative score modifiers, where the basic score is the fundamental score assigned to the building. However, the positive score modifiers are related to building qualities or performance attributes that positively enhance the building's performance in the event of an earthquake. These attributes increase the RVS score, indicating better earthquake resistance. Next, for the negative score modifiers are associated with building attributes that have a negative impact on the building's performance during an earthquake. They decrease the RVS score, indicating greater vulnerability to seismic damage. By considering these score modifiers and the basic score, the RVS score provides an overall assessment of a building's vulnerability to seismic activity. The RVS scores are categorized into different ranges, and these ranges are used to determine the building's potential for damage.

These categories are grouped into five grades, ranging from Grade 1 to Grade 5. As per the findings from Mohamad *et al.* (2019), these grades are associated with the following score ranges and levels of potential damage. Grade 1 with a score higher than 2.5 indicates that the building can be considered as having negligible damage potential, with minimal to no structural damage expected in the event of an earthquake. Meanwhile, Grade 2 with a score range of 2.0 to 2.5 is moderately damaged typically exhibiting slight structural damage such as cracks on column frames and walls. In addition, a score between 0.7 to 2.0 is specified as Grade 3 represents structures that would suffer heavy damage in the event of an earthquake, often with cracks in column and beam-column joints of frames at the base and joints of coupled walls. Grade 4 denotes a score range between 0.3 to 0.7 deemed to be at very high risk of damage, where a few columns or a single upper floor may collapse, and lastly, Grade 5 represents a score of less than 0.3 indicates a destructive level of damage potential, where the ground floor parts of the building may collapse during an earthquake. These grades and score ranges help in understanding the expected seismic vulnerability and potential damage levels for the surveyed buildings, which is critical for risk assessment and mitigation planning in Tawau.

RESULT AND DISCUSSION

There are approximately existing RC buildings in Tawau that differ in terms of occupancy, stories, building type, soil type, and building irregularities to calculate the RVS score and evaluate the building damage potential for seismic vulnerability assessment. These variables are considered when calculating the RVS score, which is essential for evaluating the potential for building damage and seismic vulnerability in the study area. Building irregularities, in particular, have a detrimental impact on the seismic performance of a building. They lead to the concentration of seismic forces and demands at specific floor levels or structural elements, which can result in damage, failure, and in severe cases, even building collapse during an earthquake.

The buildings with irregularities in both their vertical and plan configurations are more susceptible to earthquake-induced damage than those with regular shapes. Irregularities contribute to stress concentrations at the corners of the structures, causing the imposed seismic loads to be unevenly distributed. This non-uniform distribution of forces can lead to structural vulnerabilities and potential weaknesses during seismic events. It is crucial to recognize and assess these irregularities in buildings as part of the seismic vulnerability assessment in order to develop appropriate mitigation strategies and enhance the earthquake resilience of the building stock in Tawau. The findings from the study conducted by Khan *et al.* (2019) indicate that vertical irregularities tend to have a more significant negative impact on the seismic performance of buildings compared to plan irregularities. Therefore, in their assessment, plan irregularity receives a lower score modifier since it has a relatively lesser adverse effect on the building's seismic performance.

Based on Figure 4, the data illustrates that the most prevalent plan irregularity of buildings on beams do not align with columns, accounting for 41% of the cases. The other plan irregularities include non-parallel system (35%), re-entrant corner (19%), and diaphragm openings (5%). In Figure 5, it is revealed that half of the surveyed buildings have vertical irregularities, particularly those related to a weak and/or soft story (80%). These irregularities are more common than other vertical irregularities such as out-of-plane setback (15%) and split levels (5%). These findings highlight the significance of addressing and mitigating vertical irregularities, particularly those related to weak and soft stories, as they appear to be the most prevalent and potentially damaging irregularities in the building stock of study area.

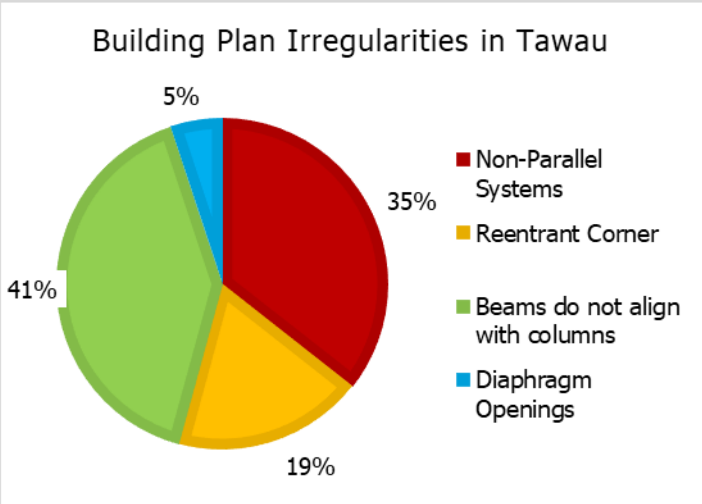

Figure 4. Pie chart of building plan irregularities

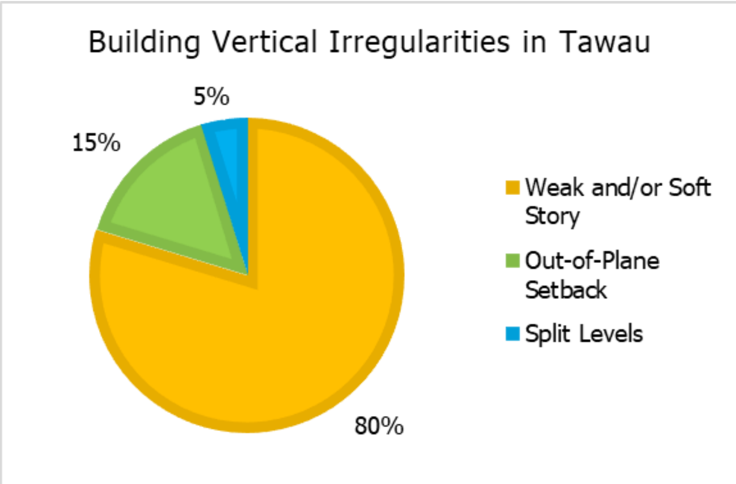

Figure 5. Pie chart of building vertical irregularities

Most buildings with irregularities where beams do not align with columns, as shown in Figure 6 throughout the survey, can indeed introduce significant vulnerabilities that compromise a building's ability to withstand earthquakes. Proper alignment and connection between beams and columns are crucial for the structural integrity and earthquake resistance of a building. The beams and columns work in unison to transfer the loads or forces acting on a structure. Columns are responsible for bearing vertical loads, while beams carry horizontal loads. When these components, beams, and columns, are not correctly aligned or connected, they may not effectively transfer the lateral forces generated during an earthquake. This misalignment can result in an uneven distribution of forces within the structure, increasing the likelihood of structural failure or damage. As noted by Somma *et al.* (2015), the complexity and magnitude of the forces exerted on a building during an earthquake have a significant impact on the strength and performance of its individual structural components. In the context of structural engineering and earthquake resistance, the proper alignment of beams and columns is fundamental to ensuring the safety, stability, and resilience of a building during seismic events. Addressing irregularities in the alignment of beams and columns is an important step in enhancing the earthquake resilience of structures.

Figure 6. Typical buildings with beams do not align with columns

In addition, the majority of buildings with irregularities on weak and/or soft story identified in Figure 7 during the survey, can significantly increase the seismic vulnerability of multi-story buildings. This vulnerability is particularly pronounced in buildings that have an open area on the ground floor. In the case of soft-story buildings, the design often incorporates a robust beam at the first level but features a weak column design. During an earthquake, the seismic forces experienced by these buildings can lead to significant displacement and damage at these weak column joints, as observed in the research conducted by Dora *et al.* (2017). Previous investigations, as indicated by Ganasan *et al.* (2020), have shown that certain buildings, especially those with soft-story designs, suffered substantial damage during the 2015 Ranau earthquake. This type of failure mode is characterized by the concentration of damage in a single story, typically marked by the absence of infill walls or a bare frame. This results in reduced stiffness in these stories, in contrast to the upper stories that often have infill walls. These findings highlight the need to address soft and/or weak story irregularities to enhance the earthquake resilience of multi-story buildings.

Figure 7. Typical buildings with weak and/or soft story

Consequently, the process of assessing the building's seismic vulnerability using the RVS method involves the selection of the appropriate building type, circles it on the data collection form, and then locates and circles any score modifiers to adjust the basic score. The score modifiers reflect the performance characteristics of the building and can either increase or decrease the basic score. The resulting RVS score provides an overall assessment of the building's ability to withstand earthquakes, with higher scores indicating a higher likelihood of the building performing well and being resistant to collapse, as noted in Haryanto *et al.* (2020). Table 6 presents the building damage potential in terms of percentage in the study area compared to Ranau, a region with the same seismicity level as Tawau.

Table 6. Comparison of building damage potential between Tawau and Ranau

Building damage potential	Tawau (%)	Ranau (Roslee *et al.*, 2018) (%)
Grade 1	-	2
Grade 2	17	8
Grade 3	56	60
Grade 4	27	30
Grade 5	-	-

It shows that no building in Tawau and 2% of buildings in Ranau have Grade 1 damage. The buildings have a tendency to Grade 2 damage in Tawau with 17% and Ranau with 8%. However, a higher percentage have Grade 3 damage in Tawau and Ranau with 56% and 60%, respectively. The Grade 4 damage was found with 27% in Tawau and 30% in Ranau, meanwhile none of the buildings for Grade 5 in both areas. In both moderate seismicity regions in Sabah, the majority of buildings are classified as having Grade 3 damage, followed by Grade 4 damage, and a smaller proportion with Grade 2 damage. This information provides valuable insights into the distribution of seismic vulnerability in these regions and can inform mitigation strategies to improve the earthquake resilience of the building stock.

The seismic vulnerability assessment in Tawau was completed with the creation of two versions of maps that display the distribution of building damage potential. Figure 8 illustrates the overall distribution of screened buildings and their damage potential in a 2D map, providing an overview of the seismic vulnerability across the study area. Additionally, Figure 9 presents a 3D building

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damage map that focuses on a specific concentrated area within a 1 km² region. This area likely contains numerous screened buildings due to factors related to development and the environment in the study area. These detailed maps serve as valuable tools for visualizing and understanding the distribution of seismic vulnerability in Tawau. As noted in the study conducted by Mohamad *et al.* (2019), these damage maps are of high utility to both authorities and the local community. They aid in establishing building safety standards and reducing the risk of damage in the event of future earthquakes by providing a means to evaluate and address the damage potential of buildings in the region. Thus, the maps can be used as an instrument for disaster preparedness, risk reduction, and decision-making processes related to earthquake resilience.

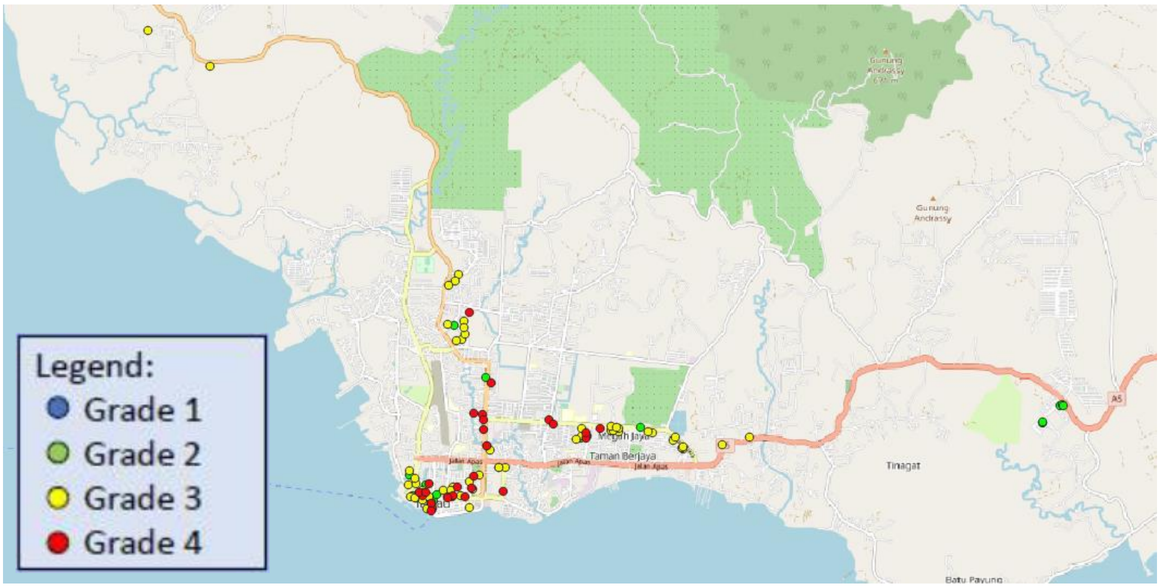

Figure 8. Overall building damage map

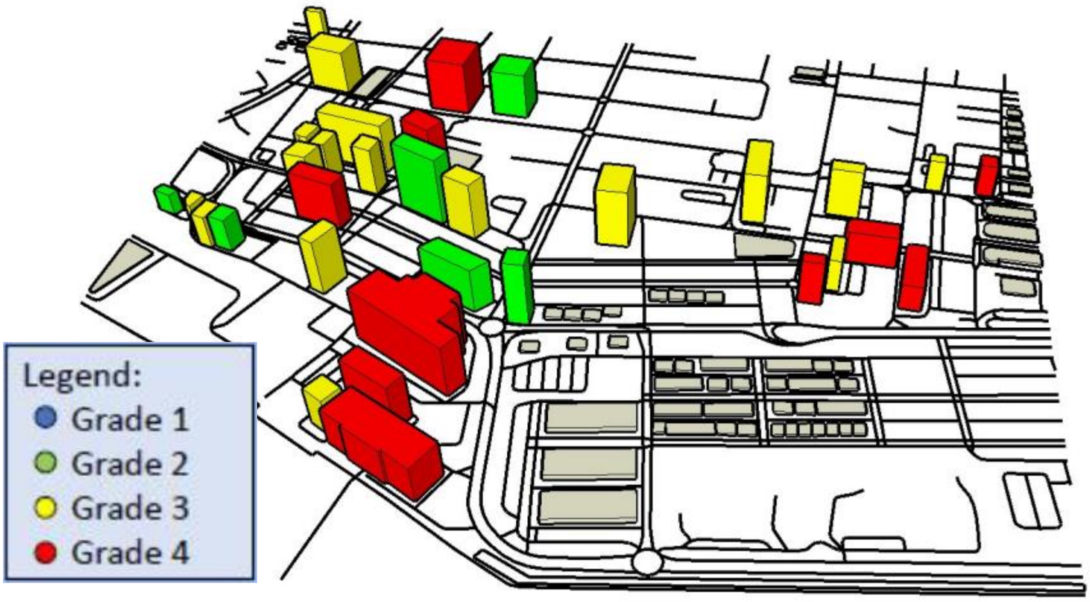

Figure 9. Building damage map in a concentrated area

CONCLUSION

This study conducted as a field survey using the RVS method to assess the damage potential of existing RC buildings in Tawau. An analysis of the RVS results for a total of 105 screened buildings revealed the highest number of buildings with Grade 3 damage (56%), followed by Grade 4 damage

(27%), and the lowest number of buildings with Grade 2 damage (17%). Subsequently, the study used this data to create a building damage map within the study area, serving as a valuable communication tool for decision-making in disaster management. It can be simplified as one of the most effective measures to mitigate the effects of earthquakes in Tawau is for local authorities to enforce earthquake-resistant building design and construction. This involves the development and implementation of building standards and practices that enhance earthquake resistance, ensuring the safety and stability of structures in seismic-prone regions as a such measures are crucial for disaster risk reduction and the overall earthquake resilience of the community.

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