COPENHAGEN BUSINESS SCHOOL
HANDELSHØJSKOLEN

The Impact of Earthquakes on the Japanese Stock Market

Master Thesis

M.Sc. in Business Administration & Economics

Finance and Investments

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Date of Submission: May 15, 2023

Number of Pages / Characters: 67 / 116,547

Abstract

This paper examines how major earthquakes impact the Japanese stock market and industries most vulnerable to the consequences of natural disasters. Using an event study methodology, this study investigates the impact of 117 earthquakes occurring from 1980 to 2023 on the whole market and the construction, insurance, transportation, food and real estate industries. The short-term abnormal returns are tested for significance using a parametric and a non-parametric test. The results indicate that, on average, earthquakes have a predominantly negative impact on the financial markets. However, the market reaction varies significantly across industries. While the insurance, food, and transportation industries are impacted negatively, the construction industry generates positive responses. In general, earthquakes causing higher economic damage generate a more pronounced market response. There is no difference in the response to low and high-fatality earthquakes or to recent and old earthquakes. Stronger earthquakes in terms of magnitude show a more substantial market reaction in the transportation industry.

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List of Abbreviations

- AR Abnormal return
- $\overline{\text{AR}}$ Average abnormal return
- ARMA Autoregressive–moving-average model
- CAPM Capital asset pricing model
- CAR Average abnormal return
- $\overline{\text{CAR}}$ Cumulative average abnormal return
- EMH Efficient-market hypothesis
- GARCH Generalised autoregressive conditional heteroskedasticity model
- GDP Gross domestic product
- GEM Oxford economics global economic model
- NGDC National Geophysical Data Centre
- OLS Ordinary least squares
- PIM Portfolio impacts model
- TOPIX Tokyo Stock Price Index
- TSE Tokyo Stock Exchange
- USGS United States Geological Survey

1. Introduction

1.1. Background and motivation for the study

The 2011 Tōhoku earthquake of March 11, 2011, stands as the costliest natural disaster in recorded history. According to the World Bank (2011), the earthquake and the consequent tsunami inflicted an estimated $235 billion in damages, resulting in the total destruction of more than 128,000 buildings and damage to almost a million more. It stands as a stark reminder of the immense economic consequences that earthquakes can bring. Japan is situated on the boundary of four tectonic plates, making it one of the most seismically active regions in the world. Due to its geographical location along the Pacific Ring of Fire, Japan encounters approximately 1,500 detectable earthquakes annually. While many of these tremors have little to no impact, some have the potential to cause severe damage to infrastructure. (Hongo, 2007) This high frequency of earthquakes can have a substantial impact on the country's economy and stock market. Unlike other macroeconomic events, earthquakes are unpredictable. Despite advances in technology and research, they cannot be predicted with complete accuracy, and their timing and magnitude remain uncertain. Therefore, they can be regarded as non-financial, exogenous shocks to the economy (Pagnottoni, Spelta, Flori, & Pammolli, 2022) and represent a sudden surprise to the market, which can cause significant fluctuations in stock prices. Such exogenous shocks can disrupt the usual patterns of economic activity and lead to lasting effects on the economy, including changes in business operations and investment decisions. As such, understanding the relationship between earthquakes and the stock market is essential for financial investors to make informed investment decisions and assess the potential risks and opportunities associated with this kind of natural disaster.

The relationship between multiple types of natural disasters and the stock market has been the subject of significant research over the past few decades. While some studies have found that natural disasters can lead to significant declines in stock prices (Pagnottoni, Spelta, Flori, & Pammolli, 2022; Tavor & Teitler-Regev, 2019; Lackner, 2018; Yamori & Kobayashi, 2002), others have suggested that such events can also create investment opportunities for investors. (Mahalingam et al., 2018; Ferreira & Karali , 2015; Wang & Kutan, 2013) However, much of the existing literature has focused on the broader impact of natural disasters on the economy rather than on the specific relationship between earthquakes and the stock market. There

remains a need for further research into the impact of earthquakes on specific industries and the potential risks and opportunities associated with investing in regions that are susceptible to seismic activity. The mixed empirical results of previous literature, in conjunction with their economy-wide analysis, make it challenging to interpret existing evidence and draw conclusive insights regarding specific investment opportunities. Therefore, this study aims to address this gap in the literature by examining the abnormal returns observed in industries that are significantly impacted by earthquakes. Japan, being the third-largest economy in the world, presents a unique and opportune economy for investigating the impact of natural disasters.
To achieve the above goals, the study utilised a theoretical event study based on the framework proposed by MacKinlay in 1997. The impact of 117 earthquakes across different industries is being analysed.

1.2. Research question and objectives

The central focus of this study is to investigate the impact of earthquakes on specific industries in Japan and examine the potential risks and opportunities associated with investing in the aftermath of an earthquake. This serves as a guiding principle for the research process, including data collection, literature review, and methodology selection. To achieve the aforementioned goal, this paper will analyse abnormal stock returns around the days of powerful earthquakes in Japan. The main research question and guiding principle is formulated as the following:

<u>How do earthquakes influence short-term abnormal returns in different industries in Japan?</u>

This study addresses several sub-questions to gain a thorough understanding of the presence and meaning of potential abnormal returns. These sub-questions guide the sensitivity analysis performed to validate and further analyse the results obtained. I perform different analyses to examine the impact of various characteristics concerning the earthquakes and industries under investigation. Therefore, this paper addresses the following sub-questions in order to develop an in-depth comprehension of investment opportunities:

- **What is the impact of earthquakes on the overall economy?**
- **Are there any similarities/differences in the market reaction of different industries?**
- **Do earthquake-specific characteristics affect the Japanese stock market's reaction?**
- **What are the investment opportunities that arise in the aftermath of natural disasters?**

1.3. Scope and limitations of the study

This thesis aims to investigate the effect of earthquakes on stock prices in different industries in Japan. In consideration of the data availability and the primary focus of this thesis on providing insights for financial investors' investment decisions, the scope of this study is confined to a select number of macroeconomic factors and characteristics.

This research investigates the impact of earthquakes on the Japanese stock market from 1980 to 2023, encompassing a total of 117 powerful earthquakes. The selection of earthquakes for the analysis is based on multiple factors, such as the number of fatalities, total damage and the magnitude of the earthquakes. Multiple analyses are conducted in this study, employing different characteristics as criteria to yield comprehensive results. Various indices, including general and sector-specific ones, will be utilised to conduct the event study. To ensure the robustness of the results, several sensitivity checks are performed by modifying the characteristics and model specifications. Further elaboration of the methodology and data selection, including the sensitivity checks, is presented in the fourth section.

In order to select the industries that are most likely to be impacted by an earthquake for analysis of abnormal returns, a thorough review of previous literature is conducted. This review focusses on studies examining the impact of earthquakes on specific industries. The insurance industry has been the subject of several studies related to earthquakes. (Wang & Kutan, 2013; Yamori & Kobayashi, 2002) Other literature from experts in the field of earthquakes has determined that this type of natural disaster can affect several industries, including construction, real estate, food, and transportation. (Kachali et al., 2015; Yezer, Kunreuther, & Doherty, 1992) Based on the findings of these studies, several industry sectors are identified as being the most affected by earthquakes and therefore included in this study. The industries selected for this analysis are as follows:

- Construction
- Insurance
- Real Estate
- Food
- Transportation

In a later stage, the identified industries will be further divided into sub-industries to enable more precise analyses. Each industry's specific analysis depends on the availability of relevant sector indices in Japan. Some industries may not yield statistically significant results throughout the study and, therefore, will receive a less detailed analysis and be dropped consequently. A more in-depth analysis is performed for the industries that yield statistically significant results. Those analyses will be subject to several robustness checks to confirm the results and examine their economic implications in order to provide valuable insights for financial investors regarding the risks and opportunities associated with their investment decisions.

Although this study makes significant contributions to the understanding of the impact of earthquakes on the Japanese stock market, it is crucial to acknowledge the limitations that may impact the interpretation of its findings. The study only focuses on Japan, and the results cannot be generalised to other countries. Japan stands out as a unique case, given its position as one of the largest economies in the world, combined with being one of the most seismically active regions globally, making it difficult to compare results across countries. It is essential to consider that Japan has a specific social, economic, and institutional context that differs from other countries. For example, Japan's robust infrastructure and disaster prevention systems, coupled with its well-established insurance and financial markets, make it more resilient to natural disasters than other countries (Fisch, 2022). Therefore, the study's findings cannot be applied to countries with different contexts.
Moreover, given that Japan is one of the most influential economies globally and has been a role model for other developing countries in Asia, any shock to its stock market may trigger a contagious effect on other financial markets around the world. Asian economies have benefited

significantly from the exemplary economic growth of Japan (Wang & Kutan, 2013). Thus, an impact on the stock market in Japan can influence other countries, which is not considered in this study, although it might raise investment opportunities in other economies.

Another limitation of this study is that this study only considers short-term abnormal returns, which are typically used in event studies. Longer horizon event studies are often subject to criticism because they face fundamental issues in choosing the proper research methodology and summarising findings from existing simulation studies about the performance of commonly used methods (Ang & Zhang, 2015). Additionally, longer horizon studies require numerous assumptions that complicate the analysis and may not accurately represent the real-world impact of earthquakes on the financial markets. Accordingly, this paper only focuses on the short-term abnormal returns associated with earthquakes.

1.4. Significance of the Study

This study aims to contribute to the existing literature and provide valuable insights for investors, financial analysts and policymakers. Existing literature has largely focused on the global impact of natural disasters on stock markets, while this paper aims to examine the impact on specific industries that are most affected by earthquakes. Several studies have focused on the impact of earthquakes on specific industries, but to the best of my knowledge, none have comprehensively analysed all the major affected industries to detect specific investment opportunities. This research is therefore important for financial investors looking to invest in different industries in Japan. It aims to contribute to the development of investment strategies that can mitigate the risks associated with these unpredictable events. Investors who understand the link between stock markets and unforeseen disasters can make better-informed investment decisions, minimise risk exposure, and potentially earn abnormal returns in the initial days following such events.

Furthermore, the findings of this study have implications for policymakers in Japan. The Japanese government has already implemented various measures to mitigate the impact of natural disasters on its economy. It actively promotes disaster-resistant infrastructure and increases disaster preparedness by often running awareness campaigns (Fisch, 2022). The research in this paper can therefore support the development of more effective policies and strategies for mitigating the impact of earthquakes.

Lastly, this thesis provides a framework for future research on the impact of earthquakes on financial markets in other regions. While this study focuses on Japan, the framework and methodology can be applied to other regions that are prone to natural disasters. This can help to build a more comprehensive understanding of the impact of natural disasters on financial markets globally.

1.5. Structure

The paper is be divided into several sections. The structure is designed to provide a comprehensive and coherent analysis of the impact of earthquakes on the stock market and investment opportunities in Japan. Each section serves a distinct purpose in achieving the study's objectives. The introduction sets the stage for the research question and objectives. The literature review section summarises and analyses relevant literature on the impact of natural disasters on stock markets, including previous studies with a specific focus on Japan. Section three presents the research hypotheses that is tested in the study. The fourth section discusses data collection and methodology, followed by a presentation of the empirical results in the fifth section. The results include a comparison of the findings with previous studies and a sensitivity analysis. The final part provides a discussion of the study's findings, implications and limitations and offer suggestions for future research. The reference list and any appendices, such as supporting materials like tables and figures, is included at the end of the study.

2. Literature review

This section will begin by outlining the primary theories and concepts relevant to this paper's research. First, studies that have explored the effects of natural disasters on financial markets, with a particular focus on the stock market, are being analysed. Subsequently, previous research on the impact of earthquakes on the Japanese stock market is presented. Finally, the Efficient Market Hypothesis (EMH) is introduced as the theoretical framework for the study.

2.1. Review of existing literature on the impact of natural disasters on stock markets

Natural disasters have the potential to cause significant economic and financial damage. The impact of these events on stock markets around the world has been the subject of numerous studies. As global warming intensifies and the world experiences more and more natural disasters, the effects on financial markets and economies become increasingly complex. Consequently, in the past few years, we saw a growing body of studies in a new emerging research area called 'climate finance' that focuses on the impact of climate change-related events on financial markets. Kelly, Giglio, and Stroebel (2020) explore different methods for integrating climate-related risks into macro-finance models. They investigate the valuation of climate risks in a broad range of asset classes, such as equities, fixed-income securities, and real estate. Within this framework, their paper discusses how to construct portfolios that hedge against climate risk by using these assets. As climate finance gains more popularity, there has been a surge of research that focuses explicitly on risk transmission from natural disasters to financial systems. Stolbova, Monasterolo and Battiston (2018) developed a methodology that is based on financial networks and enables the analysis of the transmission of positive or negative shocks induced by specific climate policies across the financial sector.

2.1.1 Negative impact on stock markets:

As a first point, this paper summarises and analyses previous literature that sheds light specifically on the negative impacts of natural disasters on stock markets. In this research area, this has been a widely held belief over the past century, and many studies that explored this subject reached similar conclusions. Pagnottoni, Spelta, Flori and Pammolli (2022) analyse the effect of multiple categories of natural disasters, including biological, climatological, geophysical and meteorological disasters on 27 global stock market indices worldwide. Their paper includes events from 104 countries over the period 2001 to 2019. They used an event study methodology for their analysis and concluded that the response of stock markets to natural hazard shocks is heterogeneous depending on the type of event. On average, climatological and biological, followed by geophysical shocks (including earthquakes), induce the most extreme market reactions. They conclude that geophysical shocks like earthquakes are statistically significant, mainly in a negative way. Furthermore, the authors point out that abnormal returns vary according to the geographical location of the natural hazards. Stock indices are more responsive to shocks occurring in developed countries. This thesis builds upon this previous research and its conclusions by explicitly focusing on the impact of earthquakes in a developed country, namely Japan.

Scholtens and Voorhorst (2013) performed a comparative analysis and obtained similar results. However, contrary to Pagnottoni, Spelta, Flori and Pammolli, they concentrate their research specifically on earthquakes which is more relevant to this paper. Scholtens and Voorhorst analyse the impact of more than 100 earthquakes in 21 countries from all five continents from 1973 to 2011 on multiple stock indices. The authors use an event study methodology to discover significant negative effects on stock market value. Their study highlights three points that this paper further analyses in the case of Japan. Firstly, in their research, the impact of earthquakes on the stock market has become more significant in recent years. Secondly, they conclude that there is no significant difference in the stock market's reaction to earthquakes of varying intensity. Finally, their findings suggest that earthquake characteristics do not significantly impact the stock market's response.

Another study investigating the effects of environmental disasters on stock performance has been done by Seetharam (2017). However, unlike the first two articles, Seetharam only focuses on one single country. The author utilises an event study methodology using the daily stock returns of all publicly listed companies in the United States. The study finds that, on average, environmental disasters have a significant negative impact on stock performance. However, the impact varies significantly between companies operating in industries exposed to such disasters and non-exposed firms. This literature is helpful in my own analysis as this study investigate the impact of earthquakes on various industries. Drawing on these findings, I can identify which industries are more or less affected by earthquakes and reach conclusions about their specific impacts.

A research paper which follows the aforementioned logic is written by Tao (2014). This paper, similar to the present thesis, analyses the impact of earthquakes on the whole market and on different industrial sectors. The author uses the Shanghai Composite Index, Shenzhen Component Index, and CSI300 Index to analyse the impact on the overall market and analyses nine different industry sectors. However, the study was conducted in China, rather than in Japan, and it only focuses on one single event, the M7.0 Lushan Earthquake. In contrast, this thesis goes one step further and analyses the impact of multiple events on various industries. Tao uses an event study methodology with the Constant-mean return model and the Market model, which is also being used in this paper and explained further in the methodology section. Tao's research finds that while no statistically significant abnormal returns were observed for the whole market on the day of the event and the following ten days, some industries experienced negative abnormal returns on certain days after the earthquake. Specifically, significant negative abnormal returns were found for the energy and materials sectors. Nevertheless, the paper concludes that the overall economic effect of the earthquake was limited. Furthermore, it is essential to note that this study only focuses on the economic effects and does not examine investment opportunities. In this research, I will build upon these findings by analysing which industries can present investment opportunities after natural disasters in Japan.

2.1.2 Negative or positive reaction

However, the literature on the impact of natural disasters on the stock market and the economy is not entirely consistent. While some studies conclude that natural disasters only result in negative abnormal returns and negative effects on the economy, other studies suggest that the impact may be more nuanced. For instance, some researchers find that natural disasters can lead to significant abnormal returns, which may be positive or negative, depending on the specific event and industry. According to Worthington and Valadkhani (2004), natural disasters can have both, positive and negative impacts on capital markets. These effects are typically most pronounced on the day of the event, with some residual impact felt in the subsequent days. This study focused entirely on the Australian equity market by analysing 42 severe storms, floods, cyclones, earthquakes and wildfires from 1982 to 2002. In contrast to the previous studies, the authors used autoregressive moving average (ARMA) models to model the returns. Their findings suggest that especially bushfires, cyclones and earthquakes majorly affect market returns. However, they specify that significant earthquakes in Australia have a mixed impact on market returns. The stock market experiences a statistically significant negative impact on the event day, but after several days abnormal returns are significantly positive. This observation is relevant to the present study because the impact of earthquakes on the whole market (in Japan) is also being analysed. This research will examine whether the market exhibits a similar rebound reaction, as well as whether this varies across different industries.

2.1.3 No impact of earthquakes

On the other hand, some studies report no significant effects of natural disasters on the stock market at all. In a subsequent study, Worthington (2008), reassesses the impact of natural disasters on the Australian stock market. However, this time he uses a GARCH-Mean model to model the return series and comes to a different conclusion than in his study with Valadkhani in 2004. His findings suggest that natural events and disasters do not significantly impact market returns at all. Despite covering a similar period (1980 – 2003) to his previous study, the author employs an entirely different methodology and a more extensive set of events in this research. He uses the data of all severe storms, floods, cyclones, earthquakes and wildfires recorded during this period. The different findings from the earlier research may be attributed to these differences in methodology and event definition. This literature powerfully highlights the importance of choosing an appropriate methodology and event definition. In my research, an event study methodology, which is a widely-used approach in this field of research, is being used.

2.1.4 Rare positive effects of earthquakes

Moreover, other researchers suggest that natural disasters can have positive effects on the economy and the stock market. Although short-term abnormal returns may often be negative, in the long term, natural disasters can positively impact growth. Some studies also reveal that despite the overall negative trend, a few exceptions can benefit from such events. Skidmore and Toya (2002) analysed how long-term growth is affected by natural disasters. The authors used a sample of 89 countries and analysed the impact of multiple kinds of natural disasters on the per capita GDP growth rate from 1969 to 1990. As the authors did not analyse short-term abnormal returns but long-term growth, their approach involves conducting a cross-sectional analysis on various factors, which sets it apart from other methods used in similar studies. Skidmore and Toya's empirical analysis indicates that while controlling for many variables, climatic disasters positively correlate with economic growth, human capital investments, and total factor productivity growth. The study highlights that natural disasters can serve as an incentive for upgrading capital stock and adopting new technologies, leading to long-term productivity improvements. Even though this study differs from the approach of my research, which focuses on short-term abnormal returns, this paper provides a valuable complement to the existing literature by examining a less explored aspect of the impact of natural disasters on the economy.

Mahalingam et al. (2018) also explore the potential impact of severe natural catastrophes on financial markets and subsequent economic downturns. However, rather than analysing historical data, the authors create hypothetical scenarios of major natural disasters and analyse their potential outcomes using two in-house developed models. Their findings show that natural catastrophes have the potential to produce losses on a scale that is likely to disrupt market returns from high-quality investment portfolios. However, they also note that while natural catastrophes can trigger market shocks, there are some rare winners in these situations. For example, industries that gain from future reconstruction investment as well as competitors of disrupted businesses that gain in market share, profit from these shocks in the long term. This finding is particularly interesting to my research as it explicitly analyses the short-term effects of natural disasters on the construction industry.

Another industry that is more thoroughly analysed in this research is the insurance industry. In a study by Shelor, Anderson and Cross (1992), the stock reaction of US insurance companies after a severe earthquake in California in 1989 was analysed. Similar to this thesis, they performed an event study analysing short-term abnormal returns. They found statistically significant positive abnormal returns for the event day, but the cumulative abnormal returns of the entire two-day event window were not statistically significant. This result will be interesting to compare to the Japanese insurance sector in my research.

In contrast to the previous literature focusing only on a specific industry, some research shows that earthquakes can generate positive effects on average on returns in capital markets over the long term. Ramirez and Altay (2011) based their research on Schumpeter's (1942) creative destruction theory. They aimed to test the theory that earthquakes can create an opportunity for firms to improve their technology by destroying older technology. They performed a cross-sectional empirical analysis using a sample of 229 earthquakes and a panel of over 50 countries. The empirical analysis showed that earthquake damage is generally positively correlated with market capitalisation. However, they also pointed out that the more developed a country is, the smaller the positive effect on the economy. This essential is important to keep in mind for this paper, especially given that Japan is a highly developed country.

2.2. Previous studies about the impact of earthquakes on the Japanese stock market

Given that Japan is one of the most seismically active countries in the world, numerous studies have already been conducted to examine the effects of earthquakes and other natural disasters on its economy and stock market. Some studies have analysed the impact on the overall global economy and the stock market, while others have focused on specific industries. Kajitani, Changand Tatano (2013) provide an overall assessment of the economic impact of the 2011 Tohoku-Oki Earthquake and Tsunami, the costliest natural disaster in history with an officially estimated damage of ¥16.9 trillion ($235 billion) in direct damage. The authors note that fisheries and agriculture were severely impacted in regions with physical damage. In addition, the manufacturing industry experienced significant impacts from supply-chain disruptions, while retail, trade, and tourism industries were affected by lower consumption and reduced electric power generating capacity. In light of these findings, it will be valuable to compare the reaction of these critical sectors to a larger panel of earthquakes in my research and to derive general conclusions that can be attributed to earthquakes in general and not only to the most devastating one in history.

Ferreira and Karali (2015) conducted a study to examine how major earthquakes impacted the returns and volatility of aggregate stock market indices in 35 financial markets over the last twenty years. Unlike other studies that use an event study methodology, the authors used a GARCH-X (1,1) model to investigate the impact of earthquakes on abnormal returns and stock market volatility. Their findings are of great significance for this thesis as they revealed that earthquakes had no impact on the volatility of stock markets in 34 out of 35 financial markets studied, except for Japan. In the case of Japan, they found statistical significance that domestic earthquakes increased the volatility of its financial returns. The authors' findings indicate that the Japanese stock market is unique and reacts differently than other markets, suggesting that more thorough research is needed that focuses solely on the Japanese market.

Tao (2012) conducted an event study to analyse the impact of the Tohoku-Oki Earthquake on abnormal returns of the Nikkei 225 stock index. Using the Constant-mean return model, she discovered that abnormal returns from the overall market were negative and significant at a 1% significance level on the day of the event and the following four days. This paper uses the same methodology to compare these findings to a larger number of earthquakes and draw general conclusions. Furthermore, Tao analysed the impact of the earthquake on 14 stocks of several large Japanese manufacturing companies. Four companies in the automobile and energy sectors showed statistically significant negative abnormal returns at a significance level of 0.01 in the ten days following the event. This thesis complements this paper by analysing a more comprehensive range of sectors and examining the overall impact of earthquakes, not just on a single event.

The impact of natural disasters on Japan’s insurance sector was at the centre of numerous research papers. Wang and Kutan (2013) used GARCH models to analyse the stock response of Japan's insurance sector to various natural disasters between 1990 and 2011. Their findings showed that the sector exhibited significant positive abnormal returns following natural disasters. However, a contrasting result was found in Yamori & Kobayashi’s (2002) event study analysis of the impact of the 1995 Hanshin-Awaji Earthquake on the same industry. The author found significant negative abnormal returns in insurance company stocks. These divergent findings highlight the crucial role of methodology and data selection in determining the outcome of an analysis. This thesis incorporates elements from both of the aforementioned studies An event study methodology is employed, and a larger dataset of earthquakes is selected. It will be interesting to compare the results of this paper with both studies, given their contrasting results.

Table 1: *Summary of previous studies about the impact of natural disasters on abnormal returns*

Author	Data	Period	Methodology	Event	Impact	Remarks
Worthington and Valadkhani (2004)	Australia	1982 – 2002	ARMA	Multiple	- / +	Disaster type dependent
Pagnottoni et al. (2022)	27 financial markets	2001 – 2019	Event study	Multiple	-	
Scholtens and Voorhorst (2013)	21 financial markets	1973 – 2011	Event study	Earthquakes	-	
Seetharam (2017)	US	1980 – 2014	Event study	Multiple	-	
Tao (2012)	Japan	2011	Event study	Earthquake	-	
Yamori and Kobayashi (2002)	Japan	1995	Event study	Earthquake	-	
Shelor et al. (1992)	US insurance	1989	Event study	Earthquake	+	
Tao (2014)	China	2013	Event study	Earthquake	0 / -	Industry dependent
Worthington (2008)	Australia	1980 – 2003	GARCH	Multiple	0	
Wang and Kutan (2013)	Japan insurance	1990 – 2011	GARCH	Multiple	+	
Ferreira and Karali (2015)	35 financial markets	1994 – 2011	GARCH	Earthquakes	0	+ volatility in Japan
Mahalingam et al. (2018)	hypothetical scenarios	/	In-house models (GEM / PIM)	Multiple	- / +	Industry dependent

2.3. Theoretical framework for the study: Efficient Market Hypothesis

The theoretical framework serves as a foundation for interpreting the data and analysis that is used in this paper. It provides a lens through which to view the results of this research and helps to explain why specific patterns or relationships may exist. This thesis uses an event study methodology which is based on the assumption that markets are efficient. Therefore, the Efficient Market Hypothesis (EMH) serves as the theoretical framework. The EMH is crucial for studies using the event study methodology. In essence, event studies aim to examine the market's efficiency and, therefore, the validity of the EMH (Campbell, Lo, & MacKinlay, 1997).

It was Eugene Fama who introduced the Efficient Market Theory in 1970. The theory marked a turning point in the modern literature on market efficiency. The fundamental idea of the EMH is that financial markets are informationally efficient, meaning that prices always reflect all available information in the market. The theory suggests that arbitrage opportunities should not exist in an efficient market because new information is rapidly reflected in the price. Fama (1970) argued that consistently achieving higher-than-average returns by using any public information is impossible. This implies that neither a technical analysis nor a fundamental analysis can provide a strategy to generate returns that exceed those obtained from investing in a randomly selected portfolio of stocks (Malkiel, 1999).

However, despite the widespread acceptance of the EMH and its use as a base for many studies in the finance literature, it has also been the subject of extensive debate. Critics of the EMH point to several schools of thought that challenge its assumptions. One is momentum investing, which combines technical and fundamental analysis and claims that certain price patterns persist over time, indicating that markets are not always efficient (Lui, Strong, & Xu, 1999). Another is behavioural finance, which suggests investors are often guided by emotions and biases rather than rationality and efficiency, leading to market inefficiencies (Shleifer, 2000). Finally, fundamental analysts argue that certain valuation ratios can predict outperformance and underperformance in future periods, contradicting the EMH's claim that it is impossible to achieve above-average returns through analysis consistently (Abarbanell & Bushee, 1998).

The EMH is undoubtedly one of the most debated propositions in finance, and despite empirical evidence supporting it, it remains controversial. Consequently, it is essential to distinguish between different forms of efficiency rather than assuming a single form of the hypothesis. Therefore, Fama (1970) categorised the efficient market hypothesis into three forms based on the type of information that shapes investors' expectation regarding future stock performance.

The **weak form** states that stock prices already reflect all the information that can be derived by analysing historical trading data, such as historical stock prices and trading volume. Therefore, investors cannot use technical analysis to predict future stock prices, as this information is already incorporated into current prices (Bodie, Kane, & Marcus, 2014).

The **semi-strong form** suggests that stock prices reflect all publicly available information, including both historical trading data and fundamental information such as financial statements, news releases, and economic reports. This form implies that insider trading, or the use of non-public information, is the only way to achieve above-average returns.

The **strong form** states that stock prices fully reflect all available information. This includes historical and public information but also insider information that is not available to the general public. If the strong form of the EMH is correct, then no investor can consistently outperform the market (Fama, 1970).

The event study in this paper adopts the semi-strong form of market efficiency, focusing on the information and characteristics surrounding earthquakes. It is assumed that the available public information about the event will be accurately and rapidly reflected in the stock prices of industries that may be affected by the disaster. As earthquakes are inherently unpredictable natural phenomena, it is impossible for anyone to have non-public information about them. Furthermore, despite advances in seismology, an earthquake's exact timing, location, and intensity cannot be predicted with certainty. Therefore, it is clear that the strong form of the efficient market hypothesis cannot be applied in this study.

3. Hypotheses

This chapter presents the hypotheses that will be investigated in this paper. These hypotheses are based on both theoretical and empirical evidence discussed in the literature review section. The hypotheses will be tested for significance in the subsequent analysis, which will help to draw valuable conclusions about the research question. This paper aims to answer the research questions by analysing six hypotheses:

***H_1*: Earthquakes have a negative impact on the short-term return on Japan's stock market**

Given that this thesis builds on and complements previous literature, it is worth noting that most previous studies that used an event study methodology concluded that natural disasters negatively impact the stock market (Table 1). Therefore, the main hypothesis of this paper is to verify whether earthquakes have a negative impact on the short-term return of Japan's stock market. This central hypothesis serves as the foundation for further analysis of other factors and characteristics.

***H_2*: Earthquakes causing a higher economic damage have a more negative effect on Japan's stock market**

This hypothesis draws upon prior research that analysed the impact of the most catastrophic earthquakes. For example, several studies have been conducted on the 2011 Tohoku-Oki earthquake, which caused the greatest economic damage in history and resulted in remarkably high abnormal returns. (Kajitani, Chang & Tatano, 2013; Tao, 2012). Similarly, other highly devastating and destructive earthquakes, such as the 1995 Hanshin-Awaji earthquake (Yamori & Kobayashi, 2002) or the Lushan Earthquake in China (Tao, 2012), have produced comparable results. Testing this hypothesis can help in establishing a criterion based on economic damage to select the appropriate earthquakes to be tested in various industries. By determining the earthquakes that have an impact on stock markets, based on the extent of economic damage, it is possible to create different groups of earthquakes. This approach will ensure a consistent and relevant analysis of the impact of earthquakes on various industries.

***H_3*: Earthquakes have an effect on stock returns of specific industries in Japan**

In order to provide valuable insights to investors in Japan and address the main research question, this hypothesis aims to examine the effects of earthquakes on various industries. Furthermore, by conducting tests for abnormal results, the aim is to identify which industries are significantly impacted by earthquakes, either positively or negatively.

***H_4*: The Japanese stock market has a stronger reaction to earthquakes with a higher magnitude.**

***H_5*: The Japanese stock market has a stronger reaction to earthquakes with a higher number of fatalities.**

***H_6*: The Japanese stock market has a stronger reaction to recent earthquakes than to earthquakes in the distant past.**

With the final three hypotheses, this research tests several earthquake-specific characteristics to understand better how different types of earthquakes affect markets. This could reveal valuable knowledge to investors as it allows them to react strategically to earthquakes with specific characteristics. In particular, this study focuses on three earthquake characteristics: magnitude, number of fatalities, and date of occurrence. The magnitude of an earthquake is a crucial piece of information that experts can determine quickly and share with the public almost immediately. It serves as a critical indicator of the potential extent of damage that the earthquake may have caused. Moreover, the number of fatalities can be another essential signal, especially if a building collapses and a large number of people are inside. Therefore, in this study, the impact of these factors are being analysed. Additionally, by analysing the impact of recent earthquakes compared to those in the distant past, I can gain insights into how the stock market's response to earthquakes may have changed over time.

4. Data

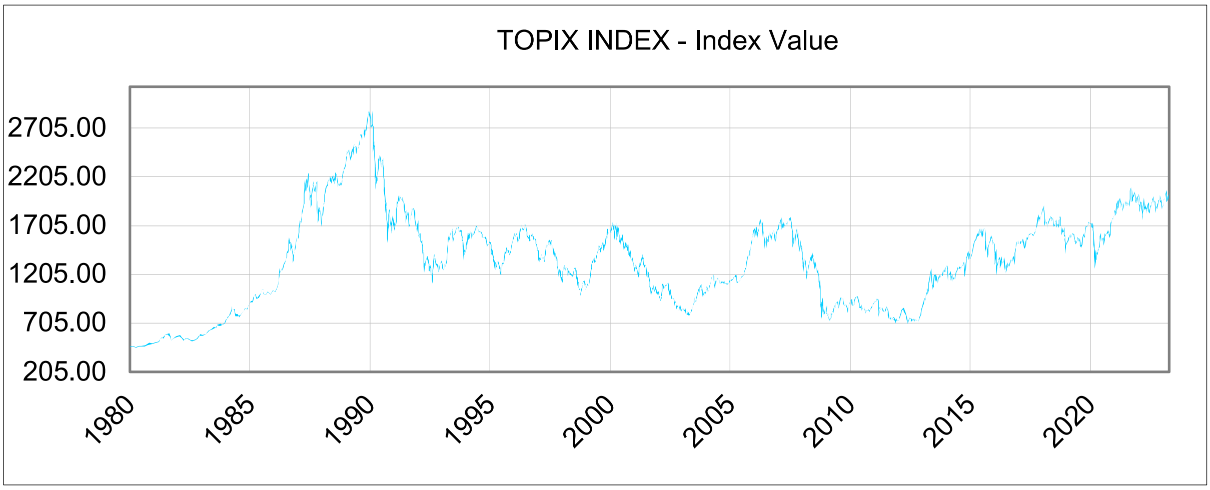
The event study methodology utilised in this paper requires two essential data sets. Firstly, data is needed that represents the Japanese stock market, including several different indices, which were selected based on specific criteria. Secondly, a dataset is required that includes information about earthquake events. In this section, I explain the selection process for earthquake events and outline the criteria and characteristics that are being considered when selecting these events for analysis. By using this rigorous approach to data selection, I can ensure that this analysis is based on relevant and reliable data, which is essential for drawing accurate conclusions.

4.1. Stock market data

The benchmark index that is being used in the event study that represents the broader Japanese stock market is the Tokyo Stock Price Index, commonly known as TOPIX. It is a free-float adjusted market capitalisation-weighted index calculated and published by the Tokyo Stock Exchange (TSE) in Japan (Japan Exchange Group, 2023). The index tracks all domestic companies of the exchange's Prime market division. As of April 1, 2023, the TOPIX index includes 2158 companies (Japan Exchange Group, 2023). The TOPIX, therefore, constitutes a measure of the overall performance of the Japanese stock market, serving as a reliable benchmark for investment in Japanese stocks.
Another highly recognised and widely used index in Japan is the Nikkei 225. In contrast to the TOPIX, the Nikkei 225 is a price-weighted index and is comprised of the top 225 blue chip companies traded on the TSE. However, the central analysis in this paper is based on the TOPIX index because it is considered a better measure of the overall Japanese stock market than the Nikkei 225 (Reuters, 2012). There are several reasons why the TOPIX is a better fit for the analysis in this paper. First, the TOPIX index is broader, as it covers all the stocks listed on the Tokyo Stock Exchange's first section, not only the top 225 stocks. This makes the TOPIX index a more accurate representation of the entire market as it includes large and small companies. Second, the TOPIX index is weighted by market capitalisation, whereas the Nikkei 225 index is weighted by stock price. This means that the TOPIX index better reflects the true size of the companies and is less affected by large price swings of individual stocks.

For this analysis, daily data of the adjusted closing price of the TOPIX index was downloaded from S&P Capital IQ. This platform is regarded as one of the most well-known and reliable sources of financial data. The analysis period in this paper covers the years from 1980 to 2023. This time frame is chosen due to the availability of reliable data in the earthquake information data sets. Previous research has also rarely included data from before 1980 (Table 1), as the documentation of surrounding information of earthquakes, such as the extent of economic damage, was not yet as comprehensive or accurate as it is today.

***Figure 1**: TOPIX index (1980–2023)*



Historically, the Japanese stock market has been known for its volatility compared to other developed markets. It has experienced periods of growth and decline, with volatility driven by factors such as government policy changes, global economic conditions, and natural disasters. According to Aktas, De and Cousin (2009), the event study method can experience a significant loss of power in the presence of increased volatility. This can impact the comparability of event study results obtained in different empirical contexts, such as different time periods or geographical zones. Therefore, it is important to highlight again that due to the specificity of the data used in this paper, it is challenging to generalise the conclusions to other markets.

To evaluate the influence of earthquakes on the abnormal returns of the Japanese stock market, industry-specific indices from the TOPIX-17 Series are being used. The TOPIX-17 Series Indices are created by categorising the constituents of TOPIX into 17 categories based on various sectors defined by the Securities Identification Code Committee. The relevant industry-specific indices used in this study are listed in the table below:

***Table 2**: List of industry-specific market indices*

TOPIX-17 Series (Industries)	TOPIX sector indices	Ticker	Number of Constituents
Construction & Materials	Topix Construction Index	TSECON	92
	Topix Metal Products Index	TSEMET	42
	Topix Iron and Steel Index	TSEIRO	31
Financials (Excluding Banks)	Topix Insurance Index	TSEINS	8
	Topix Other Financing Business Index	TSEOTHF	27
Real Estate	Topix Real Estate Index	TSEREA	75
Foods	Topix Fishery, Agriculture and Forestry Index	TSEFIS	8
Transportation	Topix Land Transportation Index	TSELAN	42

4.2. Earthquake data

The earthquake data has been retrieved from the National Geophysical Data Center (NGDC) / World Data Service (2023). This is a division of the National Centers for Environmental Information of the United States. The NGDC's Global Significant Earthquake Database maintains a significant archive of information related to significant earthquakes that have occurred worldwide. The information in the Global Significant Earthquake Database includes data on the location, magnitude, intensity, deaths, injuries, as well as other associated impacts and effects of earthquakes. The data in the Global Significant Earthquake database is collected from various sources, including government agencies, academic institutions, and international organisations.

The database has several criteria for classifying an earthquake as significant, which will also be used as criteria in this paper:

- Moderate damage (approximately $1 million or more)
- 10 or more deaths
- Magnitude of 7.5 or greater
- Modified Mercalli Intensity of 10 or greater
- The earthquake generated a tsunami.

Although these criteria may appear straightforward, their implementation can be challenging due to the limited availability of information. For example, estimating the actual economic damage caused by an earthquake in terms of dollar value is often difficult. The NGDC does not estimate the economic damage itself but relies on various sources, making it sometimes problematic to provide an accurate number.

Furthermore, regarding the number of deaths recorded in the database, it should be noted that data includes not only direct earthquake-related deaths but also secondary deaths resulting from after-effects such as tsunamis or nuclear accidents triggered by the earthquake. However, obtaining such data is often a process that takes time and effort, making it challenging to maintain consistency between earthquakes.

The magnitude of an earthquake measures the energy released at the source of the earthquake (NGDC, 2023). It is determined from measurements on seismographs and it is then categorised based on the following scale

Table 3: *Moment Magnitude Scale*

Moment Magnitude Scale	**Earthquake intensity**
< 3.0	/
3.0 – 3.9	Minor
4.0 – 4.9	Light
5.0 – 5.9	Moderate
6.0 – 6.9	Strong
7.0 – 7.9	Major
> 8.0	Great

Source: Earthquakes Hazard Program

In contrast to the magnitude, which measures the energy released, the Modified Mercalli Intensity (MMI) is a scale used to measure the intensity of shaking and the damage caused by an earthquake (NGDC, 2023). Developed in 1931 from Giuseppe Mercalli's Mercalli intensity scale of 1902, it relies on subjective interpretations of an earthquake's effects.

Table 4: *Modified Mercalli Intensity (MMI)*

Intensity	Shaking	Description
1	Not Felt	Not felt except by a very few under especially favourable conditions.
2	Weak	Felt only by a few persons at rest, especially on the upper floors of buildings.
3	Weak	Felt quite noticeable by persons indoors. Many people do not recognise it as an earthquake. Standing cars may rock slightly; vibrations are similar to a passing truck.
4	Light	Felt indoors by many, outdoors by few. At night, some are awakened. Dishes, windows, and doors are disturbed. Sensation like a heavy truck striking a building. Standing cars rock noticeably.
5	Moderate	Felt by nearly everyone; many awakened. Dishes and windows are broken. Unstable objects are overturned. Pendulum clocks may stop.
6	Strong	Felt by all; many frightened. Heavy furniture moved. A few instances of fallen plaster. Damage is slight.
7	Very Strong	Negligible damage to buildings of good design/construction. Slight to moderate damage in well-built/ordinary construction. Considerable damage in poorly built/designed structures. Some chimneys break.
8	Severe	Slight damage to specially designed structures. Considerable damage to ordinary construction, including partial collapse. Damage is great in poorly built structures. Fall of chimneys, columns, monuments, and walls. Heavy furniture overturned.
9	Violent	Considerable damage to specially designed structures; well-designed frame structures are thrown out of plumb. Damage is great in substantial buildings, with partial collapse. Buildings shifted off foundations.
10	Extreme	Some well-built wooden structures are destroyed; most masonry and frame structures with foundations are destroyed. Rails are bent.
11	Extreme	Few, if any, structures remain standing. Bridges destroyed. Broad fissures in the ground. Underground pipelines are completely out of service. Earth slumps, and land slips in soft ground. Rails bent greatly.
12	Extreme	Damage total. Waves are seen on ground surfaces. Lines of sight and level distorted. Objects are thrown upward into the air.

Source: United States Geological Survey

The final criterion for the database, which is the generation of a tsunami by the earthquake, can also sometimes be misleading. This is because the occurrence of a tsunami does not necessarily indicate destructive consequences (United States Geological Survey, 2023). While these events are still recorded in the database, they may not be relevant for our analysis, as non-destructive tsunamis seem unlikely to have any impact on the stock market.

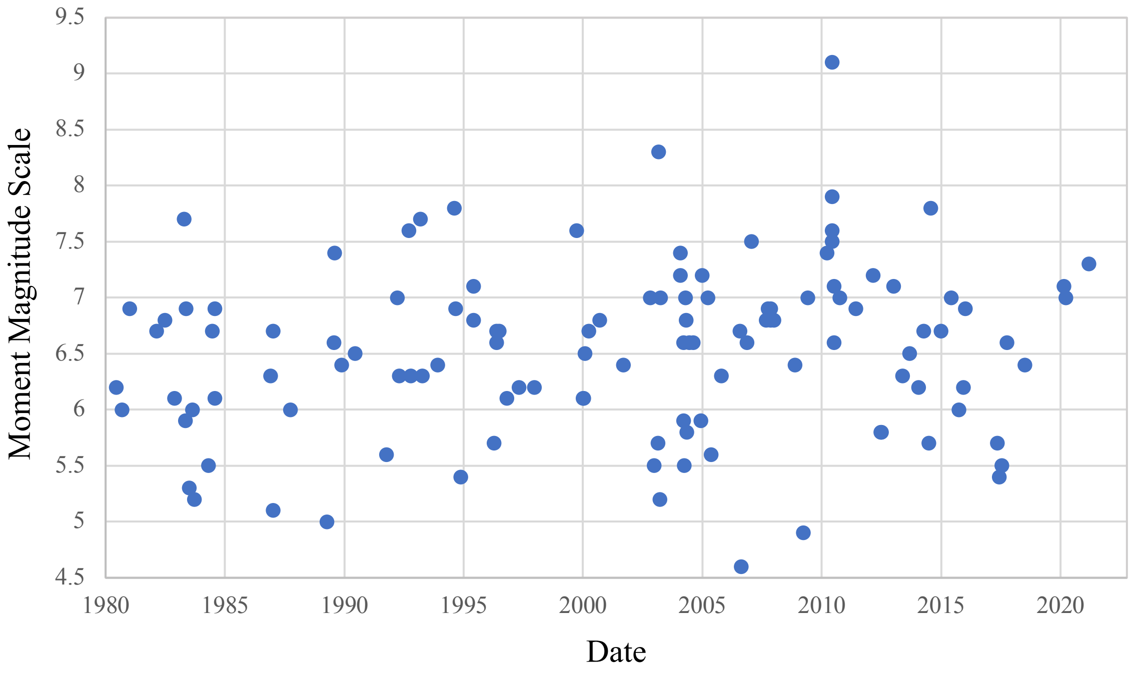
In the period analysed in this study, a total of 117 significant earthquake events occurred between 1980 and 2023. A list of all earthquakes, including all the available data on economic damage ($mil), number of deaths, magnitude, MMI intensity and the presence of a tsunami, can be found in Appendix 1. However, not all of these events are relevant to this study. Therefore, the events used in the analysis will be selected based on several criteria, with the main one being the economic damage caused by the earthquake. This criterion is chosen based on the intuitive understanding that the criterion of economic damage caused by an earthquake has the most impact on stock markets. This idea has also been adopted by previous studies, where the selection of natural disasters for their analysis is often based on the economic damage caused by the event. However, for a complete and thorough analysis, other characteristics, precisely the magnitude, number of fatalities, and date, are also being analysed. Several different sub-groups of events will be determined throughout the analysis, as not all of the 117 significant earthquakes in the NGDC's Global Significant Earthquake Database will be meaningful for this study.

Table 5*: List of significant earthquakes per date*

Date range	Number of earthquakes
1980 – 1984	16
1985 – 1989	7
1990 – 1994	11
1995 – 1999	11
2000 – 2004	21
2005 – 2009	18
2010 – 2014	17
2015 – 2019	13
2020 – 2023	3

Significant earthquakes are unpredictable and can occur randomly at any time. To date, there is no reliable method to accurately determine the exact timing of an earthquake. Sometimes they occur in quick succession, while other times, there may be long periods of time between them. It is not uncommon for there to be multiple strong earthquakes in a single year, while sometimes there can be none at all for several years. (see Table 5)

***Figure 2**: Earthquake magnitude of every significant earthquake between 1980 and 2023*



Furthermore, significant earthquakes are extremely rare events. From 1980 to 2023, only 117 occurred with a greatly varying magnitude. Only a few of them are considered as major or great on the moment magnitude scale (Figure 2). In statistical modelling, this kind of data is described as rare events (Ghil et al., 2011). These events occur with low frequency but often have a widespread effect which might destabilise systems such as the stock market. Therefore, rare events can be challenging to study and analyse statistically. Typically, event studies analyse a high number of events in order to make an accurate prediction. In studies with a limited number of events, the empirical results can be strongly influenced by outliers (Osborne & Overbay, 2004). In this paper, several sub-groups of earthquakes present a relatively small sample size of events. However, this can be attributed to the inherent nature of earthquake occurrences, which are rare and infrequent by their very nature. To account for this this, various other characteristics of earthquakes are being analysed as a robustness check.

5. Methodology

This section outlines the methodology and steps involved in conducting the event study in this paper. The primary research question is focused on examining how earthquakes affect short-term abnormal returns across various industries in Japan. To answer this question, an event study is intuitively considered the most suitable method due to its rigorous nature and well-established reputation in economics and finance research. Event studies have been used extensively in past research, making them a reliable and accurate approach to investigate the effects of economic events on stock returns. The event study design and methodology employed in this paper draw inspiration from the framework outlined by MacKinlay in 1997.

5.1. Event Study Design

In his paper "Event Studies in Economics and Finance," MacKinlay (1997) defines an event study as a statistical method used to analyse the effect of an event, such as a corporate announcement or a natural disaster, on the price of a security or a financial market. The author explains that the first step in an event study is to identify the event and the specific point in time when it occurred. In the context of this paper, this refers to the date on which significant earthquakes occurred in Japan. Once the events are identified, the next step is to measure the excess return of the market in question relative to a benchmark over a certain period around the event date. The benchmark serves as a reference point for measuring the performance of the specific industry in relation to the event. It is chosen based on its ability to provide a measure of the normal performance of the market. This study selected the TOPIX index as the benchmark as it is the most appropriate representation of the entire Japanese stock market. After measuring the abnormal return, statistical analysis is conducted to determine whether it is significant and whether it can be attributed to the event. This analysis involves testing the null hypothesis that the event has no impact on the market in question. If the null hypothesis is rejected, the abnormal return is identified as statistically significant, indicating that the earthquakes have a significant impact on the returns. The empirical results are then analysed and contextualised to draw conclusions and answer the research questions.

In essence, the event study methodology used in this paper is divided into the following consecutive steps:

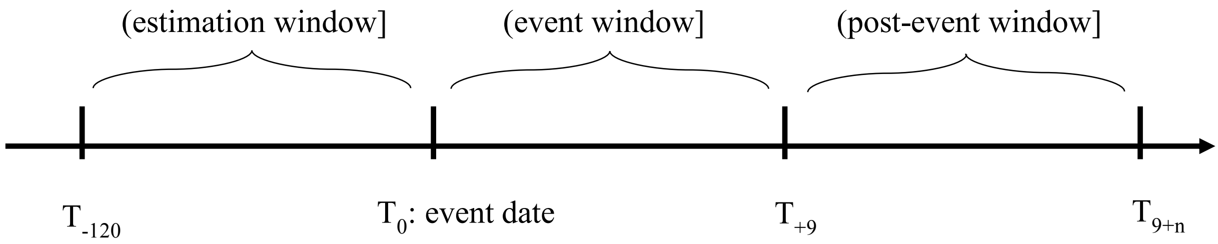
- Defining the event and timeline
- Estimating normal returns
- Estimating abnormal returns
- Testing abnormal returns
- Analysing the results

5.1.1 Defining the Event and Timeline

The initial step of an event study is to define the event of interest, which in this paper is the occurrence date of significant earthquakes. Earthquakes are considered significant according to the standards of the widely recognised Global Significant Earthquake Database. If the earthquake occurs during trading hours on the Tokyo stock exchange, the event date (T_0) corresponds to the day of the occurrence. It is important to note that the trading hours of the Tokyo stock exchange have been adjusted multiple times during the period under analysis in this study. The current trading hours are scheduled from 9:00 am - 11:30 am for the morning session and from 12:30 pm - 3:00 pm for the afternoon session. Moreover, the exchange remains closed on weekends, public holidays and from December 31 to January 3 (Japan Exchange Group, 2023). If a significant earthquake occurs on these days or outside of trading hours, the event day (T_0) will be determined as the following trading day.

Figure 3 shows the timeline of the event study adopted in this paper with the event date marked as T_0. The frequency of data utilised in this study is daily data, which has become the standard in event studies since the mid-1980s. This is because daily data offers a higher level of detail and captures more nuanced information about the stock market's reaction to an event. Brown and Warner (1985) explain that, as intuitively expected, the power of each test in an event study is much greater with daily data than with monthly data. Furthermore, Figure 3 illustrates the estimation window, the event window, and the post-event window used in this study.

Figure 3*: Event study timeline*



In an event study, the event window is the time period during which the effects of the event, in this case, the significant earthquake, are analysed. It is the period in which abnormal returns are computed to measure the impact of the earthquakes on the respective market. The selection of the event window is crucial as it should capture the full market reaction to the event and identify any abnormality in the market's return. Therefore, the length of the event window is specific to each event study as it is determined based on the formulation of the analysis and the nature of the events being studied. Event studies generally acknowledge that event windows typically extend beyond the event day itself, including days before and after the event announcement (MacKinlay, 1997). This approach recognises that the market may react to the event before it actually occurs. For some types of events, such as corporate announcements, investors may adjust their positions in anticipation of the event based on their predictions of the outcome. However, in this paper's context, as earthquakes are completely unpredictable, there is no possibility of market anticipation before the event. Therefore, the event window in this study solely focuses on the event date and the period post the event date.

It spans from the day of the earthquake T_0 to the next nine trading days T_9, totalling a period of ten days. The event window needs to be of sufficient length to encompass the entire market reaction and allow for the analysis of any potential transitory effects resulting from the shock, for instance, potential market rebounds. However, it is important to ensure that the event window is not too long, leading to a loss of statistical significance.

This study utilises a relatively short event window compared to previous literature, as the focus is specifically on the short-term abnormal returns of the stock market. However, this approach is beneficial as it reduces the risk of contamination from external factors and other information that may affect the market's reaction (Ferreira & Karali , 2015). Brown and Warner (1985) also suggested that if the event window is too large, the accuracy of the tests may decrease. In line with these conclusions, a ten-day event window is appropriate for the type of analysis conducted.

The estimation window is the time period used to estimate the expected return of the market in the absence of an event. It is a period of time before the actual event occurs and serves as a baseline for comparison with the event window. The standard practice in event studies is to ensure that the estimation window and the event window do not overlap. This approach is used to estimate the parameters of the normal return without being influenced by the returns surrounding the event (MacKinlay, 1997). Finding the optimal length of the estimation window is a crucial aspect of conducting an event study. According to Brown and Warner (1985), the estimation window should be long enough to capture the normal behaviour of the stock market but not so long that it includes the effects of the event being studied. While a longer estimation window intuitively seems like it may capture more information about the stock market's behaviour, it carries significant risks. For instance, it may include data irrelevant to the specific event being studied. A longer estimation window may contain data from a different economic environment or period of time that is not representative of the current market conditions any more.
Campbell, Lo, and MacKinlay (1997) argue that when using daily stock prices, an estimation window of 120 trading days is appropriate to create good parameter estimates. This translates to approximately six months before the event, and it is considered to provide a sufficient number of observations for estimating a reliable normal return while also ensuring that the data does not include non-relevant data. Therefore, aligning with Campbell, Lo, and MacKinlay (1997), this study uses a 120-day estimation window that begins 120-trading days before to the event until the day preceding the event date.

Furthermore, Figure 3 illustrates the post-event window, which is a period that comes after the event window. This is commonly utilised in event studies to capture any delayed market reactions or long-term effects of the event. However, since this study is primarily concerned with short-term abnormal returns and does not perform a long-term analysis, the post-event window beyond the ninth day after the event date is not significant.

5.1.2 Estimating Normal Returns

Measuring normal returns in an event study means estimating the expected returns of a market index during the event window if the event being studied had not occurred. This estimation is based on historical data from the estimation window that is used to establish a baseline for expected returns. According to MacKinlay (1997), different approaches are available to calculate the normal returns of a given security. He explains that they can be grouped into two categories: statistical and economic models. Economic models have the advantage of incorporating economic restrictions and, therefore, can obtain more precise measures of normal returns. However, these models still require additional statistical assumptions, making them more complicated and less applicable in the real world. The most commonly used economic model providing such restrictions is the Capital Asset Pricing Model (CAPM), widely used in event studies during the 1970s (MacKinlay, 1997). However, the author notes that these studies may be sensitive to the specific restrictions imposed by the CAPM. Therefore, statistical models are generally sufficient for event studies. Statistical models, conversely, make statistical assumptions to determine the behaviour of returns. They assume that returns are independently and identically distributed over time (MacKinlay, 1997). The statistical models proposed for modelling the normal returns are the Constant-mean return model and the Market model. This paper will also use these two models in line with previous research.

To calculate normal returns, historical returns of markets are needed. However, the data that was downloaded consists of daily adjusted closing prices. Therefore, the actual returns of these markets are first being calculated in accordance to equation 1.

$$R_{it} = \ln\left(\frac{P_{it}}{P_{it-1}}\right) \tag{1}$$

Where:

R_{it} is the time-t return of the market index i.

P_{it} is the price of index i for time t.

P_{it-1} is the price of index i for time $t-1$.

- **Constant-mean return model**

The Constant-mean return model assumes that the mean returns of a given security are constant over time. Despite being a relatively simple statistical model, Brown and Warner (1985) found that when using daily data, this model often produces results similar to those of the Market model.

The authors explain that this lack of sensitivity is explained by the variance of the abnormal return, which is often not reduced much by choosing a more sophisticated model. The Constant-mean return model is calculated as follows:

$$R_{it} = \mu_i + \xi_{it} \tag{2}$$

$$E(\xi_{it}) = 0 \qquad\qquad Var\,(\xi_{it}) = \sigma^2_{\xi_i}$$

Where:
R_{it} is the time-t return of the index i.
μ_i is the mean return for i.
ξ_i is disturbance term for time period t.

To analyse hypotheses H_1 and H_2, which are concerned with the impact of earthquakes on the Japanese stock market as a whole, the Constant-mean return model is utilised. The Market model requires benchmark returns for comparison with normal returns. However, when analysing the entire stock market, it becomes challenging to find a significant benchmark. Typically, a global stock market index is used as a benchmark. However, for hypotheses H_1 and H_2, the TOPIX index, which represents the entire Japanese stock market, is being analysed, making it difficult to find another index to benchmark it to. Therefore, and due to the similarity of results with the market model when using daily returns, the Constant-mean return model is considered appropriate for analysing the whole market.
On the contrary, for the industry-specific analysis (hypothesis H_3), the Market model is being used:

- **Market model**

The Market model estimates expected security returns by considering the benchmark returns of a market. It assumes that the returns of assets follow a joint normal distribution and, therefore, there is a linear relationship between the returns of a security and the returns of the market benchmark (MacKinlay, 1997). In this paper, industry-specific market indices (Table 2) are analysed and compared to the TOPIX index, which serves as a benchmark. The Market model, under the condition of a high R^2, can be considered a potential improvement over the Constant-mean return model since it removes the portion of the return that is related to variation in the market's return. As a result, the variance of the abnormal return is reduced, which can enhance the ability to detect event effects (Campbell, Lo, & MacKinlay, 1997). Therefore, to analyse industry-specific market reactions where a significant benchmark, such as the TOPIX, can be established, the Market model is being used:

$$R_{it} = \alpha_i + \beta_i R_{mt} + \varepsilon_{it} \tag{3}$$

$$E(\varepsilon_{it}) = 0 \qquad\qquad Var\ (\varepsilon_{it}) = \sigma^2_{\varepsilon_i}$$

Where:

R_{it}	is the time-*t* return of the index *i.*
R_{mt}	is the time-*t* return of the benchmark index *i.*
ε_{it}	is the zero mean disturbance term.
α_i, β_i and $\sigma^2_{\varepsilon_i}$	are the parameters of the Market model

It is important to note that α_I and β_i are obtained by using the Ordinary Least Squares (OLS) regression method. The estimation of the normal returns is defined as the residuals or prediction errors of equation 4:

$$\hat{R}_{it} = \hat{\alpha}_i + \hat{\beta}_i R_{mt} \tag{4}$$

The estimation of α_I and β_i during the event window ($T_{0,9}$) is realised by $\hat{\alpha}_i$ and $\hat{\beta}_i$ from the estimation window ($T_{-120,-1}$). The normal returns or expected returns can be represented by $E(R_{it})$.

5.1.3 Estimating abnormal returns

To estimate the abnormal returns for one event, the expected returns are subtracted from the actual returns:

$$AR_{it} = R_{it} - E(R_{it}|X_t) \tag{5}$$

Where:

AR_{it} is the time-t abnormal return i.

R_{it} is the time-t actual return i.

$E(R_{it}|X_t)$ is the time-t expected return of i with X_t = constant using the Constant-mean return model and $X_t = R_{mt}$ using the Market model.

The AR for a single event on a single day gives a specific indication of the market reaction of that day. However, to observe the total market reaction to an event of interest over a longer period of time, abnormal returns are accumulated for the entire event window ($T_{0,9}$). The Cumulative abnormal returns (CAR) are calculated as follows:

$$CAR_i = \sum_{T_0+1}^{T_9} AR_{it} \tag{6}$$

Where:

CAR_i is the cumulative abnormal return of *i*.

However, the intention of the study is not to analyse the CAR for a single event. The objective is to examine whether there is a general trend in abnormal returns after multiple events. Therefore, abnormal returns need to be aggregated over multiple events. This is achieved by computing the average abnormal returns ($\overline{AR_t}$) of all events per event date:

$$\overline{AR_t} = \frac{1}{N}\sum_{i=1}^{N} AR_{it} \quad (7)$$

Where:

$\overline{AR_t}$ is the time-*t* average abnormal return of N events.

Once the abnormal returns have been aggregated over multiple events, the next step is to aggregate them over time to observe the total market reaction to all events over a longer period. The cumulative average abnormal return ($\overline{CAR}$) is:

$$\overline{CAR} = \frac{1}{N}\sum_{i=1}^{N} CAR_i \quad (8)$$

Where:

$\overline{CAR}$ is the cumulative average abnormal return of N events.

5.2. Testing abnormal returns

To evaluate the significance of $\overline{AR_t}$ and $\overline{CAR}$, they are subjected to a test. This involves comparing the computed abnormal returns to a null hypothesis of zero abnormal returns using statistical tests. The results are then assessed to determine whether they are significant enough to reject the null hypothesis or not. Many tests are available to assess significance, some being parametric in nature and some being non-parametric tests. Parametric tests are widely distributed, but they require specific assumptions about the distribution of abnormal returns. Non-parametric tests, on the other hand, make no assumptions concerning the distribution of returns. The choice between parametric and non-parametric tests depends on the type of data and assumptions made about the data. Normality of abnormal returns is a key assumption when parametric tests are used in the event study (McWilliams & Siegel, 1997). However, despite the normality assumption, it is important to recognise that, in reality, the distribution of the samples may deviate from a normal distribution. Dyckman et al. (1984) conducted a study to evaluate the impact of non-normality in daily return data on various statistical tests used in short-term event studies. They concluded that non-normality does not significantly affect the power of commonly used parametric tests such as the t-test. Following this example, this study uses the parametric t-test to assess the significance of abnormal returns. However, as the use and effectiveness of different tests for event studies are debated, it is common practice to employ a combination of parametric and non-parametric tests. Therefore, as an alternative to the parametric t-test, the non-parametric Wilcoxon signed rank test is conducted as a robustness check. (King & Eckersley, 2019)

5.2.1 Parametric test

The t-test is a statistical test commonly used in the event study methodology to determine whether there is a significant difference between two populations in terms of their means. It tests the null hypothesis to determine whether the observed abnormal returns are significant or not. The test computes a t-value which is then compared to the critical value at the chosen significance level at 0.1, 0.05 and 0.01. The results are considered statistically significant if the calculated t-value exceeds the corresponding critical value.

Hypotheses H_1 and H_2 assume, based on previous literature, that earthquakes have a negative impact on short-term returns. To test for statistical significance in the one direction of interest, a one-sided t-test is chosen with the following null- and alternative hypotheses:

$$H_0: \overline{AR} = 0 \tag{9}$$

$$H_A: \overline{AR} < 0 \tag{10}$$

For the industry-specific analysis (hypothesis H_3), a two-tailed test is more appropriate as there is no prior assumption of the direction of the effect. Therefore, a different alternative hypothesis is presented:

$$H_0: \overline{AR} = 0 \tag{9}$$

$$H_A: \overline{AR} \neq 0 \tag{11}$$

The critical values of the t-test for the chosen significance levels of 0.1, 0.05, and 0.01 for all sub-groups of earthquakes analysed in this study are displayed in Appendix 2. The test statistics are:

$$t_{\overline{AR}_t} = \frac{\overline{AR_t}}{std(\overline{AR_t})} \sim N(0,1) \tag{12}$$

Where:

$std(\overline{AR_t})$ is the standard deviation which is computed by utilising the standard deviations of the residuals from the estimation window.

The test statistic of the cumulative average abnormal return $\overline{CAR}$ is calculated in a similar manner:

$$t_{\overline{CAR}} = \frac{\overline{CAR}}{std(\overline{CAR})} \sim N(0,1) \tag{13}$$

5.2.2 Non-parametric test

The Wilcoxon signed-rank test is a non-parametric statistical test used as an alternative to the t-test (Siegel, 1956). This paper examines the significance of the realised return in the aftermath of an earthquake by comparing it to the normal return. In the Wilcoxon signed-rank test, the differences between the pairs of observations are ranked by their absolute values. Then, the positive and negative ranks are summed separately, resulting in two test statistics: W^+ and W^-. The test statistic W is defined as the smaller of W^+ and W^- and then compared to a critical value (Appendix 3). If the observed value of W is less than or equal to the critical value, we reject H_0 in favour of H_a. The test statistic W is:

$$W = \sum_{i=1}^{N_r} \left[sng\left(x_{2,i} - x_{1,i}\right) * R_i \right] \tag{14}$$

Where:

W	is the test statistic
N_r	is the sample size (excluding pairs where x1 = x2)
sgn	is the sign function
$x_{1,i}\,;x_{2,i}$	are the corresponding ranked pairs from two distributions
R_i	is rank i

6. Empirical analysis

This section provides an overview of the empirical results from the event study. It includes the results of two significance tests, a parametric test (t-test) and a non-parametric test (Wilcoxon signed-rank test). The results are presented in three parts. Firstly, the impact of significant earthquakes on the overall Japanese stock market is discussed. Secondly, the industry-specific analysis is presented. Lastly, the effects of earthquakes with different characteristics are examined.

6.1. Effect on the Japanese stock market (Hypotheses H_1 & H_2)

The first hypothesis (H_1) of the study focuses on the negative short-term abnormal returns of the Japanese stock market. To measure abnormal returns, an event study is conducted. Table 6 displays the obtained average abnormal returns. The table shows the average abnormal return ($\overline{AR_t}$) for each event date and the computed t-value using the parametric t-test. Additionally, the non-parametric Wilcoxon signed-rank test is conducted, and the corresponding p-value is presented in the last column.

Table 6*: Average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with all 117 significant earthquakes using the constant-mean return model*

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
0	-0.06%	-0.387	0.657
1	-0.20%	-1.556*	0.175
2	-0.14%	-1.093	0.951
3	0.07%	0.460	0.872
4	-0.14%	-1.183	0.427
5	0.27%	1.516	0.186
6	0.09%	0.620	0.582
7	0.11%	0.746	0.941
8	0.03%	0.205	0.869
9	0.11%	0.882	0.357

***, **, * indicate significance of 1%, 5%, 10%

Table 7 presents the results of the cumulative average abnormal return ($\overline{CAR}$) computation for two different periods: a five-day period from the event day to day four [0; +4] and the whole ten-day event window [0; +9]. The table includes the $\overline{CAR}$ values for each period, as well as the corresponding t-values.

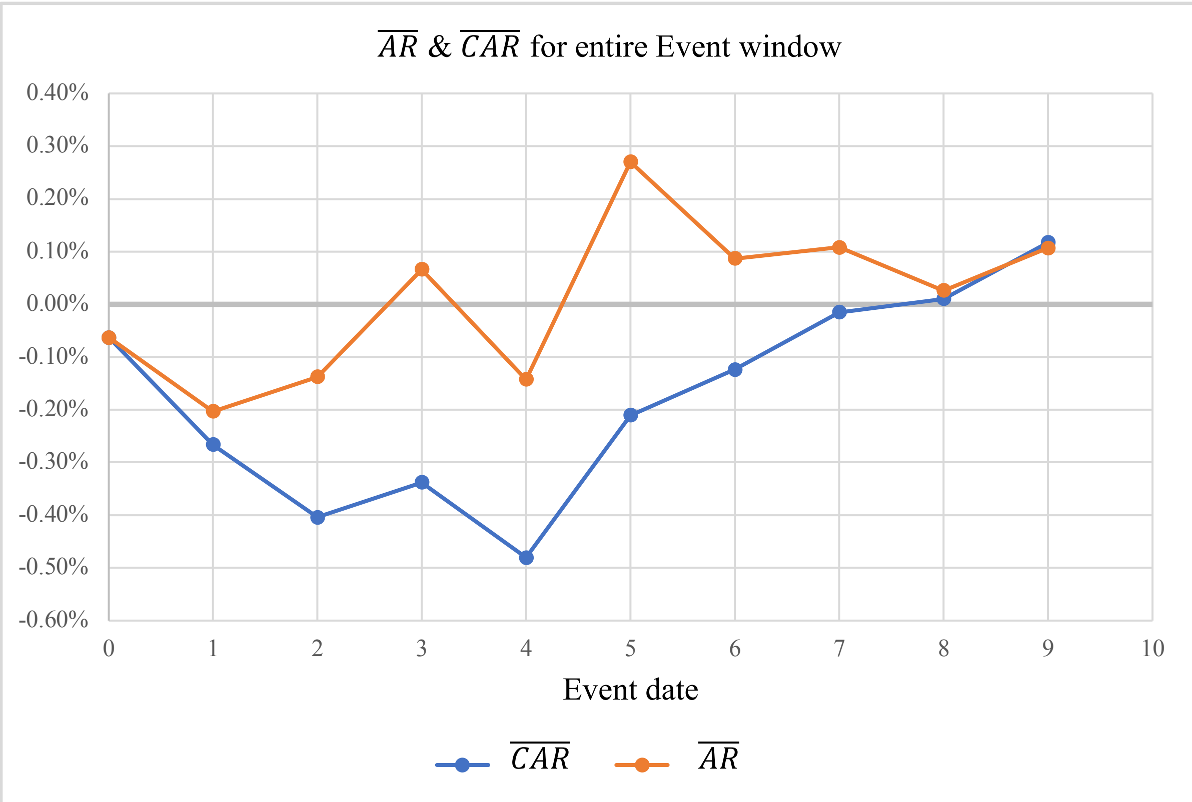
***Table 7**: Cumulative average abnormal return of the entire Japanese stock market with all 117 significant earthquakes using the constant-mean return model*

Event window	$\overline{CAR}$	t-test
[0; +4]	-0.48%	-1.10
[0; +9]	0.12%	0.36

***, **, * indicate significance of 1%, 5%, 10%

The following graph (Figure 4) provides a visual representation of $\overline{AR}$ and $\overline{CAR}$ in the Japanese stock market over time. It illustrates the market's reaction and the drift of abnormal returns over the event window.

***Figure 4**: Reaction of the entire Japanese stock market to all 117 significant earthquakes using the constant-mean return model*



The analysis of 117 earthquakes listed in the Global Significant Earthquakes Database on the Japanese stock market indicates the presence of abnormal returns on the event day and the first, second, and fourth day after the event. However, only the abnormal return on the event date 1 (T_1) (-0.20%) is significant at a 10% level, while all other days do not present significant abnormal returns.

In contrast to previous research, the negative abnormal returns on the event day (T_0) are small and statistically insignificant. Typically, in prior literature, significant abnormal returns were already observable on the day of the event. However, in this study, the reaction is different and only on event date 1 (T_1), significance at a 10% level is observable. A possible explanation could be that this paper analyses a much more extended period than most previous literature, with data that starts already from 1980. In the 1980s, news was primarily disseminated through traditional media outlets such as newspapers, television, and radio. Therefore, it could take several hours or even days for news to spread across the population (Mehrabi, Hassan, & Ali, 2009).

Furthermore, Japan experiences a very high frequency of earthquakes, with hundreds occurring each year, but the majority have no significant impact. As a result, the public may not be immediately alarmed by the news of an earthquake, and it may take some time for it to become clear that the earthquake has severe consequences. (Hongo, 2007) This could explain the delayed reaction of negative abnormal returns observed in this study.

The cumulative abnormal return during the event window [0; +4] is negative but not statistically significant. It is close to 0 when considering the whole event window [0; +9]. Figure 4 visually represents the initial market reaction which depicts a downward trend immediately after the event. However, a bounce back in the market is observed from event date 5 (T_5) on. The market's return to its initial level indicates the presence of a transitory component in the returns following the shock. Such a bounce back in the market is not uncommon after external shocks, especially when the market overreacts to the initial shock (Giglio, Maggiori, Stroebel, & Utkus, 2020).

Previous studies examining the impact of earthquakes on the Japanese stock market, such as Tao (2012) and Yamori and Kobayashi (2002), reported significant $\overline{CAR}$ in contrast to this study. However, it is essential to note that these studies only considered the impact of a single, very devastating earthquake and did not take into account all significant earthquakes. One possible explanation for the absence of significant abnormal returns in this study is that not all of the 117 earthquakes classified as significant by the NGDC led to negative returns. As previously stated, the Global Significant Earthquakes Database employs specific criteria for categorising an earthquake as significant, and it is possible that not all earthquakes meeting one of these criteria have an impact on the economy. Some earthquakes may have had minimal or no impact on the economy and, therefore, on the stock market.

For that reason, this study examines hypothesis H_2, which suggests that earthquakes causing a higher economic damage have a more negative effect on Japan's stock market. This hypothesis has been tested by classifying significant earthquakes into several groups based on the criterion of the value of their economic damage. The following groups were analysed and compared to evaluate the impact of more devastating earthquakes on the stock market:

- Damage > $100 million: 19 earthquakes
- Damage > $500 million: 13 earthquakes
- Damage > $5000 million: 8 earthquakes

Table 8*: Average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with 19 significant earthquakes (damage >* ***$100 million****) using the constant-mean return model*

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
0	0.00%	-0.011	0.717
1	-0.49%	-1.021	0.295
2	-0.63%	-1.104	0.629
3	0.45%	0.990	0.295
4	-0.40%	-1.459*	0.126
5	0.18%	0.829	0.573
6	0.19%	0.582	0.904
7	-0.04%	-0.201	0.904
8	-0.37%	-1.057	0.398
9	0.11%	0.304	0.748

***, **, * indicate significance of 1%, 5%, 10%

***Table 9**: Cumulative average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with 19 significant earthquakes (damage > **\$100 million**) using the constant-mean return model*

Event window	$\overline{CAR}$	t-test
[0; +4]	-1.08%	-1.068
[0; +9]	-1.01%	-1.028

***, **, * indicate significance of 1%, 5%, 10%

Tables 8 and 9 show that despite an increase in the negative for $\overline{AR}$ for most event dates, the negative abnormal returns for earthquakes that result in more than \$100 million in damage are not statistically significant, except for event date 4 (T_4) at a 10% level. The cumulative average abnormal return for the event window [0; +9] is -1.01%, compared to 0.12% when considering all significant earthquakes. However, it also is statistically insignificant.

***Table 10**: Average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with 13 significant earthquakes (damage > **\$500 million**) using the constant-mean return model*

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
0	-0.10%	-0.191	0.600
1	-0.58%	-0.826	0.422
2	-0.78%	-0.958	0.972
3	0.63%	0.946	0.279
4	-0.50%	-1.212	0.279
5	0.22%	0.854	0.701
6	0.40%	0.866	0.507
7	0.08%	0.303	0.807
8	-0.65%	-1.521*	0.196
9	0.03%	0.065	0.917

***, **, * indicate significance of 1%, 5%, 10%

***Table 11**: Cumulative average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with 13 significant earthquakes (damage > **500 million**) using the constant-mean return model*

Event window	$\overline{CAR}$	t-test
[0; +4]	-1.33%	-0.910
[0; +9]	-1.25%	-0.998

***, **, * indicate significance of 1%, 5%, 10%

The 13 significant earthquakes resulting in economic damage of over $500 million show no statistically significant $\overline{AR}$ and $\overline{CAR}$. Only for event date 8 (T_8) a 10% level of significance can be observed.

***Table 12**: Average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with 8 significant earthquakes (damage > **$5000 million**) using the constant-mean return model*

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
0	-0.56%	-0.941	0.263
1	-0.81%	-0.717	0.575
2	-1.07%	-0.815	0.889
3	1.25%	1.407	0.208
4	-0.87%	-1.437*	0.123
5	0.38%	1.016	0.401
6	0.43%	0.636	0.779
7	-0.02%	-0.076	0.779
8	-1.27%	-2.330**	0.050**
9	0.22%	0.313	0.779

***, **, * indicate significance of 1%, 5%, 10%

***Table 13**: Cumulative average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with 8 significant earthquakes (damage > $**5000 million**) using the constant-mean return model*

Event window	$\overline{CAR}$	t-test
[0; +4]	-2.06%	-0.878
[0; +9]	-2.33%	-1.453*

***, **, * indicate significance of 1%, 5%, 10%

Table 13 shows that earthquakes producing economic damage over $5 billion show negative cumulative average abnormal returns (-2.33%) for the event window [0; +9] significant at a 10% level. However, it is essential to note that this significance level is still relatively low, especially considering that the analysis employs a one-tailed test. Nonetheless, the $\overline{CAR}$ shows some significance in contrast to two other defined sub-groups of earthquakes. For the $\overline{AR_t}$ on the respective event date, a significant negative abnormal return is observed at a 10% level on event date 4 (T_4) and at a 5% level on event date 8 (T_8). The Wilcoxon signed-rank test also confirms significance at a 5% level on event date 8 (T_8). Notably, this finding cannot be explained in terms of previous research as there has been no prior evidence of statistical significance on event date 8 (T_8).

Figure 5*: Cumulative average abnormal return of event date ($T_{0,9}$) of the entire Japanese stock market with all significant earthquakes and the three defined sub-groups of earthquakes using the constant-mean return model*

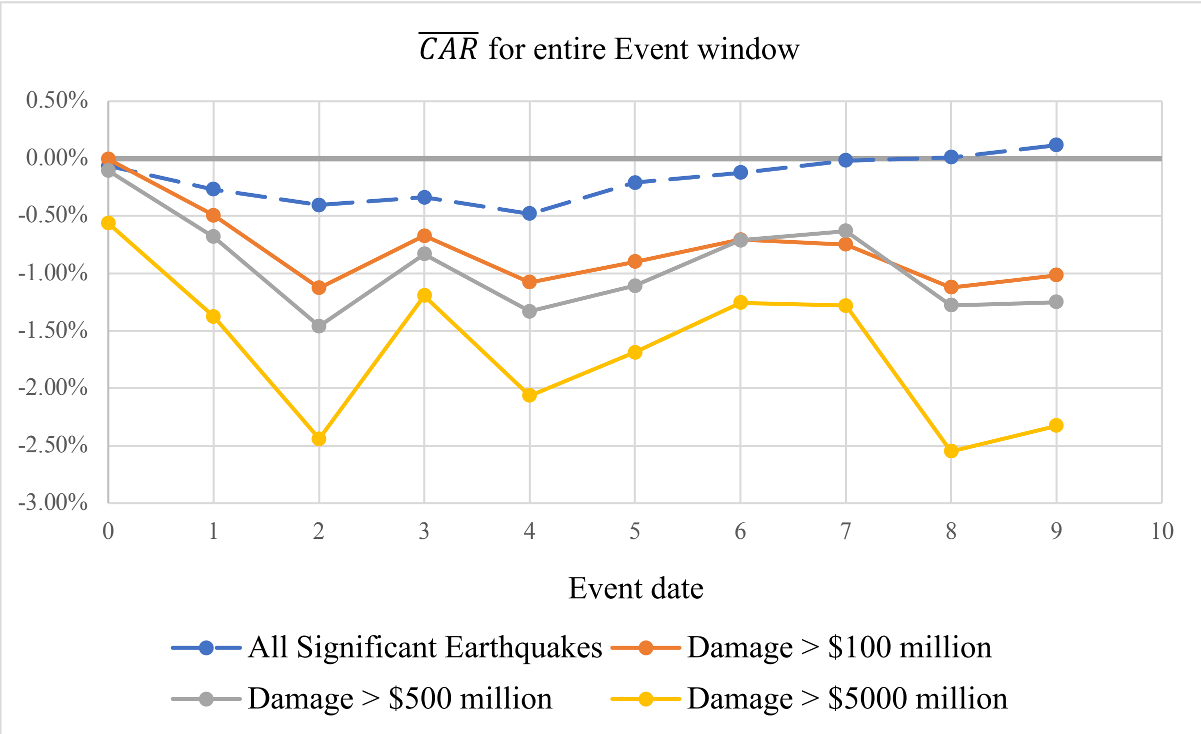


Figure 5 demonstrates a positive correlation between the economic damage caused by earthquakes and the corresponding $\overline{CAR}$ for each earthquake sub-group. Specifically, the $\overline{CAR}$ is higher for earthquakes that cause more economic damage. There is a notable difference between the analysis, including all significant earthquakes and the two sub-groups with economic damage greater than $100 and $500 million. The highest $\overline{CAR}$ is observed for the most devastating earthquakes with economic damage exceeding $5000 million. However, although there is a noticeable increase in $\overline{CAR}$ for earthquakes that result in higher economic damage, the abnormal returns of these earthquakes are only marginally more significant. The $\overline{CAR}$ of earthquakes in the first three sub-groups are statistically insignificant. Only the $\overline{CAR}$ of the most devastating earthquakes is found to be statistically significant, although weakly (-1.453*), at a 10% significance level.

The weak statistical significance can be explained by the high standard deviation in the sample, particularly for the sub-group with earthquakes that cause economic damage exceeding $5000 million. In this sub-group, several outliers do not result in negative abnormal returns. Therefore, despite the more prominent negative abnormal returns on average for the more devastating earthquakes, their statistical significance is limited as the standard deviation is considerably high.
These findings are consistent with the results of Scholtens and Voorhorst's (2013) study, which also indicates no significant difference in abnormal returns related to the severity of earthquake damage.

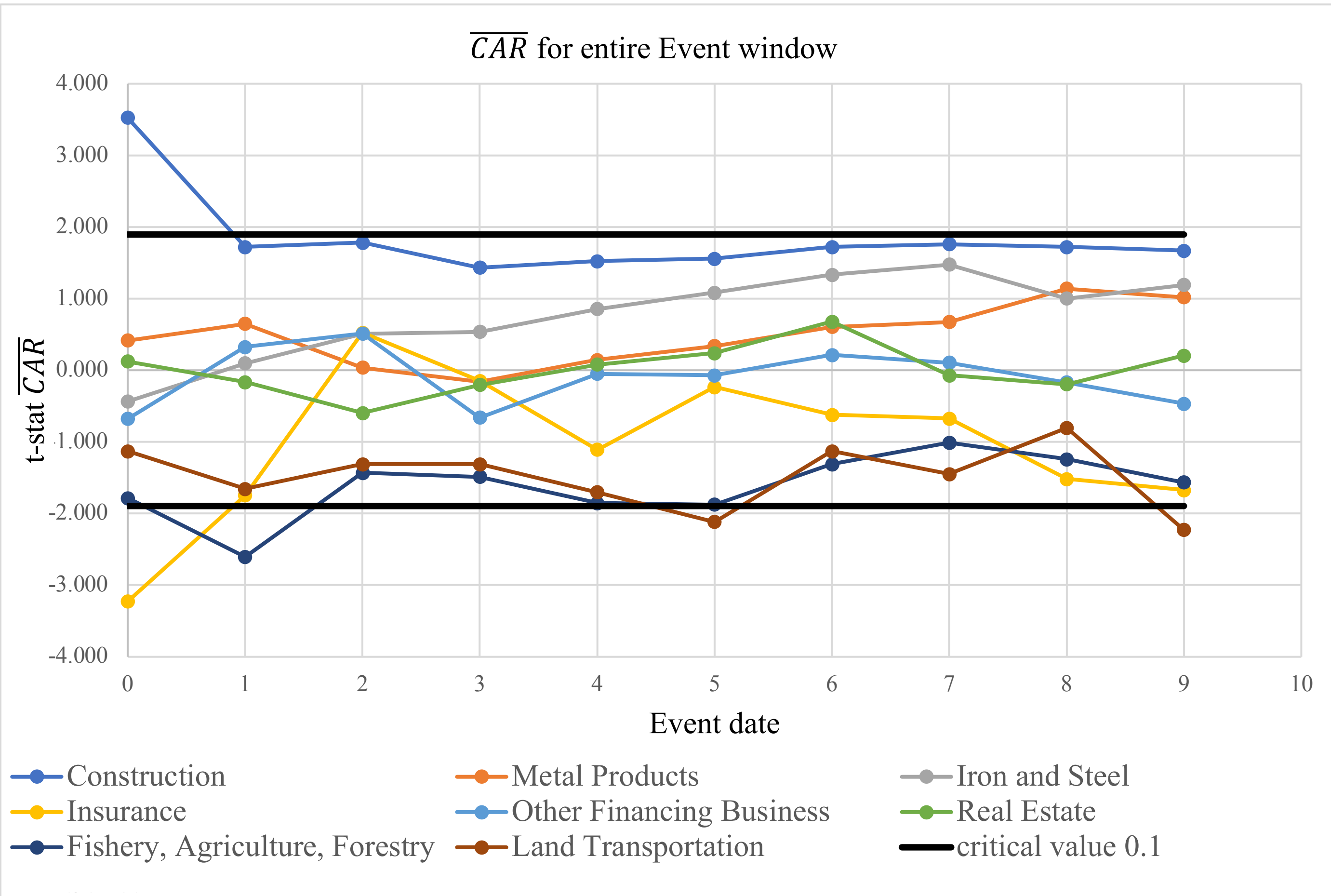
In summary, the results of this study provide only weak evidence for hypotheses H_1 and H_1, which examine the impact of earthquakes on the overall Japanese stock market. The findings show that there are only weakly statistically significant abnormal returns on one day when considering all 117 significant earthquakes. However, this statistical significance only marginally increases when analysing earthquakes that cause more economic damage. This indicates that the economic damage criterion alone is insufficient to determine whether earthquakes produce significant negative abnormal returns. The analysis of other characteristics and factors is needed to provide a better understanding of their impact on stock market performance.

6.2. Industry-specific analysis (Hypothesis *H_3*)

An industry-specific analysis was carried out to address hypothesis (*H_3*) and investigate whether earthquakes significantly impact the stock returns of specific industries in Japan. Following an event study approach, the abnormal returns are calculated using the market model. Finally, the cumulative average abnormal returns ($\overline{CAR}$) for the event window [0; +9] of each industry are tested for significance.

When considering all 117 significant earthquakes for the analysis, none of the industries showed statistically significant $\overline{CAR}$ (Appendix 4). This can be attributed to the fact that not all significant earthquakes have an impact on stock market returns, as previously explained. Therefore, the sub-groups causing higher economic damage were considered for the industry-specific analysis. Figure 5 presents the statistical significance of the $\overline{CAR}$ of each industry. The graph displays the t-values of the $\overline{CAR}$ for each event date, along with the critical value at a 10% significance level.

***Figure 6**: Cumulative average abnormal return of event date ($T_{0,9}$) of all industries with 8 significant earthquakes (damage > **\$5000 million**) using the market model*



In contrast to the analysis using all significant earthquakes, the analysis focusing on the most devastating earthquakes (damage > $5000 million) reveals significant cumulative average abnormal returns ($\overline{CAR}$) for several industries. Specifically, the construction industry displays positive abnormal returns following an earthquake, while the insurance, food, and transportation industries show negative abnormal returns. Notably, the abnormal returns observed on the event day (T_0) for the construction and insurance industries were highly significant, indicating a immidiate impact of earthquakes on those industries. The real estate industry, on the other hand, showed no significant abnormal returns. Given the observed significant $\overline{CAR}$ in specific industries, further in-depth analysis for these industries is conducted.

6.2.1 Construction industry

Table 14: *$\overline{AR}$ and $\overline{CAR}$ of event date ($T_{0,9}$) of the Topix Construction Index with 19 significant earthquakes (damage > $100 million) and 8 significant earthquakes (damage > $5000 million) using the market model*

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
	19 events (damage > $100 million)			**8 events (damage > $5000 million)**		
0	0.71%	3.030***	0.012**	1.34%	3.524***	0.012**
1	0.78%	1.012	1.000	1.82%	1.004	0.779
2	-0.14%	-0.850	0.494	-0.26%	-0.771	0.575
3	-0.14%	-0.803	0.421	-0.49%	-1.909*	0.123
4	0.14%	0.602	0.936	0.42%	1.267	0.161
5	0.03%	0.165	0.778	0.44%	1.205	0.161
6	0.41%	1.545	0.398	1.09%	2.340*	0.017**
7	0.02%	0.202	0.904	0.08%	0.441	0.575
8	0.12%	0.637	0.687	0.28%	0.683	0.401
9	-0.09%	-0.368	0.099	0.36%	0.664	0.889
Event window	$\overline{CAR}$	**t-test**		$\overline{CAR}$	**t-test**	
[0; +4]	1.21%	1.589		2.82%	1.525	
[0; +9]	1.85%	1.228		5.07%	1.668	

***, **, * indicate significance of 1%, 5%, 10%

The Japanese construction stocks are represented by the Topix Construction Index. Statistically significant positive abnormal returns are observed at a 1% level for the (damage > $100 million) sub-group (3.030***) as well as for the sub-group including only the most devastating earthquakes (damage > $5000 million) (3.524***) The Wilcoxon signed-rank test confirms these results with a significance at a 5% level. These findings are consistent with the hypothetical scenario created by Mahalingam et al. (2018), which suggests that the economy benefits from potential reconstruction investment, leading to positive abnormal returns of construction stocks. This study their findings by detecting highly significant positive abnormal returns on the day the earthquake occurred (T_0).

However, it is essential to note that no statistically significant $\overline{CAR}$ was found for both sub-groups in the event window [0; +4] and the entire event window [0; +9]. This could be attributed to the relatively small sample size and comparatively high standard deviation of both sub-groups, which makes it challenging to detect statistical significance (VanVoorhis & Morgan, 2007). Nonetheless, the significant impact on the event day (T_0) confirms the effect of significant earthquakes on the construction industry.

Furthermore, Table 14 presents a clear gap between the abnormal returns in the (damage > $100 million) sub-group and the (damage > $5000 million) sample. The former only yields abnormal returns on the event day (T_0), while the latter produces abnormal returns on event dates (T_0), (T_3), and (T_6). Moreover, the $\overline{CAR}$ is also considerably higher for the (damage > $5000 million) sub-group (5.07% versus 1.85%). These results suggest that earthquakes resulting in higher economic damage have a more profound impact on the construction industry than less devastating earthquakes. This conclusion aligns with the initial intuition of this paper since higher economic damage requires more reconstruction, leading to a more substantial impact on these stocks.

To further validate the positive abnormal returns observed in the construction sector, this paper also analysed the Topix Metal Products Index and the Topix Iron and Steel Index, which are included in the group of the TOPIX-17 Series Construction & Materials. Although both indices showed signs of positive abnormal returns, particularly in the sub-group of the most devastating earthquakes, none of the results was statistically significant (Appendix 5; Appendix 6). These results suggest that significant earthquakes have a positive impact on companies in the construction industry but not on companies focused on raw materials such as metal, iron or steel.

6.2.2 Insurance industry

Table 15: $\overline{AR}$ and $\overline{CAR}$ of event date ($T_{0,9}$) of the Topix Insurance Index with 19 significant earthquakes (damage > \$100 million) and 8 significant earthquakes (damage > \$5000 million) using the market model

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
	19 events (damage > \$100 million)			8 events (damage > \$5000 million)		
0	-0.64%	-1.816*	0.064*	-1.19%	-3.228**	0.025**
1	0.02%	0.066	0.469	0.07%	0.127	0.327
2	0.86%	1.523	0.227	1.70%	1.356	0.208
3	-0.56%	-1.880*	0.117	-0.67%	-1.133	0.263
4	-0.22%	-0.834	0.070*	-0.54%	-2.068*	0.069*
5	0.04%	0.112	0.904	0.47%	0.748	0.401
6	-0.03%	-0.103	0.936	-0.31%	-0.664	0.575
7	0.04%	0.167	0.334	-0.03%	-0.103	0.327
8	-0.21%	-0.822	0.260	-0.64%	-1.543	0.161
9	-0.29%	-1.352	0.212	-0.50%	-1.312	0.263

Event window	$\overline{CAR}$	t-test	$\overline{CAR}$	t-test
[0; +4]	-0.54%	-1.348	-0.63%	-1.108
[0; +9]	-1.00%	-1.514	-1.63%	-1.673

***, **, * indicate significance of 1%, 5%, 10%

Significant negative abnormal returns are observed on the event day (T_0) for the insurance industry. The $\overline{AR}$ are statistically significant at a 10% level for the (damage > \$100 million) sample and at a 5% level for the (damage > \$5000 million) sub-group. These findings are further confirmed by the Wilcoxon signed-rank test, which shows the same significance level. This emphasises the significant impact of earthquakes on the insurance industry. Moreover, similar to the construction industry, the sub-group of earthquakes causing higher economic damage also has a more profound impact on the insurance industry. Both sub-groups' $\overline{CAR}$ show negative returns but are not statistically significant.

The results of this study are in stark contrast to the findings of Shelor, Anderson, & Cross (1992), who examined the stock reactions of US insurance companies to earthquakes and observed statistically significant positive abnormal returns for the event day (T_0). These contrasting results indicate that Japan's insurance sector's response to earthquakes is different from that of insurance companies in the US. Moreover, the negative stock reaction found in this study aligns with the research conducted by Yamori & Kobayashi (2002). They conducted an event study and found significant negative abnormal returns in the insurance sector following the highly destructive 1995 Hanshin-Awaji Earthquake.

Interestingly, Wang & Kutan (2013), that used GARCH models to analyse the stock response of Japan's insurance sector to natural disasters, found opposing results and detected significant positive abnormal returns following natural disasters. This indicates that the methodology employed in the analysis can significantly influence the results. The present study, as well as Yamori & Kobayashi's (2002) research, both used an event study methodology and found negative abnormal returns, while Wang & Kutan (2013), which used GARCH models, found positive abnormal returns in the insurance industry.

Additionally, the Topix Other Financing Business Index, which is also categorised in the TOPIX-17 Series Insurance & Financials, was analysed for further clarification. However, no statistically significant abnormal returns could be detected (Appendix 7).

6.2.3 Real Estate industry

The results of the event study indicate that the real estate industry, represented by the Topix Real Estate Index, did not show any significant abnormal returns (Appendix 8). This suggests that even devastating earthquakes have no significant impact on the real estate industry.

6.2.4 Food industry

Table 16: $\overline{AR}$ and $\overline{CAR}$ of event date ($T_{0,9}$) of the Topix Fishery, Agriculture and Forestry Index with 19 significant earthquakes (damage > \$100 million) and 8 significant earthquakes (damage > \$5000 million) using the market model

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
	19 events (damage > \$100 million)			**8 events (damage > \$5000 million)**		
0	-0.12%	-0.771	0.445	-0.33%	-1.785	0.069
1	-0.49%	-2.178**	0.053*	-0.82%	-2.374**	0.050**
2	-0.68%	-1.481	0.243	-0.82%	-0.809	0.889
3	0.14%	0.626	0.872	-0.05%	-0.200	0.575
4	-0.24%	-0.739	0.717	-0.28%	-0.692	0.484
5	-0.02%	-0.109	0.601	0.21%	0.631	0.484
6	0.36%	1.401	0.295	0.61%	1.394	0.263
7	0.09%	0.393	0.717	0.40%	0.917	0.401
8	-0.23%	-1.018	0.469	-0.23%	-0.511	0.779
9	-0.04%	-0.180	0.573	-0.29%	-0.780	0.327

Event window	$\overline{CAR}$	t-test	$\overline{CAR}$	t-test
[0; +4]	-1.38%	-2.097*	-2.30%	-1.855
[0; +9]	-1.24%	-1.696	-1.60%	-1.564

***, **, * indicate significance of 1%, 5%, 10%

It is worth highlighting that, unlike in the construction and insurance industries, no significant differences are observed in the food industry between the impact of the (damage > \$100 million) and (damage > \$5000 million) sub-groups. Notably, both sub-groups exhibited significant negative $\overline{AR}$ at a 5% level on the event date (T_2), with the Wilcoxon signed-rank test confirming these results. These findings align with the research of Kajitani, Chang, and Tatano (2013), which indicated that the fisheries and agriculture sectors were significantly impacted by the devastating 2011 Tohoku-Oki earthquake. Moreover, it confirms that their findings are not only valuable for the devastating earthquake in 2011 eleven, but it is valid for a larger sample of earthquakes as well.

6.2.5 Transportation industry

Table 17: $\overline{AR}$ and $\overline{CAR}$ of event date ($T_{0,9}$) of the Topix Land Transportation Index with 19 significant earthquakes (damage > \$100 million) and 8 significant earthquakes (damage > \$5000 million) using the market model

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
	19 events (damage > \$100 million)			8 events (damage > \$5000 million)		
0	0.01%	0.049	0.520	-0.28%	-1.129	0.401
1	-0.31%	-1.271	0.227	-0.51%	-1.393	0.263
2	-0.37%	-1.360	0.376	-0.36%	-0.741	1.000
3	0.18%	1.363	0.184	0.13%	0.524	0.674
4	-0.06%	-0.244	0.936	-0.06%	-0.185	0.779
5	-0.31%	-1.715	0.184	-0.13%	-0.471	0.889
6	0.21%	0.679	0.687	0.65%	1.543	0.208
7	-0.18%	-0.999	0.717	-0.39%	-1.341	0.327
8	0.09%	0.476	0.872	0.25%	0.644	0.674
9	-0.59%	-4.319***	0.001***	-0.92%	-3.545***	0.025**

Event window	$\overline{CAR}$	t-test	$\overline{CAR}$	t-test
[0; +4]	-0.54%	-1.211	-1.09%	-1.705
[0; +9]	-1.32%	-2.399**	-1.62%	-2.229*

***, **, * indicate significance of 1%, 5%, 10%

Remarkably, the Topix Land Transportation Index exhibits a highly significant negative $\overline{AR}$ solely on event date 9 (T_9), with the t-value being significant at a 1% level for both sub-groups. The non-parametric test confirms the significance at a 1% level and a 5% level, respectively. The $\overline{CAR}$ for the event window [0; +9] is found to be statistically significant at a 10% level, and there is no notable difference in significance between the two sub-groups.

The negative impact of earthquakes on the transportation industry can be explained by damage to transportation infrastructure such as roads, bridges and railways. These damages can cause disruptions in the movement of goods and people, leading to repair costs and increases in travel time, ultimately resulting in economic losses (Abadi et al., 2022)

However, the significance of the abnormal return, specifically on event date 9 (T_9), is different from previous research and lacks a clear economic rationale.

6.3. Earthquake-specific characteristics analysis (Hypotheses H_4, H_5 & H_6)

Hypotheses H_4, H_5 and H_6 examine the impact of earthquakes with specific characteristics on stock markets. Firstly, earthquakes with a magnitude of 7.0 or greater, which are classified as major (7.0 – 7.9) or great (≥ 8.0) on the Moment Magnitude Scale (Table 3), are being analysed. They are compared to significant earthquakes with a magnitude of less than 7.0. Secondly, the analysis focuses on the number of fatalities caused by an earthquake, with a comparison between earthquakes that account for 1 to 5 deaths and those that result in more than 5 fatalities. Earthquakes with no fatalities are excluded from this analysis. Finally, the study focuses on earthquakes that occurred in the recent past (after 2005) and those that occurred in the distant past.

6.3.1 Magnitude

***Table 18**: t-values of $\overline{CAR}$ of earthquakes with magnitude ≥ 7.0 and earthquakes with magnitude < 7.0, using the constant-mean return model for the overall stock market and the market model for the industries*

Event window	Overall stock market	Construction	Insurance	Food	Transportation
	Magnitude ≥ 7.0				
[0; +4]	-1.009	0.003	0.422	-1.798*	-2.393**
[0; +9]	-0.398	-0.630	0.009	-0.580	-1.881*
	Magnitude < 7.0				
[0; +4]	-1.379	1.106	0.444	-0.779	-0.961
[0; +9]	0.267	1.060	0.651	-0.871	-1.000

***, **, * indicate significance of 1%, 5%, 10%

Table 18 shows that significant negative abnormal returns were only observed in the food and transportation industries for earthquakes with a magnitude of 7.0 or above. Notably, there was no significant difference in the overall stock market between earthquakes with lower or higher

magnitudes. This finding is consistent with Ferreira and Karali (2015), who found that larger earthquakes in terms of magnitude did not have a negative impact on returns in the majority of financial markets, including Japan.
Interestingly, the analysis revealed that the magnitude of earthquakes in the construction and insurance industry does not seem to have a significant impact on stock returns. However, when economic damage was considered, as shown in Table 14 and Table 15, earthquakes that caused more significant damage (damage > \$5000 million) resulted in more significant abnormal returns in the construction and insurance industry than those that caused less damage.
In contrast, the findings in the food and transportation industry indicate a different pattern. In these industries, earthquakes with a higher magnitude tend to have a more significant impact on abnormal returns, while those with a smaller magnitude did not produce significant results. On the other hand, when economic damage caused by the earthquakes was considered, no significant difference was observed in abnormal returns between more or less devastating earthquakes (Table 16; Table 17). These contrasting findings suggest that the impact of earthquakes on stock returns is highly dependent on various factors and cannot be attributed to a single criterion. The results show that earthquakes of higher magnitude lead to significant abnormal returns in some industries. In contrast, the economic damage caused by earthquakes plays a more crucial role in other industries. This demonstrates the complexity of the relationship between earthquakes and stock returns and the need to consider multiple factors when analysing their impact. Due to the unpredictable nature of earthquakes and their unpredictable consequences, it is challenging to draw general conclusions and make accurate predictions about their impact on stock returns.

Furthermore, it is crucial to point out (Table 18) that in the transportation industry, earthquakes with a magnitude of 7.0 or greater show significant negative abnormal returns (-1.881) for the event window [0; +9], while earthquakes with a magnitude below 7.0 show no effect. This can be explained by the technological challenges to building earthquake-resilient road infrastructure (Nakazawa, et al., 2020). Buildings can be designed with features such as base isolators and shock absorbers, which help them withstand earthquake forces. In contrast, road infrastructure is exposed to lateral forces from the ground that cannot be absorbed, leading to the formation of cracks and other damage. As a result, as the magnitude of an earthquake increases, which indicates a greater amount of seismic energy being released, road infrastructure is very likely to suffer significant damage, unlike buildings which are more resilient and do not systematically suffer from damage of high magnitude earthquakes

(Anbazhagan, Srinivas, & Chandran, 2012). This explains why the transportation industry is particularly vulnerable to earthquakes with higher magnitudes.

6.3.2 Number of fatalities

Table 19: *t-values of* $\overline{CAR}$ *of earthquakes with 1 – 5 deaths and earthquakes with > 5 deaths, using the constant-mean return model for the overall stock market and the market model for the industries*

Event window	Overall stock market	Construction	Insurance	Food	Transportation
	> 5 deaths				
[0; +4]	-0.785	1.201	0.045	-1.736	-0.413
[0; +9]	-0.699	0.883	-1.091	-1.583	-0.659
	1 – 5 deaths				
[0; +4]	-2.288**	0.424	0.266	-1.322	-2.135*
[0; +9]	-1.021	0.298	-0.129	0.554	-1.869

***, **, * indicate significance of 1%, 5%, 10%

The results indicate that hypothesis (H_5) cannot be supported, as earthquakes causing a higher number of fatalities did not demonstrate more significance than those with a lower fatality count. The study tested two samples, each including 16 earthquakes, and contrary to the research expectations, the lower fatality number sample produced significant results for the event window [0; +4] in the overall stock market and the transportation industry.

Scholtens and Voorhorst (2013) similarly contradicted the hypothesis that higher fatality numbers result in more abnormal returns. However, in contrast to the present study, they did not find significance in the low fatality number sample and indicated that fatalities might not be a major driver of abnormal returns in response to earthquakes.

6.3.3 Date of occurrence

***Table 20**: t-values of $\overline{CAR}$ of earthquakes before the year 2005 and earthquakes the year 2005, using the constant-mean return model for the overall stock market and the market model for the industries*

Event window	Overall stock market	Construction	Insurance	Food	Transportation
	Before the year 2005				
[0; +4]	-0.397	0.444	-0.714	-0.385	-1.191
[0; +9]	0.271	0.138	-0.004	-0.561	-1.671*
	After the year 2005				
[0; +4]	-1.016	1.063	0.763	-0.791	-1.034
[0; +9]	0.323	0.962	0.883	-0.883	-0.969

***, **, * indicate significance of 1%, 5%, 10%

Table 20 shows that only in the transportation industry for the event window [0; +9], significance at a 10% level for older earthquakes could be found. In contrast, recent earthquakes did not demonstrate any significance, thereby invalidating the hypothesis (H_6). These results contradict the findings of Scholtens and Voorhorst (2013), who claimed that recent earthquakes lead to a more pronounced response. The authors hypothesised that factors such as increased welfare and urbanisation in the recent past increased the amount of economic value at risk, and suggested that stock markets have accounted these changes. However, it is important to note that the study by Scholtens and Voorhorst (2013) encompassed strong earthquakes in multiple countries, while this thesis is solely focused on Japan, which could explain the divergent results.

7. Discussion

***Table 21**: Summary of hypotheses and conclusions after testing*

Hypothesis	Presence of abnormal returns	Support of hypothesis
H_1: Earthquakes have a negative impact on the overall stock market	✓	✓
H_2: Earthquakes causing higher economic damage have a more negative impact	✓	(✓)
H_3: Earthquakes have an impact on specific industries	✓	(✓)
H_4: Stock market has a stronger reaction to earthquakes with a higher magnitude.	✓	(✓)
H_5: Stock market has a stronger reaction to earthquakes with a higher number of fatalities.	×	×
H_6: Stock market has a stronger reaction to recent earthquakes than to earthquakes that happened in the distant past.	×	×

( ) indicates that the hypothesis is partially supported when multiple sub-groups were tested

The study's results indicate that while earthquakes do negatively impact the stock market, the impact is much less significant than in most previous literature (Table 1). When considering all significant earthquakes, the market showed significant negative returns only on one event day, while the $\overline{CAR}$ over the entire event window was not statistically significant.
The study showed the presence of a transitory component after the shock, indicating that the impact is not permanent and that the market can recover from it after a few days. When concentrating the analysis on earthquakes that caused significant economic damage, only those that resulted in more than \$5 billion of damage showed statistically significant $\overline{CAR}$ for the entire event window [0; +9]. However, the sample size of this group was limited to only eight earthquakes occurring from 1980 to 2023, confirming that highly destructive earthquakes are rare events. Nonetheless, despite being rare events, the occurrence of highly destructive earthquakes has been increasing in recent years, with five out of the eight events included in the sample occurring in the past decade. This highlights the unpredictability of earthquakes and

their consequences. This group of earthquakes (damage > \$5000 million) also had a significant impact on the construction and insurance industry, with highly significant negative returns observed on the day of the earthquake (T_0). However, the market reaction was short-lived, with no abnormal returns detected on the day after the event (T_1). This suggests that investors need to make quick investment decisions immediately after the occurrence of the earthquake, as the market's reaction is limited to the event day (T_0).
However, it is worth noting that a different reaction pattern was observed in the food and transportation industry, with significant cumulative abnormal returns over several days. Therefore, it may be necessary to devise a distinct investment strategy for those industries as they show a prolonged impact.

To expand the scope of the analysis, a group of earthquakes causing less economic damage (damage > \$100 million) was included, as these events are more frequent in Japan (Appendix 1). These findings reveal that, as expected, when earthquakes are less devastating, the construction and insurance industry does not react as significantly. However, in the food and transportation industry, no notable difference between earthquakes that cause more or less damage could be observed. This suggests that beyond the criterion of economic damage, other characteristics of earthquakes are of great importance. Specifically, further analysis revealed that the magnitude plays a significant role, particularly in the food and transportation sector. In the transportation industry, investment opportunities may arise after high-magnitude earthquakes occur, as these events are highly likely to cause damage to road infrastructure. In contrast, the number of fatalities does not significantly impact returns and therefore does not reveal any investment opportunities.

However, it is essential to consider the difficulties of isolating the effects of an earthquake's impact on the stock market as they occur unexpectedly and at random intervals. Other financially relevant events may be occurring simultaneously, complicating finding significance in abnormal returns. As a result, predicting the market reaction becomes challenging, and it may react differently depending on the information surrounding the event. This difficulty of isolating the event because of its unpredictability is a contributing factor to the weak significance of abnormal returns. The presence of outliers in the NGDC’s Global Significant Earthquake Database that cause a market reaction against this paper’s expectations leads to a lack of consistency in the results.

Nonetheless, several investment opportunities arise after the occurrence of a significant earthquake. The reaction to significant earthquakes of the overall stock market typically involves a short-term negative impact, which tends to correct itself within the following two to three days. The range of market reactions appears to be correlated with the economic damage caused by the earthquake. However, this trend is particularly pronounced in the case of catastrophic earthquakes that cause exceptionally high levels of economic damage. In contrast, this correlation is less clear for earthquakes that cause more limited economic damage.

Additionally, supplementary investment opportunities manifest in the construction and insurance industries. The most devastating earthquakes often present the largest investment opportunities, with substantial abnormal returns on the day of the event. Positive returns can be expected in the construction sector, while negative returns can be expected in the insurance sector. However, the abnormal returns tend to dissipate within the following day. In comparison, earthquakes causing more limited economic damage may generate less pronounced, but still significant, abnormal returns.

In the food and transportation industries, the impact of earthquakes tends to be more nuanced and prolonged. Unlike in the construction and insurance sectors, abnormal returns are not limited to a single day with exceptionally high returns, but smaller abnormal returns persist over a more extended period of time. Therefore, a different investment strategy may be required to capitalise on these opportunities effectively. Additionally, it is worth noting that no apparent difference in market reaction is observed between earthquakes with varying degrees of economic damage. These industries tend to react negatively to earthquake events regardless of the extent of the economic impact.

Finally, investment opportunities in the transportation industry can be identified when earthquakes of high magnitude (> 7.0) occur. These strong earthquakes tend to cause damage to road infrastructure and, as a result, lead to negative returns in this industry.

8. Concluding remarks

In this thesis, I present a comprehensive study of the impact of major earthquakes on Japan's stock market. To examine this impact, a tailored event study methodology was developed to analyse the effect of 117 earthquakes included in the National Geophysical Data Centre's Global Significant Earthquake Database between 1980 and 2023 in Japan on multiple industries. The empirical analysis focuses on two main streams of investigation. Firstly, the impact on the entire Japanese stock market, represented by the TOPIX index, was studied. Secondly, an analysis of the industries most affected by earthquakes, namely construction, insurance, real estate, food, and transportation, was conducted.

Overall the findings of this study align with previous research indicating that, on average, earthquakes have a predominantly negative impact on financial markets. However, there are notable differences between the market reaction in different industries. For example, while the insurance, food, and transportation industry are affected negatively, the construction industry tends to generate more positive responses. Furthermore, the results are depended on several characteristics of the earthquakes in the sample. In particular, earthquakes that cause exceptionally high economic damage might generate different responses.

The empirical analysis controls for several key characteristics of earthquakes, such as their magnitude, the number of fatalities and the date of occurrence. Among those controls, only the magnitude of earthquakes is found to influence the impact of earthquakes in different industries. However, despite the controls taken into account, it is difficult to attribute the market reactions to specific characteristics of the earthquakes. Earthquakes occur randomly and are unpredictable, which makes it difficult to accurately predict a market reaction.

In summary, this thesis provides a comprehensive guide to identifying investment opportunities in the aftermath of major earthquakes in Japan. It contributes to the understanding of the impact of significant earthquakes on the stock market and provides valuable insights into investment opportunities in various industries. Moreover, this study sets the groundwork for future research in this area. While this study is limited to the Japanese market and earthquakes, the methodology employed can be applied to other financial markets and natural disasters, opening up opportunities for further research.

9. References

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Appendix

Appendix 1: *List of all events 1980–2023*

Event Day	Tsunami	Magnitude	MMI Intensity	Deaths	Damage ($Mil)
29/06/1980	Yes	6.2	8	0	1 – 5
24/09/1980	No	6	6	2	1
18/01/1981	Yes	6.9	.	0	0
21/03/1982	Yes	6.7	10	110	1
23/07/1982	Yes	6.8	.	0	0
28/12/1982	Yes	6.1	.	0	0
26/05/1983	Yes	7.7	8	104	800
09/06/1983	Yes	5.9	.	0	0
21/06/1983	Yes	6.9	.	0	< 1
08/08/1983	No	5.3	.	1	< 1
03/10/1983	No	6	8	0	1 – 5
30/10/1983	No	5.2	6	0	1 – 5
13/06/1984	Yes	5.5	.	0	0
06/08/1984	Yes	6.7	6	20	1 – 5
13/09/1984	No	6.1	6	29	43
18/09/1984	Yes	6.9	.	0	0
06/02/1987	Yes	6.3	.	0	0
18/03/1987	Yes	6.7	.	2	1 – 5
24/03/1987	Yes	5.1	.	0	0
17/12/1987	No	6	8	2	5
09/07/1989	No	5	6	0	1 – 5
29/10/1989	Yes	6.6	.	0	0
01/11/1989	Yes	7.4	6	0	< 1
20/02/1990	Yes	6.4	.	0	0
23/09/1990	Yes	6.5	.	0	0
01/02/1992	No	5.6	.	0	< 1
18/07/1992	Yes	7	.	0	0
11/08/1992	Yes	6.3	.	0	0
15/01/1993	No	7.6	6	2	358
07/02/1993	Yes	6.3	.	0	< 1
12/07/1993	Yes	7.7	8	231	1207
07/08/1993	Yes	6.3	.	0	0
08/04/1994	Yes	6.4	.	0	0

(continued)

Event Day	Tsunami	Magnitude	MMI Intensity	Deaths	Damage ($Mil)
28/12/1994	Yes	7.8	9	3	170
16/01/1995	Yes	6.9	11	6434	100000
01/04/1995	No	5.4	.	0	1 – 5
18/10/1995	Yes	7.1	.	0	0
19/10/1995	Yes	6.8	.	0	0
04/09/1996	Yes	5.7	.	0	0
18/10/1996	Yes	6.6	.	0	0
19/10/1996	Yes	6.7	.	0	< 1
02/12/1996	Yes	6.7	.	0	0
26/03/1997	No	6.1	6	0	1 – 5
30/09/1997	Yes	6.2	.	0	0
30/05/1998	Yes	6.2	.	0	0
28/03/2000	No	7.6	.	0	0
01/07/2000	Yes	6.1	.	1	< 1
15/07/2000	Yes	6.1	.	0	< 1
30/07/2000	Yes	6.5	.	0	< 1
06/10/2000	No	6.7	9	0	150
24/03/2001	No	6.8	9	2	500
26/03/2002	Yes	6.4	.	0	0
26/05/2003	No	7	.	0	233
25/07/2003	No	5.5	.	0	411
20/09/2003	No	5.7	.	0	< 1
25/09/2003	Yes	8.3	.	2	90
15/10/2003	No	5.2	.	0	< 1
31/10/2003	Yes	7	.	0	0
05/09/2004	Yes	7.2	.	0	< 1
05/09/2004	Yes	7.4	.	0	< 1
23/10/2004	No	6.6	.	40	28000
27/10/2004	No	5.9	.	0	< 1
08/11/2004	No	5.5	.	0	< 1
28/11/2004	Yes	7	.	0	< 1
06/12/2004	No	6.8	.	0	0
14/12/2004	No	5.8	.	0	< 1
19/01/2005	Yes	6.6	.	0	0
20/03/2005	No	6.6	.	1	1 – 5
23/07/2005	No	5.9	.	0	< 1
16/08/2005	Yes	7.2	.	0	< 1

(continued)

Event Day	Tsunami	Magnitude	MMI Intensity	Deaths	Damage ($Mil)
14/11/2005	Yes	7	.	0	0
01/01/2006	Yes	5.6	.	0	0
11/06/2006	No	6.3	.	0	0
25/03/2007	Yes	6.7	.	1	5 – 25
15/04/2007	No	4.6	.	0	1 – 5
16/07/2007	Yes	6.6	.	9	12500
28/09/2007	No	7.5	.	0	0
07/05/2008	No	6.8	.	0	< 1
13/06/2008	No	6.9	.	13	5 – 25
19/07/2008	Yes	6.9	.	0	0
23/07/2008	No	6.8	.	1	1 – 5
11/09/2008	Yes	6.8	.	0	0
10/08/2009	Yes	6.4	.	1	5 – 25
17/12/2009	No	4.9	.	0	< 1
26/02/2010	Yes	7	.	0	< 1
21/12/2010	Yes	7.4	.	0	0
09/03/2011	Yes	7.5	.	0	0
11/03/2011	Yes	9.1	.	18428	220136
11/03/2011	No	7.9	.	0	0
11/03/2011	No	7.6	.	0	0
07/04/2011	Yes	7.1	.	3	< 1
11/04/2011	No	6.6	.	7	< 1
10/07/2011	Yes	7	.	0	0
14/03/2012	Yes	6.9	.	0	0
07/12/2012	Yes	7.2	.	0	0
12/04/2013	No	5.8	.	0	< 1
17/04/2013	No	5.8	.	0	< 1
25/10/2013	Yes	7.1	4	0	0
13/03/2014	No	6.3	5	0	< 1
11/07/2014	Yes	6.5	5	0	0
22/11/2014	No	6.2	9	0	< 1
16/02/2015	Yes	6.7	4	0	0
02/05/2015	Yes	5.7	.	0	0
30/05/2015	No	7.8	6	0	0
13/11/2015	Yes	6.7	4	0	0
15/04/2016	No	7	8	50	20000
20/08/2016	Yes	6	2	0	0

(continued)

Event Day	Tsunami	Magnitude	MMI Intensity	Deaths	Damage ($Mil)
21/10/2016	No	6.2	6	0	100
21/11/2016	Yes	6.9	7	0	< 1
08/04/2018	No	5.7	.	0	5 – 25
06/05/2018	Yes	5.4	.	0	0
17/06/2018	No	5.5	.	5	7000
05/09/2018	No	6.6	7	44	2000
18/06/2019	Yes	6.4	.	0	1 – 5
13/02/2021	Yes	7.1	9	1	7700
20/03/2021	No	7	7	0	550
16/03/2022	Yes	7.3	9	4	8800

Appendix 2: *T-test critical values of all sub-groups of earthquakes*

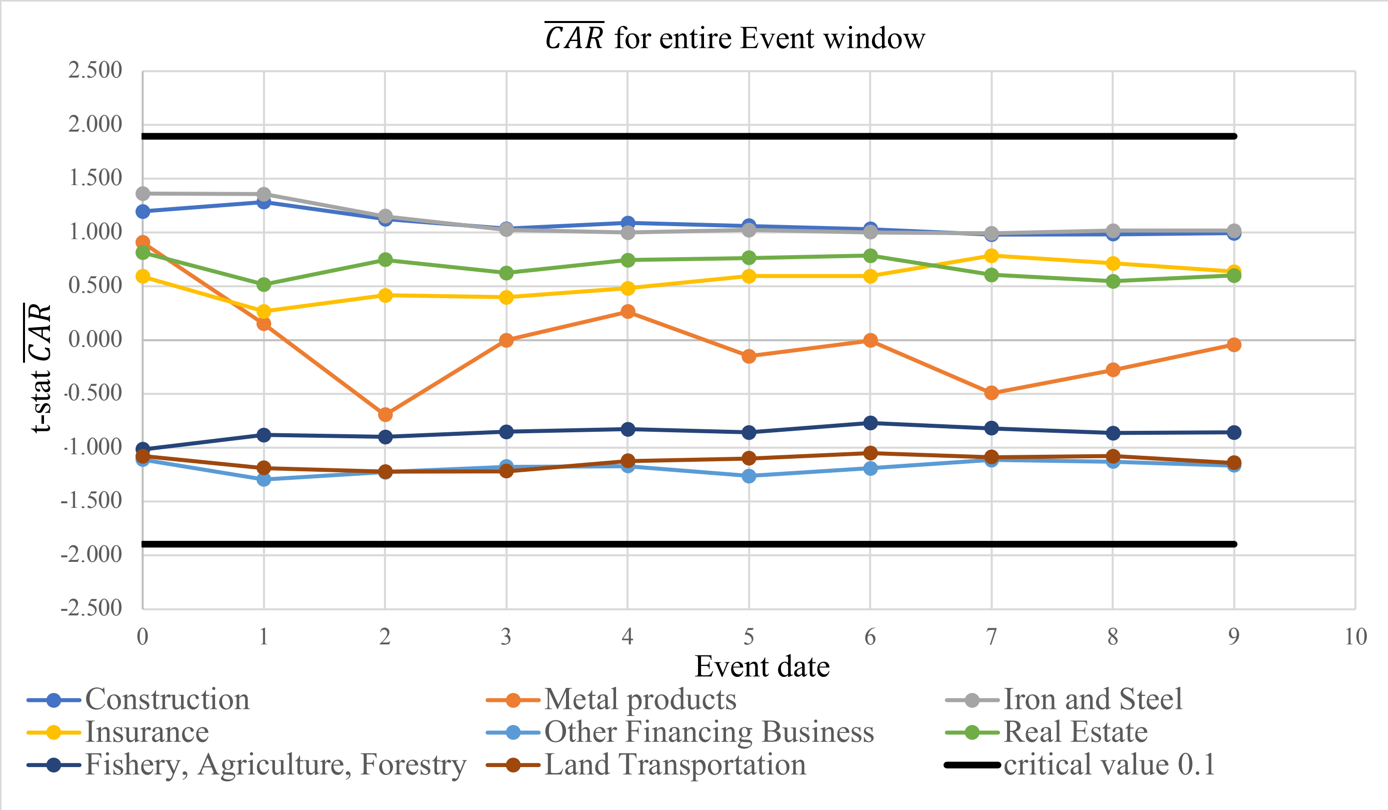
one-tailed α	**0.1**	**0.05**	**0.01**
df 7	1.415	1.895	2.998
12	1.356	1.782	2.681
18	1.330	1.734	2.552
116	1.289	1.658	2.359

two-tailed α	**0.1**	**0.05**	**0.01**
df 7	1.895	2.365	3.499
12	1.782	2.179	3.055
18	1.734	2.101	2.878
116	1.658	1.981	2.619

__Appendix 3__: Wilcoxon signed-rank test critical values

one-tailed α	**0.1**	**0.05**	**0.02**	**0.01**
two-tailed α	**0.05**	**0.025**	**0.01**	**0.005**
n				
5	1			
6	2	1		
7	4	2	0	
8	6	4	2	0
9	8	6	3	2
10	11	8	5	3
11	14	11	7	5
12	17	14	10	7
13	21	17	13	10
14	26	21	16	13
15	30	25	20	16
16	36	30	24	19
17	41	35	28	23
18	47	40	33	28
19	54	46	38	32
20	60	52	43	37
21	68	59	49	43
22	75	66	56	49
23	83	73	62	55
24	92	81	69	61
25	101	90	77	68
26	110	98	85	76
27	120	107	93	84
28	130	117	102	92
29	141	127	111	100
30	152	137	120	109

Appendix 4*: Cumulative average abnormal return of event date ($T_{0,9}$) of all industries with all 117 significant earthquakes using the market model*



Appendix 5: $\overline{AR}$ *and* $\overline{CAR}$ *of event date (*$T_{0,9}$*) of the Topix Metal Products Index with 19 significant earthquakes (damage > $100 million) and 8 significant earthquakes (damage > $5000 million) using the market model*

Event date	$\overline{AR}$	**t-test**	**p-value Wilcoxon signed-rank test**	$\overline{AR}$	**t-test**	**p-value Wilcoxon signed-rank test**
	19 events (damage > $100 million)			**8 events (damage > $5000 million)**		
0	0.24%	1.398	0.159	0.10%	0.417	0.779
1	0.06%	0.190	0.809	0.39%	0.587	1.000
2	-0.23%	-1.398	0.171	-0.46%	-1.330	0.263
3	-0.02%	-0.244	0.809	-0.15%	-1.336	0.208
4	-0.09%	-0.604	0.398	0.25%	1.074	0.484
5	-0.20%	-1.139	0.091*	0.14%	0.510	0.779
6	0.46%	1.702	0.295	0.50%	0.999	0.674
7	0.28%	1.046	0.445	0.29%	0.774	0.575
8	0.23%	1.067	0.184	0.71%	2.255*	0.091*
9	-0.25%	-1.677	0.126	-0.18%	-0.846	0.401

Event window	$\overline{CAR}$	**t-test**	$\overline{CAR}$	**t-test**
[0; +4]	-0.04%	-0.099	0.13%	0.144
[0; +9]	0.48%	0.528	1.59%	1.018

***, **, * indicate significance of 1%, 5%, 10%

Appendix 6: *$\overline{AR}$ and $\overline{CAR}$ of event date ($T_{0,9}$) of the Topix Iron and Steel Index with 19 significant earthquakes (damage > $100 million) and 8 significant earthquakes (damage > $5000 million) using the market model*

Event date	$\overline{AR}$	**t-test**	**p-value Wilcoxon signed-rank test**	$\overline{AR}$	**t-test**	**p-value Wilcoxon signed-rank test**
	19 events (damage > $100 million)			**8 events (damage > $5000 million)**		
0	-0.03%	-0.146	0.687	-0.20%	-0.436	0.575
1	0.10%	0.476	0.687	0.27%	0.723	0.779
2	-0.25%	-0.616	0.573	0.39%	0.484	0.401
3	-0.15%	-0.584	0.629	0.18%	0.411	0.674
4	0.27%	0.890	0.445	0.57%	1.276	0.123
5	0.10%	0.407	0.260	-0.06%	-0.113	0.889
6	0.15%	0.488	0.904	0.55%	0.832	0.484
7	0.24%	0.907	0.421	0.15%	0.377	0.889
8	0.22%	0.547	0.445	-0.20%	-0.376	0.575
9	0.16%	0.428	0.601	0.12%	0.166	0.779

Event window	$\overline{CAR}$	**t-test**	$\overline{CAR}$	**t-test**
[0; +4]	-0.05%	-0.071	1.20%	0.855
[0; +9]	0.81%	0.924	1.76%	1.190

***, **, * indicate significance of 1%, 5%, 10%

Appendix *7: $\overline{AR}$ and $\overline{CAR}$ of event date ($T_{0,9}$) of the Topix Other Financing Business Index with 19 significant earthquakes (damage > \$100 million) and 8 significant earthquakes (damage > \$5000 million) using the market model*

Event date	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test	$\overline{AR}$	t-test	p-value Wilcoxon signed-rank test
	19 events (damage > \$100 million)			**8 events (damage > \$5000 million)**		
0	-0.01%	-0.032	0.954	-0.14%	-0.679	0.687
1	0.33%	1.492	0.199	0.26%	0.973	0.520
2	0.15%	0.689	0.587	0.15%	0.553	0.717
3	-0.21%	-0.636	0.037	-0.53%	-2.425**	0.024**
4	0.11%	0.526	0.864	0.24%	0.962	0.494
5	-0.13%	-0.685	0.475	-0.02%	-0.098	0.936
6	0.17%	1.000	0.440	0.20%	0.994	0.421
7	-0.22%	-0.994	0.493	-0.06%	-0.259	0.968
8	-0.13%	-0.647	0.475	-0.25%	-1.067	0.260
9	-0.15%	-0.486	0.407	-0.31%	-0.850	0.184

Event window	$\overline{CAR}$	t-test	$\overline{CAR}$	t-test
[0; +4]	0.37%	0.626	-0.03%	-0.049
[0; +9]	-0.10%	-0.104	-0.47%	-0.466

***, **, * indicate significance of 1%, 5%, 10%

Appendix 8: *$\overline{AR}$ and $\overline{CAR}$ of event date ($T_{0,9}$) of the Topix Real Estate Index with 19 significant earthquakes (damage > \$100 million) and 8 significant earthquakes (damage > \$5000 million) using the market model*

Event date	$\overline{AR}$	**t-test**	**p-value Wilcoxon signed-rank test**	$\overline{AR}$	**t-test**	**p-value Wilcoxon signed-rank test**
	19 events (damage > \$100 million)			**8 events (damage > \$5000 million)**		
0	-0.01%	-0.066	0.841	0.03%	0.123	0.889
1	-0.13%	-0.850	0.573	-0.10%	-0.382	0.674
2	-0.25%	-1.056	0.520	-0.29%	-0.587	0.889
3	0.23%	0.929	0.136	0.20%	0.367	0.484
4	0.00%	-0.022	0.778	0.21%	0.718	0.327
5	-0.06%	-0.192	0.687	0.13%	0.462	0.575
6	0.20%	0.535	0.904	0.43%	0.563	1.000
7	-0.21%	-0.612	0.445	-0.68%	-1.970*	0.069*
8	0.19%	0.982	0.469	-0.11%	-0.507	0.779
9	0.07%	0.188	0.520	0.48%	0.556	1.000

Event window	$\overline{CAR}$	**t-test**	$\overline{CAR}$	**t-test**
[0; +4]	-0.16%	-0.430	0.06%	0.080
[0; +9]	0.03%	0.037	0.30%	0.204

***, **, * indicate significance of 1%, 5%, 10%