https://lib.uliege.be https://matheo.uliege.be

Mémoire de fin d'études :" Visual programming tool for seismic-resistant Ishigaki Walls in japanese Architecture ".

Auteur : Gourbeyre, Mathieu
Promoteur(s) : Jancart, Sylvie; 24341
Faculté : Faculté d'Architecture
Diplôme : Master en architecture, à finalité spécialisée en art de bâtir et urbanisme
Année académique : 2023-2024
URI/URL : http://hdl.handle.net/2268.2/22208

Avertissement à l'attention des usagers :

Tous les documents placés en accès ouvert sur le site le site MatheO sont protégés par le droit d'auteur. Conformément aux principes énoncés par la "Budapest Open Access Initiative"(BOAI, 2002), l'utilisateur du site peut lire, télécharger, copier, transmettre, imprimer, chercher ou faire un lien vers le texte intégral de ces documents, les disséquer pour les indexer, s'en servir de données pour un logiciel, ou s'en servir à toute autre fin légale (ou prévue par la réglementation relative au droit d'auteur). Toute utilisation du document à des fins commerciales est strictement interdite.

Par ailleurs, l'utilisateur s'engage à respecter les droits moraux de l'auteur, principalement le droit à l'intégrité de l'oeuvre et le droit de paternité et ce dans toute utilisation que l'utilisateur entreprend. Ainsi, à titre d'exemple, lorsqu'il reproduira un document par extrait ou dans son intégralité, l'utilisateur citera de manière complète les sources telles que mentionnées ci-dessus. Toute utilisation non explicitement autorisée ci-avant (telle que par exemple, la modification du document ou son résumé) nécessite l'autorisation préalable et expresse des auteurs ou de leurs ayants droit.

Université de Liège, Faculté d'Architecture.
titre du TFE:

VISUAL PROGRAMMING TOOL FOR SEISMIC-RESISTANT ISHIGAKI WALLS IN JAPANESE ARCHITECTURE

Travail de fin d'études présenté par Mathieu Gourbeyre en vue de l'obtention du grade de Master en Architecture.

Sous la direction de ma promotrice, la professeure Jancart Sylvie et du co-promoteur, le professeur Muramoto Makoto.

Année académique 2023-2024.

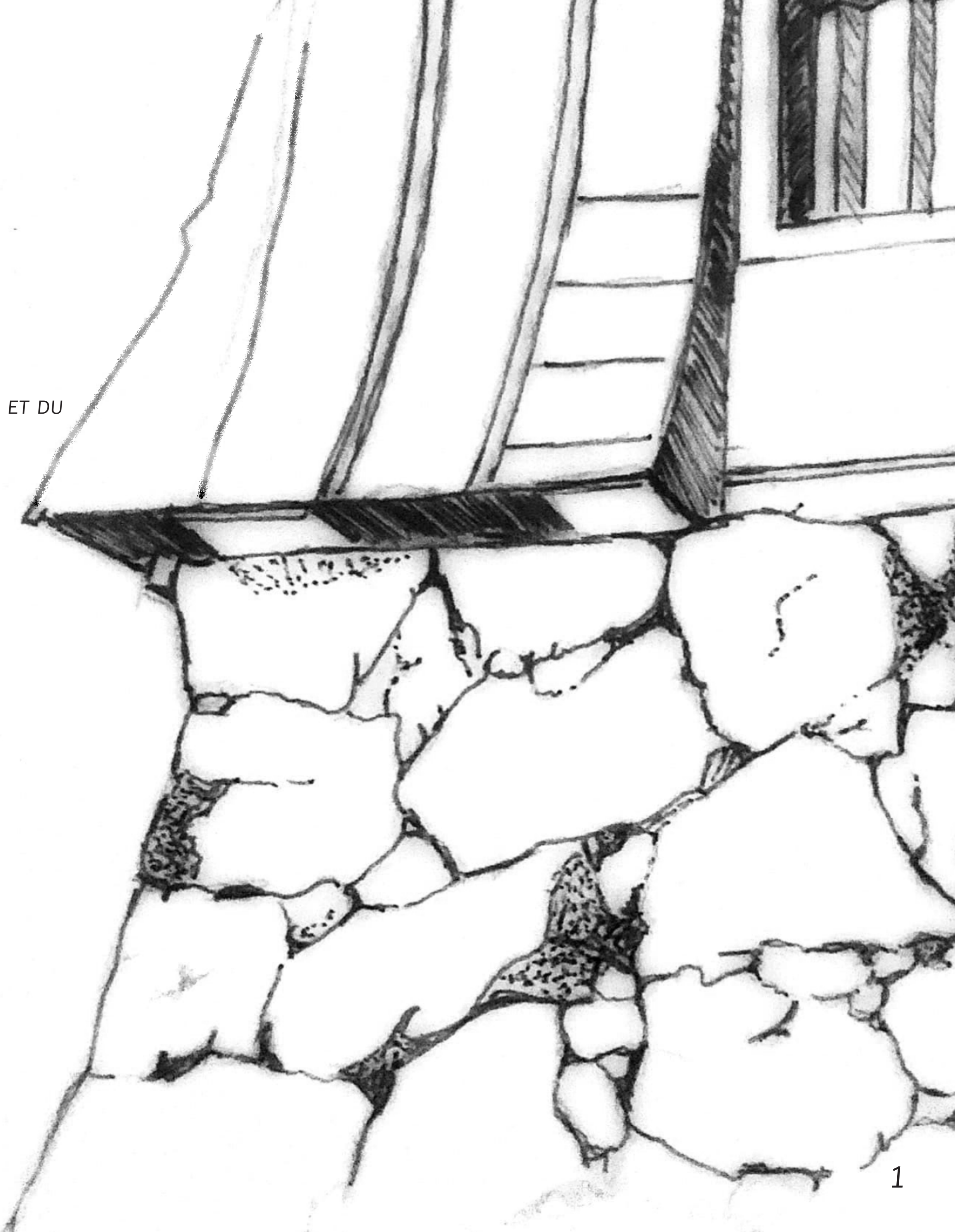
University of Liège, Faculty of Architecture.
Title of the thesis:

VISUAL PROGRAMMING TOOL FOR SEISMIC-RESISTANT ISHIGAKI WALLS IN JAPANESE ARCHITECTURE

Final work presented by Mathieu Gourbeyre with a view to obtaining a Master's degree in Architecture.
Under the guidance of my promoter, Professor Jancart Sylvie, and co-promoter, Professor Muramoto Makoto.
Academic year 2023-2024.

LIÈGE université
Architecture

京都工芸繊維大学
KYOTO INSTITUTE OF TECHNOLOGY



I would like to express my deepest gratitude to everyone who contributed to the completion of this master’s thesis. I would especially like to thank the professors who supported me throughout this research.

I am particularly grateful to my supervisor, Professor Jancart from the University of Liège, and my co-supervisor, Professor Muramoto from the Kyoto Institute of Technology. Their guidance and insightful advice, shared during our regular discussions, have been invaluable. Their patience, availability, and pertinent recommendations have greatly enriched my thinking.

I would also like to express my gratitude to the jury members, Dr Laurens Luyten, Dr Alejandro Martinez, and Dr Thomas Dissaux, for agreeing to be on the jury for my dissertation defence.

I also wish to thank the entire faculty of the University of Liège and the Kyoto Institute of Technology for their advice and for providing the tools that enabled me to overcome the challenges associated with this research.

I would like to express my sincere appreciation to the civil engineering students who assisted me in understanding complex problems, particularly Mr. Olivier Nicol, a master’s student in engineering and architecture at Estp cachan and ENSA Paris la Villette. I also wish to acknowledge Ms. 小林 奈々 (Kobayashi Nana) and the entire civil engineering laboratory at the Kyoto Institute of Technology, who kindly explained concepts and calculations that were unfamiliar to me before the start of this research.

Finally, I would like to thank my parents, family, and friends for their constant support and encouragement.

TABLE OF CONTENTS

PRESENTATION OF THE ISSUE.

Japan is an archipelago in eastern Asia, sharing borders with Taiwan, South Korea, North Korea, China and Russia. Located on the Pacific Ring of Fire, it is characterised by intense seismic and volcanic activity due to complex interactions between the four tectonic plates that run along and through it. Thus, earthquakes are an integral part of Japanese history and life, shaping the country’s culture and architecture.

However, when we examine masonry construction, one of the oldest building techniques worldwide, we see how it has evolved to produce distinct forms of bricks and blocks that characterise various regions, cultures, and eras. The methods of implementation differ based on the specific needs and constraints of each location.

Thus, if we consider Japanese conditions, masonry buildings are rare because this construction technique is not very resistant to earthquakes. However, the Japanese developed several ways of cutting rock during their history to erect dry masonry walls that are found under the general term “Ishigaki.”

Although this construction process is durable enough to serve as a foundation for military architecture in Japan, wall constructions built using the “Ishigaki” process are now little or not used[1] for buildings intended for private individuals.

In the current environmental context, drawing inspiration from this traditional way of building and proposing a technical reinterpretation could, to a certain extent, provide an alternative to the use of more contemporary materials such as concrete or steel[2]. Indeed, dry stone masonry is a construction that does not use any binder to be erected, which gives it the advantage of being more removable and adaptable. Therefore, designing blocks inspired by various vernacular Japanese dry stone masonry techniques could allow Japanese creators and users to reclaim their architecture.

With this in mind, the use of digital tools can contribute to the creation of these blocks and, by extension, walls, or even to improve some of their characteristics. Offering new digital tools to designers can allow them to simulate and visualise their ideas.

Given that most architects are neophytes in programming, visual programming seems to be the perfect choice since, as defined (Funari & al., 2021, p.3), *“the visual programming environment is user-friendly and allows the user to easily connect data from different sources while keeping a clear understanding of the relationships between them thanks to the representation in the form of a flowchart of the different components of the code”.*

Therefore, the primary objective of this thesis was to try to answer through this study to the following question: “Inspired by the Japanese “Ishigaki” walls, how can visual programming be a source of proposals and improvement of the geometry of the blocks that make up dry stone masonry walls to optimise their design for seismic conditions?

However, due to the amount of work involved, it was decided to focus on the first part of this question in order to build a solid foundation for future research regarding block optimisation.

Consequently, this thesis will attempt to answer the question, “How a visual programming tool can be used to simulate the behaviour of Ishigaki walls during seismic events?”

Therefore, the objective of this thesis will not be to find a solution to this issue but to initiate research using computer tools to explore block geometries that can help to renovate the Japanese architectural heritage while opening the way to upcoming research aimed at reinterpreting the function of the “Ishigaki” walls.

In order to answer this problem, the following sub-questions have been asked:

What are the different construction techniques grouped under the term “Ishigaki”? And which one is the most interesting to set up with visual programming?

How can visual programming be used to develop and create physical simulations of dry masonry walls? How can the simulation results be communicated to allow users to reflect on their “Ishigaki” masonry models?

In order to answer these questions and given the multidisciplinary nature of this study, it will be based on books and articles that allow us to understand the context of the different fields that will be addressed. Such as the data provided by the (気象庁[Japan Meteorological Agency], n.d.) and papers by academics (Satake, 2015) that deal with the specificities of the Japanese archipelago. As far as historical research is concerned, it is based on articles that allow us to understand the history, the composition and the different types of construction of the “Ishigaki” walls mentioned in the book 田淵実夫 published in 1975 or books such as 城郭の見方・調べ方ハンドブック[Handbook on how to see and study castles.] (西ヶ谷[Nishigaya], 2008).

---

[1] *As the technique is less used, the number of craftsmen specialized in this type of construction has become extremely rare in Japan, with only a few representatives as can be read through articles such as Devnakata, & Devnakata. (2023, June 26). 石の声を聴けー 石積みの里で穴太衆の技をつなぐ「粟田建設」 - NIHONMONO. NIHONMONO - 「にほん」の「ほんもの」を巡る旅マガジン. https://nihonmono.jp/article/32930/*

[2] *Findings based on books consulted in the library of the Faculty of Architecture of Liège. TASCHEN Publishing: Contemporary Japanese Architecture. (n.d.) and Steele, J. (2017). Contemporary Japanese Architecture: Tracing the Next Generation*

This research will also be based on articles that help understand the implication of visual programming in the field of seismic wall design, such as the articles by (Yenice & Park, 2019), who use this tool to try to design blocks which can fit together to create walls that can withstand earthquakes. Or the study by (Goyal & Agarwal, 2017) which uses visual programming to design masonry that uses an interlocking process to make their structures anti-seismic..

To link the various sources and concepts addressed in this thesis, it will be organised into four main chapters. The aim is to clarify the connections between these notions to facilitate their analysis, in order to conclude this thesis and propose future research directions.

The first chapter, titled “The Impact of Seismic Activity on Japanese Architecture and the Genesis of Ishigaki Walls”, is divided into four sub-sections. The goal is to better understand what an Ishigaki wall is and its context. This chapter will begin by presenting the seismic characteristics of the Japanese archipelago and their impact on architectural construction. It will then discuss the origins of Ishigaki walls and their current significance for Japanese designers.

The second chapter, titled “Exploring Visual Programming and Physical Simulation”, is also divided into four sub-sections. This chapter aims to introduce the various uses of these concepts. It will start by defining what visual programming and physical simulation are, and explain the mathematics used by these tools and by engineers to simulate the movement that structures might experience during an earthquake.

The third chapter, titled “Methodology and Corpus”, will introduce the methodology employed in this study and will trace, in three sub-sections, the chronology and evolution of this research to answer the question mentioned above.

Ultimately, the fourth chapter, title” Conclusion and Opening”, will synthesise the acquired knowledge into a conclusion and propose recommendations for continuing this research.

CHAPTER 1: THE IMPACT OF SEISMIC ACTIVITY ON JAPANESE ARCHITECTURE AND THE GENESIS OF ISHIGAKI WALLS.

INTRODUCTION TO THE CHAPTER OVERVIEW:

As explained in the introduction of this thesis, this chapter is composed of four sections, each of which may include several subsections if necessary to clarify the concepts discussed. The first section successively addresses Japan's geographical context, the lithospheric movements that traverse the archipelago, and their consequences for Japanese architectural practices.

Based on this foundational knowledge, subsections 2 and 3 delve deeper into these topics by introducing the nature of earthquakes, the methods used to measure them, and the behaviour of different types of seismic waves. This will provide a better understanding of the geographical context in which Ishigaki walls were created, followed by a definition of their specific characteristics and the various styles that make up this construction technique.

Finally, the last section of this chapter discusses the evolution of these walls from the Edo period (1603-1868) to the present day. It then examines the strengths and weaknesses of these techniques in relation to earthquakes, before concluding with the current resurgence of interest in this method among Japanese creators.

SECTION 1.1: UNDERSTANDING SEISMIC HAZARDS IN JAPAN

A. Introduction to Seismic Activity in Japan

Japan is a set of islands, forming an archipelago. It spans more than 100,000 square kilometres in eastern Asia. The borders of this nation are shared with Taiwan, South Korea, North Korea, China and Russia. Of these many islands, about 421 are inhabited. Four of them are particularly large: Hokkaidō, Honshū, Shikoku and Kyūshū. These four main islands constitute the predominant prefectures of the country, accounting for 95 per cent of the territory, which covers 377,975 km².

These four islands, which also correspond to regions, are part of Japan’s eight geographical regions, which range from Kyūshū in the south, Shikoku, Chūgoku, Kansai, Chūbu, Kantō, Tōhoku to Hokkaido in the north (Figure 1).

Japan also has the distinction of being located on the Ring of Fire encircling the Pacific Ocean. This belt is known to be a topographical area rich in geological and volcanic activities. This is due to complex interactions between the seismic plates that surround it. These interactions create intense subduction processes, where one tectonic plate plunges beneath another, giving rise to deep ocean trenches and numerous volcanoes.

The Japanese islands lie at the convergence of four major tectonic plates: the Pacific, the Philippine Sea, North America (also known as Okhotsk) and Eurasia (also known as Amur).

According to research conducted by (Satake, 2015),[3] in northern Japan, the Pacific Plate dips beneath the North American Plate along the Kuril and Japan Trenches. This movement occurs at a rate of about 8 cm per year.

The Philippine Sea Plate, which lies mainly south of the island, is plunging under two tectonic plates at relatively similar speeds: on the one hand, along the Sagami Trench below Tokyo, where it is plunging at a rate of about 4 cm per year under the North American Plate, and on the other hand, along the Nankai and Ryukyu Trenches that run along the southern part of Japan. In these regions, it is sinking at rates ranging from 4 to 7 cm per year under the Eurasian plate.

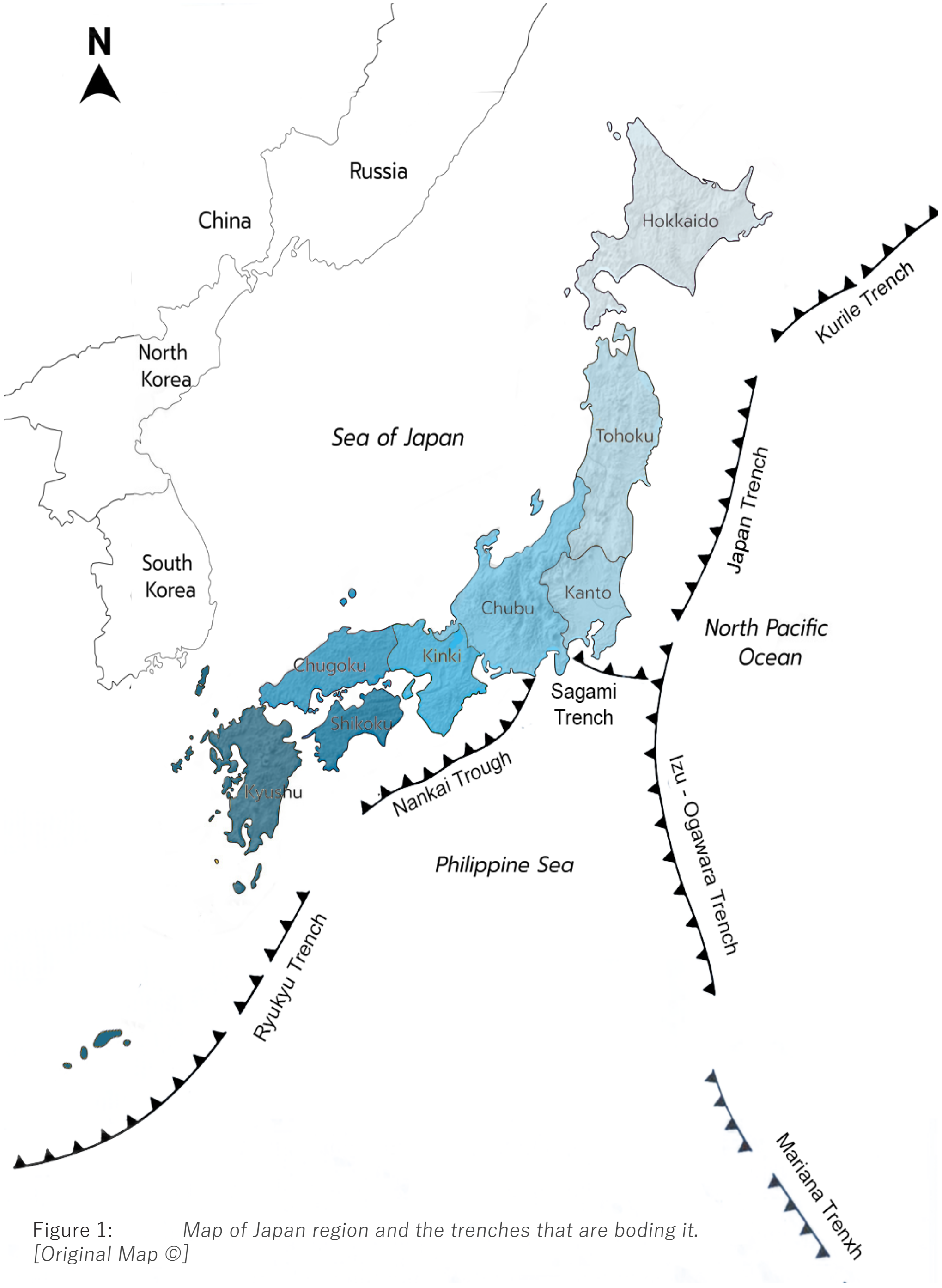


Figure 1: *Map of Japan region and the trenches that are boding it. [Original Map ©]*

---

[3] Satake, K. (2015). Geological and historical evidence of irregular recurrent earthquakes in Japan. Philosophical Transactions of the Royal Society A, 373(2053), 20140375. https://doi.org/10.1098/rsta.2014.0375

B. LITHOSPHERIC MOVEMENTS[4] AND CONSEQUENCES ON THE ARCHIPELAGO.

In order to better understand the context in which his research will evolve, it is essential to comprehend and explain concisely the geological dynamics specific to Japan. This understanding will then make it possible to analyse the consequences of these movements on the archipelago. Indeed, despite the increase in the number of earthquakes recorded in recent years due to the evolution of technologies, it is undeniable that the archipelago and Japanese culture have been profoundly shaped by the various earthquakes they have suffered. These events have left a lasting imprint on Japanese society, influencing its traditions and infrastructure.

In this context, based on the various analyses published by the site (Headquarters for Earthquake Research Promotion, 2024) and other academic articles, we will examine the four tectonic trenches that play a significant role in Japan's seismicity: the Southern Kuril Trench, the Japan Trench, the Sagami Trench and the Nankai Trench.

1. THE SOUTHERN KURIL TRENCH.

Let us start by exploring the Southern Kuril Trench, located near Hokkaido and the Kuril Islands (Figure 2). This area is marked by intense seismic activity, with evidence of giant earthquakes happening every 300 to 500 years (Nanayama, 2020). These events are often earthquakes that cause giant tsunamis to ravage the region, most recently in the early seventeenth century (Nanayama, 2003). Examples of its dangerousness occurred in 1994, 2000, 2006 and 2007, allowing researchers to deepen their knowledge of it.

Because of its threat to the archipelago, this geological fault has been meticulously studied since the nineteenth century. After the earthquakes of 1952 and 1973 and in order to better study its behaviour, the pit was subdivided into two distinct segments: the offshore region of Tokachi (Tokachi-oki) in the south and the offshore region of Nemuro (Nemuro-oki) in the north. Notable earthquakes were recorded in the Tokachi-oki area in 1843, 1952 and 2003. At the same time, the Nemuro-oki region was the scene of significant earthquakes in 1894 and 1973.

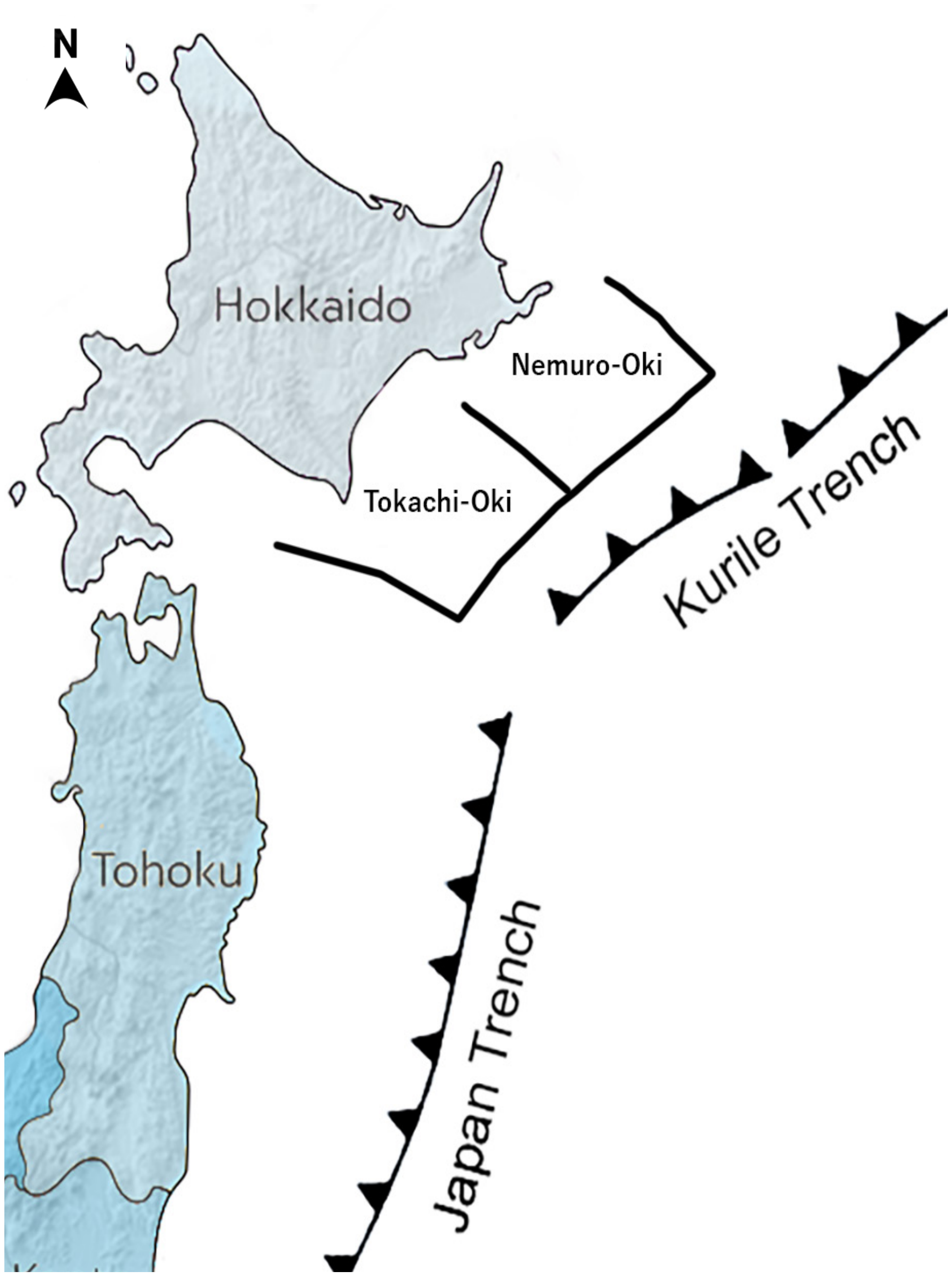


Figure 2: *Map showing the southern Kurile Trench and the various peninsulas alongside the Hokkaido prefecture. [Original Map©].*

---

[4] A tectonic plate is a large piece of the Earth's crust that floats and moves slowly on the Earth's mantle. These movements can cause earthquakes, volcanoes, and the formation of mountains.

2. The Japan trench.

As mentioned earlier, the Japan Trench is the result of the subduction of the Pacific plate, which moves westward and plunges under the North American plate (Okhotsk plate). This geological feature extends from the north, off the coast of Hokkaido, following the Japanese coast to the south and connecting to the Izu-Ogasawara Trench to the west and the Sagami Trench to the east (Figure 3). Due to its intense seismic activity, this region has been the scene of significant earthquakes that marked the twentieth century.

Similar to the previously studied regions and the two other regions to come, the Japan Seismic Fault has been divided into five geographical zones to facilitate its analysis. These areas include “Northern Sanriku”, “Central Sanriku”, “Miyagi”, “Southern Sanriku”, “Fukushima”, “Ibaraki”, and “Boso”. Although many earthquakes occur each year in this region, the most significant and notable earthquakes, such as those of 1930, 1968, 1994 and 2011, are attributed to what researchers (Xie & al., 2019) call “seismogenic asperities”[5]. These specific areas along a geological fault slow down or block tectonic movements, thus accumulating stress to a critical point. This breaking point ultimately causes the abrupt release of this energy in the form of an earthquake. These rough edges are responsible for the region’s powerful earthquakes.

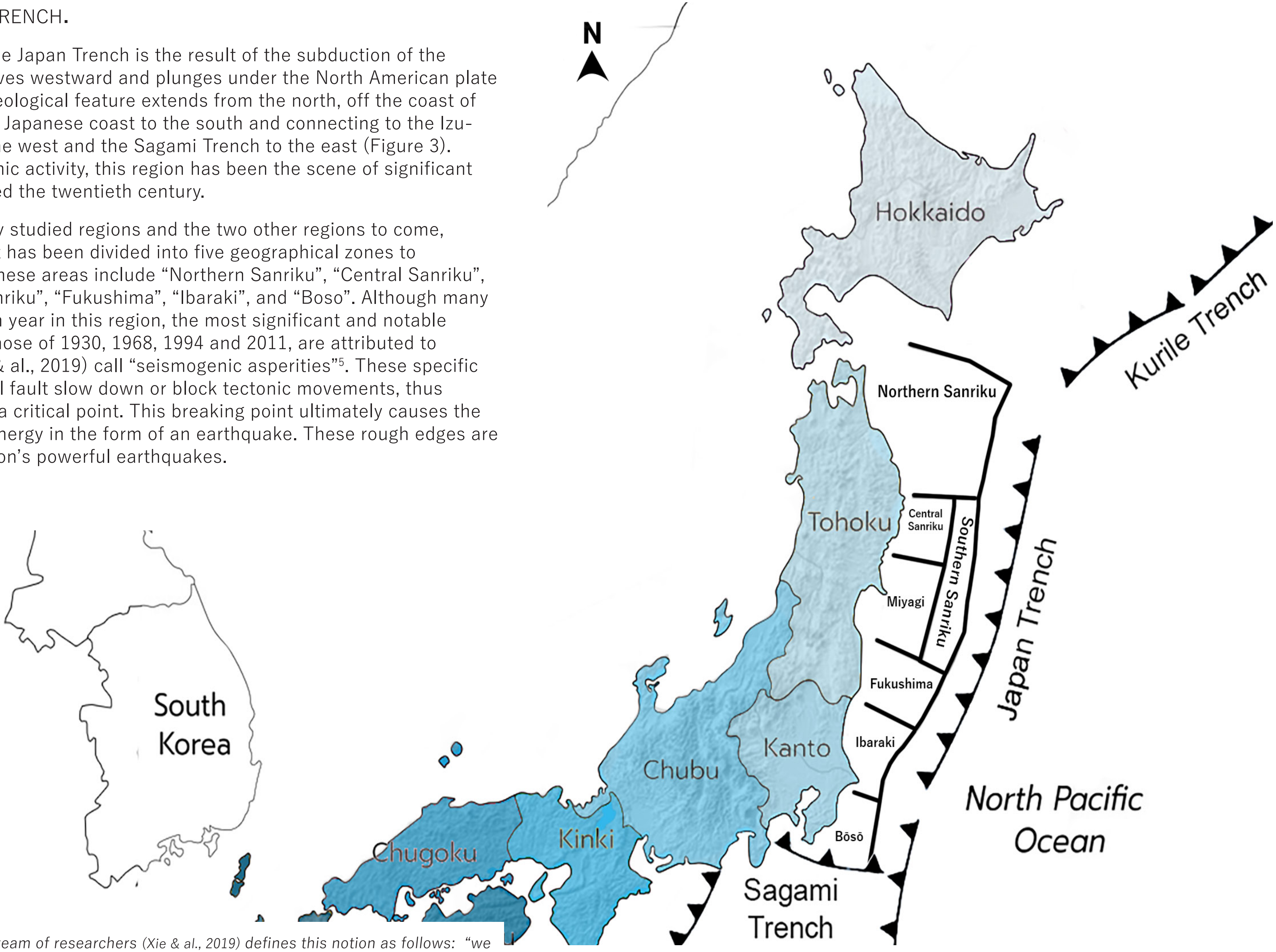


Figure 3: *Map showing the Japan Trench and the various peninsulas alongside the Kanto, Tohoku and Hokkaido prefecture. [Original Map©].*

---

[5] *To aid understanding, the team of researchers* (Xie & al., 2019) *defines this notion as follows: “we define the seismogenic asperity as the area of greater accumulation of shear and normal stresses, which is different from but consistent with the previous definition of an ‘asperity’ as the area where large post-seismic slip occurs.”*

3. The Sagami Pit.

—As for the Sagami Trench (Figure 3), it extends over 340 kilometres between two major seismic faults: the Nankai Fault, located south of the coast of Tokyo, and the Japan Fault at its Boso section. Its geographical position raises concerns, being close to Tokyo (Mori & al., 2010) (Figure 4)

Due to their location, earthquakes represent a major threat to the 36 million inhabitants of Tokyo and the 43 million inhabitants of the Kantō region. Two huge earthquakes have already struck the region: Genroku Kanto in 1703, measuring about 8.1, and Taisho Kanto in 1923, with a magnitude of 7.9 on the Richter scale. The latter caused the death of 10,000 people in 1703 and more than 105,000 in 1923 (Kanie & Kanie, 2022).

Recent research shows that the Miura Peninsula, close to the fault, is involved in earthquakes in the Kanto region, producing high-intensity earthquakes about every 200 to 400 years (Inazaki & al., 2014). Thus underlining the vital importance of protecting this region against disasters.

4. The Nankai Pit.

The Nankai Trench, located in the south of the Nankaidō region of the Japanese island of Honshū, stretches for about 900 km. Faced with this large size, researchers divide it into sub-regions to make it easier to define the different sources of danger (Kimura & al., 2022)(Figure 4).

This subduction zone is characterised by the Nankai megathrust, a phenomenon of subduction of tectonic plates where a big amount of accumulated stress is suddenly released. This process is usually observed when a denser, cooler lithospheric plate sinks beneath another, less dense plate.

In the case of Nankai, this generates magnitude 8 earthquakes at intervals of about 100 to 200 years in various parts of the Nankai Trench (Mitsui & Hirahara, 2004).

Notable earthquakes in the region include the 1944 Tonankai earthquake, which had a magnitude of 7.9, and the 1946 Nankai earthquake, which had a magnitude of 8. Both of these earthquakes had epicentres southeast of the Kii Peninsula. These events caused enormous damage and killed more than 1,000 people in this region.

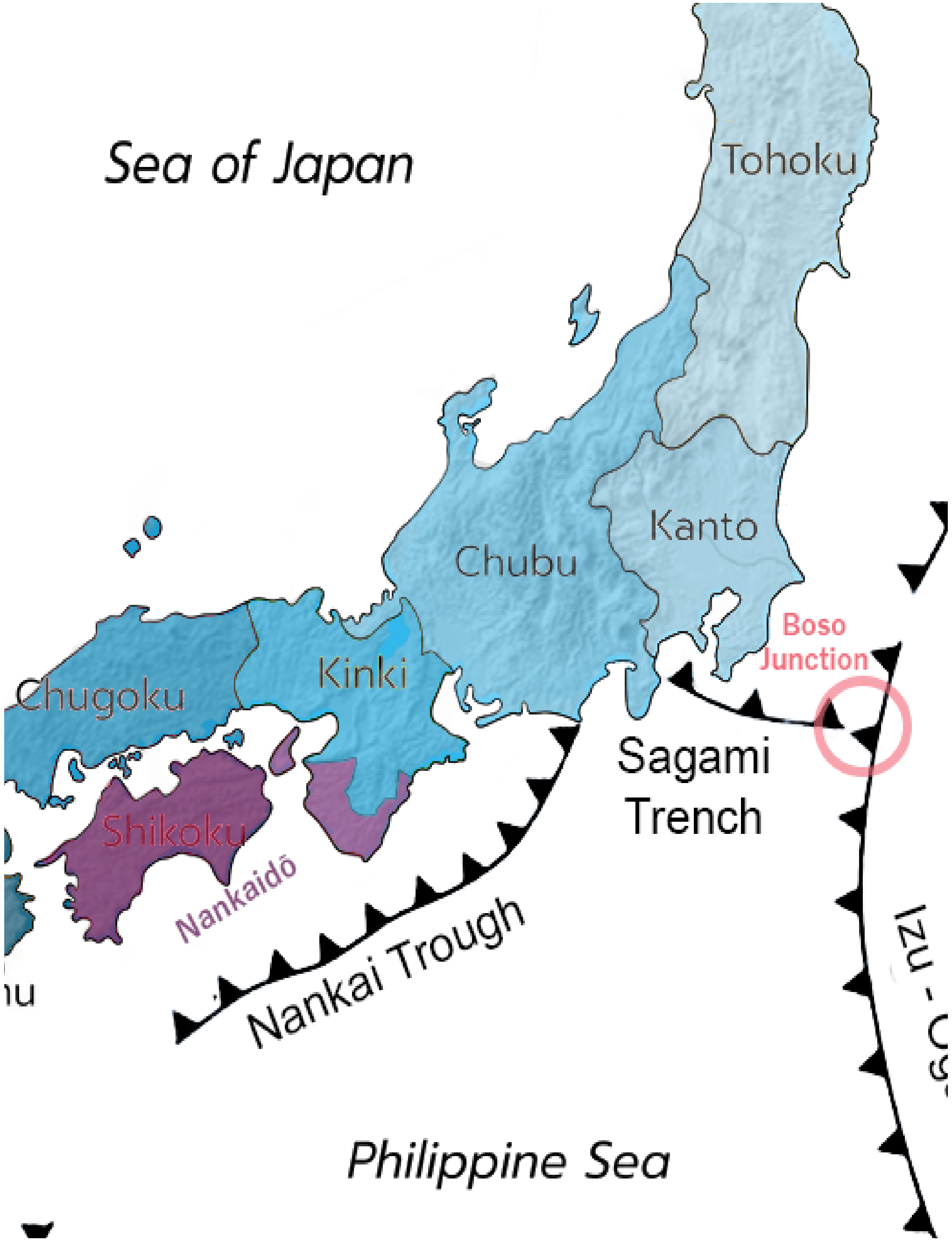


Figure 4: *Map showing the Japan Trench and the various peninsulas alongside the Kanto, Tohoku and Hokkaido prefecture. [Original Map©].*

C. THE INFLUENCE OF HISTORICAL EARTHQUAKES ON ARCHITECTURE IN JAPAN.

As we have seen previously, Japan is located at the convergence of four major tectonic plates and is regularly shaken by earthquakes. These seismic events have had a significant impact on Japanese architecture, contributing to the evolution of seismic standards and the standards that govern contemporary construction in the country. In this analysis, we will look chronologically at five major Japanese earthquakes, starting with Kanto, Kobe, Tohoku, and Kumamoto in 2016.

1. THE GREAT KANTŌ EARTHQUAKE OF 1923.

The Great Kantō Earthquake, which occurred on September 1st, 1923, remains one of the most devastating earthquakes in Japanese history. Mainly located in the Kantō region, it encompassed Tokyo and Yokohama, reaching a magnitude of 7.9 on the Richter scale. As Clancey's book discusses (Clancey, 2006), its consequences were catastrophic: massive collapse of the city, including the recently built Western Quarter, and destructive fires that claimed the lives of an estimated 140,000 people, not counting deaths from subsequent epidemics.

An assessment of the damage reveals the scale of the disaster: half of the wooden houses collapsed, 82% of the Dozo-Zukuri buildings[6] (Figure 5)were reduced to rubble, and only a third of the brick and stone buildings survived. This event highlighted the vulnerabilities of the buildings of the time.

The academic (Blanchard, 2018) underlines in his article the importance of the 1923 earthquake on urban planning in Tokyo. Indeed, in his publication, he highlights that this disaster has triggered significant research to minimise such disasters. In response, Japan has launched an extensive program to rebuild and strengthen infrastructure, focusing on earthquake and fire resistance. Building regulations have been tightened, introducing new construction methods resistant to fire and seismic shaking. From this perspective, the use of reinforced concrete has become crucial.

The researcher also highlights the role of 佐野利器 (Sano Toshikata), appointed director of the architecture section by 後藤新平 (Gotō Shinpei), mayor of Tokyo and Minister of the Interior at the time, was a precursor in the adoption of reinforced concrete in Japan.

Mr. Toshikata observed the extensive damage to the stone and brick structures during the earthquake, which convinced him of the effectiveness of reinforced concrete.

This technique combined the “tensile force” of the iron reinforcement with the “compressive force” of the concrete. This prompted architects like Sano to generalise its use in public buildings. As mentioned (藤森[Terunobu], 1993), these buildings include schools, hospitals, town halls, and housing for the Dōjunkai, a public utility foundation created to rehouse earthquake victims.

Architects such as Yoshikazu Uchida and Tachū Naitō developed additional techniques to strengthen earthquake resistance. They reinforced structural elements such as beams and pillars and added reinforcement walls in strategic locations. Both approaches have proven effective in improving buildings' resistance to earthquakes.

Thus, the addition of the study carried out following this disaster marked a significant turning point in Japanese architecture. Because, by revealing the vulnerabilities of the buildings of the time. It has also led to considerable advances in earthquake-resistant standards and construction techniques. These advances have initiated a succession of research that has given Japanese architecture its current reputation.

---

[6] *Also mentioned as the Kura-Zukuri technique which is a fire-resistant construction technique with a wooden structure and thick mud walls covered with plaster for a more in-depth description be sure to refer to the following link: System, J.A.A.A.N.U. (s.d.). JAANUS/dozou-zukuri y . https://www.aisf.or.jp/~jaanus/deta/d/dozouzukuri.htm*

Figure 5: *Picture showing a Machia in the Dozô-zukuri style. Picture from埼玉りそな銀行 [Saitama Resona Bank]. (2024, April 22) 川越蔵造りの町並みを散策しようー歴史からおすすめスポットまでご紹介!: [Take a stroll through the Kawagoe warehouses - from history to recommended spots!]. https://www.saitamaresona.co.jp/mikke/local/local_0001.html*

2. THE KOBE EARTHQUAKE IN 1995.

One of the most striking destructive earthquakes was the Kobe earthquake of January 17, 1995, which reached a magnitude of 6.9 on the momental magnitude scale. This disaster caused horizontal displacements of the ground reaching up to 1.6 meters, killing more than 6,000 people and leaving hundreds of thousands homeless.

According to the article by (Muguruma & al., 1995), it has been observed that buildings erected before the introduction of the Building Standards Act of 1971 have suffered significant damage. This damage includes the collapse of the first floor or an intermediate floor for reinforced concrete structures.

Despite efforts to enhance earthquake-resistant construction after each earthquake since 1923, the Kobe tragedy underscored a critical point. It highlighted the importance of ongoing research and upgrading as many buildings as possible to comply with the latest Japanese earthquake legislation.

Although the use of reinforced concrete became widespread, thanks to amendments such as the Kyu-taishin standards or “old earthquake-resistant construction” (1950-1981) (Nancy, 2022), many buildings still collapsed on that day. This earthquake also revealed gaps in the calculations needed to determine the permissible stresses that ensure the soundness of buildings.

In reaction to this, according to the research of (Muguruma & al. 1995), following this catastrophe, the Japan Association of Prestressed Concrete Civil Engineering (JPCEA) introduced many reforms in construction in Japan, whether in terms of design standards or the utilisation of prestressed concrete in construction. These updates have included limiting the maximum height of buildings to 31 meters, unless approved by the Japanese Ministry of Construction, and proposing new calculation approaches that consider various bending factors and allowable stresses. Measures have also been put in place to ensure that buildings are resistant to seismic load that exceeds the expected severity of future earthquakes.

The research highlighted that prestressed precast concrete buildings were more resistant to earthquakes. By observing that prestressed concrete beams resisted better than reinforced concrete columns, it was concluded that their manufacturing methods provide higher seismic resistance. The article also recommended revising pile design procedures to make them more ductile.

In conclusion, the Kobe tragedy reinforced the critical importance of the continuous improvement of seismic standards initiated in 1923 and the implementation of new construction technologies to protect lives and property in Japan.

AFTER 1995, SHIN-TAISHIN:

As seen through the earthquakes of 1923 and 1995, the seismic codes in Japan are regularly updated. As the internet article (Earthquake Building Codes in Japan, 2021) points out, during the 1995 earthquake, only 0.3% of the buildings built under the 1981 decree collapsed. This resilience has led to a classification of buildings into two categories: “Kyu-taishin” (旧耐震), or “old earthquake-resistant construction” (1950-1981), and “Shin-taishin” (新耐震), or “New anti-earthquake construction” (1981 to present)(Figure 6). Thus, despite its constant evolution, the building standard published in 1981 offers an overview of the current state of anti-seismic architectures in Japan.

Divided into three construction methods, they correspond to an increasing requirement for earthquake-resistant buildings:

· ***The resistance method (耐震構造, Taishin Kōzō)***: used in any type of building, this tactic intends to strengthen the structure of the building to resist seismic forces. It involves the use of strong materials, structural reinforcements and specific design techniques to ensure the stability of the building during an earthquake.

· ***The energy dissipation method (制震構造, Seishin Kōzō):*** more usually reserved for large buildings, this method aims to absorb and dissipate seismic energy to reduce vibrations and stresses on the structure of the building. It uses devices such as shock absorbers and seismic isolators to protect the building from damage.

· ***The seismic isolation method (免震構造, Menshin Kōzō):*** generally used for large buildings, because it is costly, this technique is very effective in isolating the structure of the building from the moving ground during an earthquake. It uses special supports that absorb shocks and reduce the transmission of vibrations to the structure, thus minimising damage.

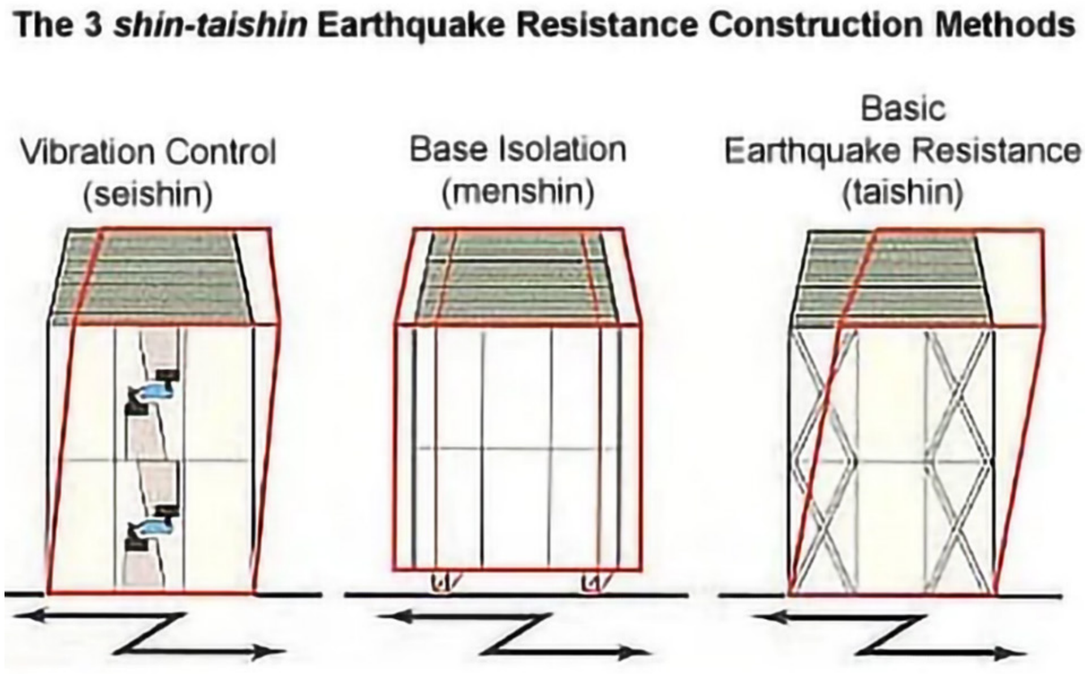


Figure 6: *Illustration from: Earthquake building codes in Japan. Illustration from JAPAN PROPERTY CENTRAL K.K. (2024, April 14). Earthquake building codes in Japan. https://japanpropertycentral.com/real-estate-faq/earthquake-building-codes-in-japan/*

3. *Tōhoku earthquake in 2011.*

On March 11, 2011, a magnitude 9.1 earthquake on the moment magnitude scale occurred off the Pacific coast of Tōhoku in Japan, hitting the northeastern region of the island of Honshū. As published in the report of the (気象庁 [Japan Meteorological Agency], 2011), this earthquake lasted about two to three minutes and spread at an estimated speed of 2.7 km/s. The epicentre was 130 km east of Sendai, Miyagi Prefecture. It resulted in a tsunami with waves exceeding 30 m in height in some places, penetrating up to 10 km inland and causing extensive damage to about 600 km of coastline, as highlighted by reports from the (気象庁 Japan Meteorological Agency, n.d.).[7]

The article dedicated to this disaster of the (内閣府 [Cabinet office, Government of Japan], 2013) also informs us that this disaster resulted in 18,079 deaths and disappearances, with many injured and enormous destruction. Although the earthquake itself was more powerful than the Kobe earthquake in 1995, the tsunami waves were responsible for more than 90% of the loss of life. Thus, despite the high magnitude of the earthquake, the Japanese earthquake-resistant construction standards of the time made it possible to limit the direct victims of the earthquake. The Fukushima Daiichi nuclear accident, triggered by the tsunami, has worsened the situation, with long-term consequences in terms of radioactive contamination and displacement. The reconstruction of Japan took several years and an estimated investment of about 210 billion dollars, making this event one of the most costly earthquakes in history, both in human life and in economic terms.

However, in response to this tragedy of researchers worldwide, there is a response stimulating important technological and scientific progress. Researchers like Andreas Reitbroc, professor of seismology at the University of Liverpool, comment in (Experts Comment on Japan Earthquake and Tsunami | Science Media Centre, 2011), “The magnitude 8.9 Japan earthquake is one of the largest earthquakes recorded worldwide in the last 100 years and the strongest one ever recorded in Japan. It have produced a wealth of new observations to advance our understanding of earthquakes.” In an interview with the Los Angeles Times (Brown, 2011), Tom Heaton and James Cave also pointed out that this disaster would provide valuable information on the resistance of buildings to seismic shaking, thus contributing to the improvement of earthquake-resistant construction standards. In response to this tragedy, Japan has put in place measures to strengthen the quality of its buildings, as evidenced by the “Building Standard Law of Japan”. (日本建築センタ [Japan Architecture Center], 2016) contributing to the seismic qualities of Japanese buildings that we know today.

---

[7] *気象庁 Japan Meteorological Agency. (n.d.). 気象庁技術報告 | 平成23年(2011年)東北地方太平洋沖地震調査報告. https://www.jma.go.jp/jma/kishou/books/gizyutu/133/gizyutu_133.html*

4. Kumamoto Earthquake Series 2016.

From April 14 and 16, 2016, two powerful earthquakes shook the prefectures of Kumamoto and Ōita. The first earthquake struck the city of Mashiki on April 14 at 9:26 p.m., recording a magnitude of 6.2 on the moment magnitude scale. The second quake, which struck at 1:00 a.m. on April 16, was of an impressive magnitude 7 on the moment magnitude scale, causing even more destruction. Thanks to modern seismic monitoring technologies, these two events could be carefully studied, allowing their behaviour to be captured in detail. The seismographs of the Japan Meteorological Agency, (気象庁 [Japan Meteorological Agency], n.d.) (Figures 7 and 8) show the violence of the two earthquakes and the energy delivered. Thus, we understand the power of those two earthquakes and the devastation they caused in the region.

As the article in (Takeda & Inaba,2022) reveals, the toll of these earthquakes is heavy: 42 deaths, 7 missing, 1,063 injured, and 2,442 homes damaged. Due to damage to infrastructure, more than 257,625 homes were left without access to water in Kumamoto, Ōita, and Miyazaki prefectures.

Adding to this the 2016 earthquakes caused extensive damage to the cultural heritage of the Kumamoto area, including the Ishigaki Walls of the Castle of Kumamoto. As the study points out (Ohsumi, 2017), this one has been particularly affected. The building's roofs and stone walls suffered considerable damage, with 23 important cultural properties affected and 27 structures needing reconstruction. There are a total of 523 deformations on the stone walls, affecting 30% of their total surface, either 8,200 m².

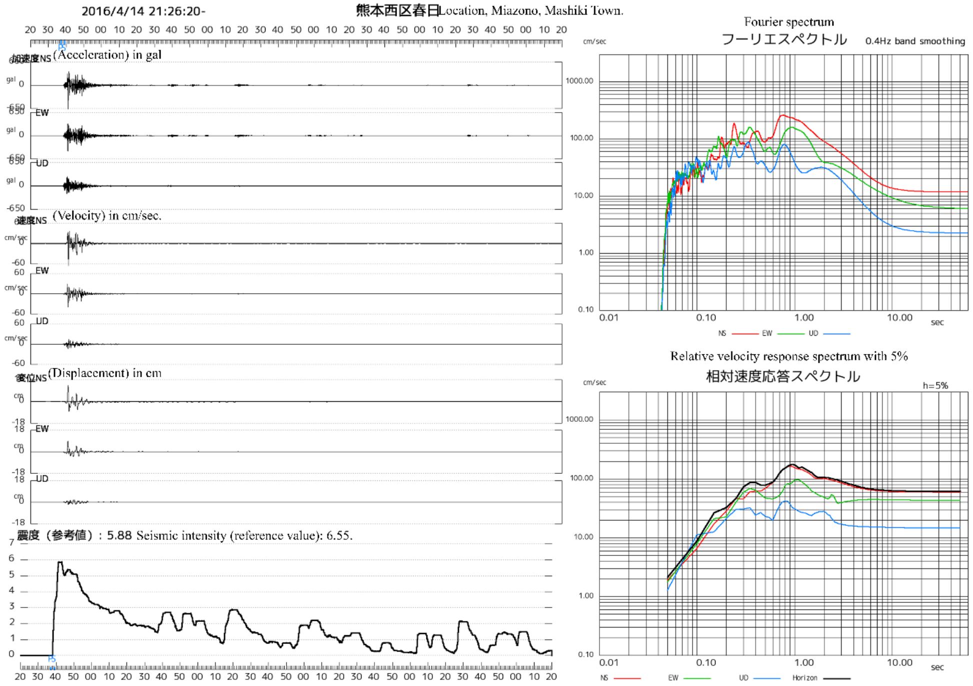


Figure 7: *Seismic Disaster Report of 2016 Kumamoto earthquake. Graphics showing the North-South, East-West, Up-Down movement of the earthquake of Kumamoto, Japan, on April 14. going from top to bottom, it contains on the left Acceleration Graphs, Velocity Graphs, Displacement Graphs and a Seismic Intensity Graph. On the right, it contains the Fourier Spectrum, the Relative Velocity Response Spectrum with 5% Damping. Graphics from, Japan Meteorological Agency (JMA). (n.d.-a). 2016/4/14 21:26:38 熊本県益城町惣領: [2016/4/14 21:26:38 Location, Sorio, Mashiki Town]. https://www.data.jma.go.jp/eqev/data/kyoshin/jishin/1604142126_kumamoto/wave/Q414EEB2.png*

The study conducted by (Ohsumi, 2017) shows that these walls, erected using two main techniques, reacted differently to seismic tremors. The Ano method (Hosokawa era), characterised by the use of precision-cut stones and a steep slope, demonstrated to be the least vulnerable. In addition, the Sangi-tsumi method (late Kato and early Hosokawa era), using rectangular stones stacked alternately on their long and short sides, proved to be more fragile.

By highlighting the damage observed on the Ishigaki walls, the study by (Ohsumi, 2017) highlights the importance of taking into account the specificities of traditional construction techniques in the assessment of the seismic weakness of built heritage. This paves the way for a better understanding of the failure mechanisms of Ishigaki walls. Thanks to the software developed by (Koutaki & al., 2022), which enables the stones to be identified and placed back in their original position, the team of (Hashimoto & al., 2021) was able to conduct physical tests on replicas of the walls of Kumamoto Castle at the National Research Institute for Earth Sciences and Disaster Prevention in Tsukuba. These tests aimed to better understand the resistance of the Ishigaki walls to seismic tremors.

Having been well studied, this earthquake will surely be a perfect case study for the research following this master's thesis. The knowledge acquired through these studies will allow to verify and improve the simulation models developed during this research, ultimately permitting to produce a tool that will be capable to predict the behaviour of stone walls during earthquakes.

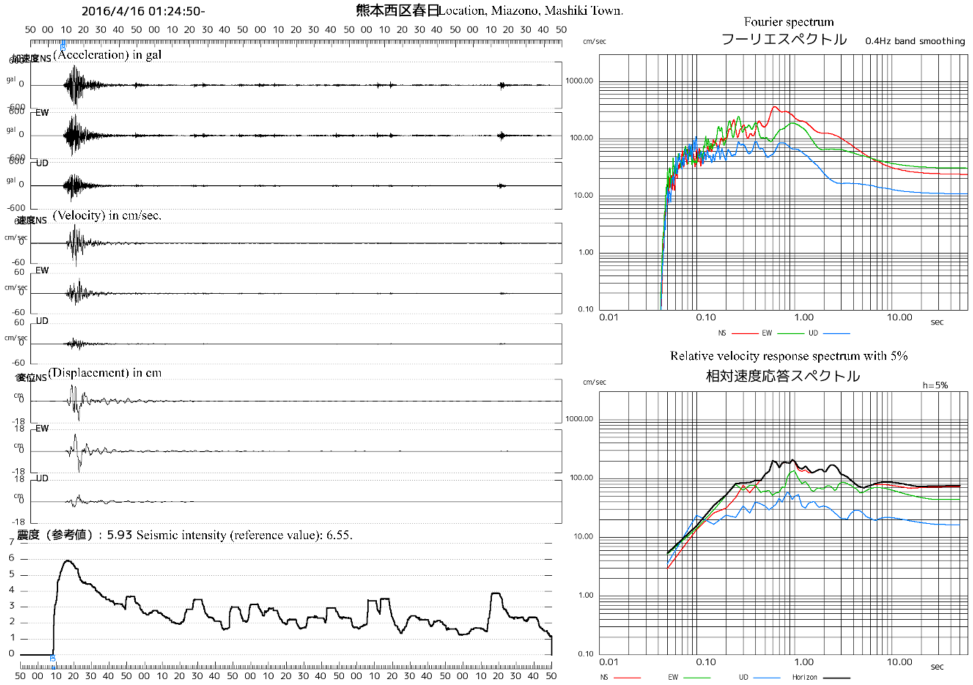


Figure 8: *Seismic Disaster Report of 2016 Kumamoto earthquake. Graphics showing the North-South, East-West, Up-Down movement of the earthquake of Kumamoto, Japan, on April 14. going from top to bottom, it contains on the left Acceleration Graphs, Velocity Graphs, Displacement Graphs and a Seismic Intensity Graph. On the right, it contains the Fourier Spectrum, the Relative Velocity Response Spectrum with 5% Damping. Graphics from, Japan Meteorological Agency (JMA). (n.d.-b). 2016/04/16/ 01:24:50 熊本県益城町: [2016/04/16/ 01:24:50 Mashiki Town, Kumamoto, Japan]. https://www.data.jma.go.jp/eqev/data/kyoshin/jishin/1604160125_kumamoto/wave/Q416EEB001.png*

SECTION 1.2: UNDERSTANDING EARTHQUAKES, WAYS TO MEASURE THEM AND THEIR MOVEMENTS.

A. Between feeling and mathematical calculations.

To understand how we measure earthquakes, we must first distinguish between *intensity* and *magnitude*, two terms that imply two distinct ways of perceiving an earthquake.

Intensity as explain the (気象庁 [Japan Meteorological Agency], n.d.-c) [8] is a way of gauging earthquakes based on observer reports. It assesses the damage and shaking felt at a specific location during an earthquake. This measurement can vary depending on the observer's location. For example, an earthquake may seem more powerful to someone near the epicentre than to somebody farther away.

In Japan, the Shindo scale measures earthquake intensity. This scale provides multiple values based on the observer's distance from the epicentre. It ranges from 0, indicating no discernible shaking, to 7, where movement without crawling is impossible, and people may even be ejected into the air. The Shindo scale helps Japan organise relief efforts and inform the population during frequent earthquakes.

Magnitude, as we can understand, thanks to (Abe, 1979), differs from intensity in that it is based on mathematical calculations rather than perception. It provides a value representing the total energy emitted by an earthquake, regardless of where it is felt. These calculations are complex and evolve with advancements in human knowledge and technology.

---

[8] Japan Meteorological Agency. (n.d.). Japan Meteorological Agency. https://www.jma.go.jp/jma/en/Activities/inttable.html

2. Richter scale.

The Richter scale, developed in 1935 in California by Charles Francis Richter and Beno Gutenberg, represents one of the first attempts to quantify the intensity of earthquakes. Unlike the Shindo scale, which assesses the damage observed, the Richter scale aims to calculate the total energy released by an earthquake, i.e. its magnitude.

To achieve this measurement, researchers (Gutenberg & Richter, 1936)[9] relied on recordings from seismographs, instruments that measure seismic waves. As an earthquake generates a lot of energy, the team of researchers dealt with large numbers or very small numbers. In consequence, a logarithmic formula in base 10 was developed, allowing them to use more manageable numbers and then use their results to create the scale we know today. This formula then takes the following form:

$$Ml = \log_{10}(A) - \log_{10}(A_0(\Delta))$$

To understand they different factors that compose this formula we can decompose it as subsequently:

- **Ml**, indicates the local magnitude.
- **A,** which is measured in fractions of a millimetre (1/1000 mm), represents the maximum amplitude of the recorded seismic wave.
- **Δ,** which is quantified in kilometres (km) symbolises the distance between the seismograph and the epicentre of the earthquake.
- **A_0,** is the correction value that allows us to act as if Δ were equal to 100 m. To estimate this, we can use tables as proposed (Bormann, 2012).

Thus, thanks to the logarithmic basis of this formula, each step of the Richter scale represents a ten-fold increase in the measured amplitude, i.e. 31.6 times the amount of energy released.

However, it is important to note that this formula has limitations. For example, its effectiveness may be compromised depending on the position of seismic stations or due to its inaccuracy. As a result, it has been replaced by calculations that are no longer based on the amplitude of seismic waves but offer a more direct method of calculating the energy delivered during an earthquake.

---

[9] Gutenberg, B., & Richter, C. F. (1936). Magnitude and energy of earthquakes. Science, 83(2147), 183–185. https://doi.org/10.1126/science.83.2147.183

3. HIRO KANAMORI AND THOMAS HANKS SCALE.

Our understanding of earthquakes has evolved over time, from local magnitude scales such as Richter to various scales that take into account the different waves propagated by an earthquake. Nowadays, we use a scale based on the noted “seismic moment” (M_0), which takes into account the stiffness of the rock involved in the failure, the average area displaced along the fault, and the average displacement along the fault (Aki, 1966).[10]

Having its importance for the following calculation and the rest of the dissertation, the formula developed by the researcher in the form $M_0 = \mu \bar{u} S$ which is translated as follows:

- **M_0:** the seismic moment, expressed in dyne-centimeters (dyn-cm). Which represents the force required to accelerate a mass of one gram to a speed of one centimetre per square second.
- **μ**: the shear modulus of the rocks involved in the fault. It represents the stiffness of the rock and its resistance to deformation. Shear modulus is usually expressed in dynes per square centimetre (dyn/cm²).
- **$\bar{u}$**: the average displacement on the fault’s surface, expressed in centimetres (cm). It represents the average distance that the fault’s two sides moved relative to each other during the earthquake.
- **S**: the surface area of the fault failure, expressed in square centimetres (cm²).

Considered more reliable, this way of measuring earthquakes allowed the emergence of the “magnitude of motion” noted (Mw), developed by (Kanamori, 1977) and then confirmed by (Hanks & Kanamori, 1979)

Their collaboration in 1979 made it possible to propose a formula to simplify the estimation of Mw in the form of $Mw = (\log_{10}(m_0) - 9.05)/1.5$, which we can understand as follows:

- ***Mw***: the moment magnitude a dimensionless number that represents the order of magnitude of the energy released by the earthquake.
- **$\log_{10}(m_0)$**: the logarithm in base 10 of the magnitude M_0 described above expressed in (dyn-cm).
- ***9.05 and 1.5***: are empirical constants determined from the analysis of a large number of earthquakes. These constants convert the magnitude of surface waves into a moment magnitude.

In conclusion, this thesis plans to use the moment magnitude developed by the researchers (Hanks & Kanamori, 1979) to reproduce and simulate the power of earthquakes in Japan. This more accurate method provides a better understanding of earthquakes’ power and effects.

---

[10] Aki, K. A. (1966). generation and Propagation of G Waves From the Niigata earthquake of june 16, 1964.: Part 2. Estimation of earthquake moment, released energy, and stress-steain drop from the G waves spectrum. Bulletin of the Earthquake Research Institute, 44, 73–88. https://ds.irid.edu/seismo-archives/quakes/1964niigata/Aki1966b.pdf

B. DIFFERENT TYPES OF WAVES AND THEIR BEHAVIOURS.

Seismic waves, often triggered by earthquakes, travel across the Earth in all directions, shaking particles in the ground like waves in water. There are generally two main categories of these waves: volume waves, such as P waves (longitudinal) and S waves (transverse), which travel through the Earth, and surface waves, such as Love and Rayleigh waves, which propagate across the Earth's surface. Although slower than volume waves, surface waves can cause more damage to surface structures.

in the context of this thesis, it is crucial to understand the different ways in which an earthquake propagates, its movements and their consequences on our constructions. This is why the next section explores their role and behaviour.

1. VOLUME WAVES.

P-WAVE.

Discovered in 1830 by mathematician Siméon Denis Poisson, P-waves, also known as pressure waves, are a type of seismic wave that travels through all sorts of terrestrial media: solid, liquid and gaseous. Based on the article of (Fowler, 2005) they are characterised by a movement of successive compression and expansion of the particles of the medium, similar to the movement of an accordion, as illustrated in (Figure 9). This vibrational motion occurs parallel to the direction of propagation of the wave, which means that the particles oscillate back and forth in the same direction as the wave is moving.

During an earthquake, the P oscillations are the first to be generated and to spread from the epicentre. Their propagation speed is about 6 km/s near the Earth's surface, making them faster than other types of seismic waves, such as S waves and surface waves. This speed explains why P-waves are responsible for the dull rumbling that sometimes precedes the arrival of stronger tremors during an earthquake. They are also the first to be sensed by seismographs, instruments used to measure ground motion.

By their movements, P-waves rarely cause damage and, if detected, can announce the beginning of the earthquake. However, geologists use the data collected by this first wave to understand the Earth's internal structure. (Fowler, 2005)[11] .

S-WAVE.

S-waves, also known as secondary waves or shear waves, are as explain (Fowler, 2005) is an another type of seismic wave generated by earthquakes. Unlike P- waves, which spread by compression and expansion, S-waves are distinguished by a vertical undulation motion, where the displacement is perpendicular to the wave's propagation direction as we can see in (Figure 9). To exemplify this, we can imagine a taut rope that you shake up and down: the ripples that propagate along the rope illustrate the movement of the S-waves.

S-waves travel at a speed of about 4 km/s, making them slower than P-waves. This difference in speed allows seismologists to calculate the distance between the seismic station and the earthquake's epicentre by measuring the time lag between the arrival of the P-waves and the S-waves.

An additional peculiarity of this type of wave is its inability to diffuse through liquids, which is therefore blocked by the liquid outer core of the Earth. Thus, generating a "shadow zone" on the surface of the globe opposite the epicentre of the seismic tremors allows a better understanding of the composition of our planet.

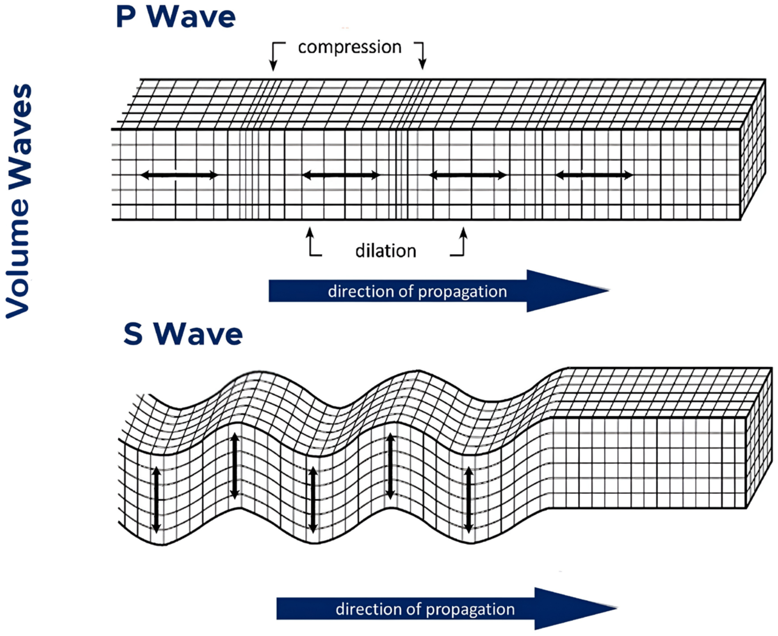


Figure 9: *Illustration of seismic "Volume Waves" from Triton, L., Earle, S., Bačić, M. B., Librić, L. L., Jurić Kaćunić, D. J., Saša Kovačević, M. S., & Wikimedia. (4 C.E., July 23). Overview_Seismic_Waves. Wikimedia. https://upload.wikimedia.org/wikipedia/commons*

---

[11] *Fowler, C. M. R. (2005). The Solid Earth: An Introduction to Global Geophysics. Cambridge* University Press.

SURFACE WAVES.

RAYLEIGH WAVES.

Discovered by (Rayleigh, 1885), the waves of the same name propagate on the Earth's surface and are characterised by a retrograde elliptical motion of particles on the surface, combining longitudinal and transverse motions within this ellipse as shown in (Figure 10). This complex behaviour can be visualised by imagining objects floating on the surface of the water. If you look at them carefully, you will notice that they follow a circular motion, going up and down while moving slightly back and forth.

With a speed of between 50 and 300 m/s, they are slower than volume waves and generally arrive after them. Constrained to the Earth's crust, they dissipate with distance. However, they can start to generate oscillations that can be felt on the surface. Considered the most devastating wave, its capacity depends on several factors, such as the earthquake's size, distance, or depth.

LOVE WAVES.

As explained, the web page from the Division of Theoretical Geoscience of the University of Tokyo on this website (Love Wave, n.d.)[12]. Love waves, named after Augustus Edward Hough Love, who predicted their existence in 1911, are surface seismic waves characterised by horizontal shear motion as we can see in (Figure 10). This motion is similar to that of S-waves but takes place perpendicular to the wave's propagation direction. Love waves result from the interference of S-waves propagating in the soft surface layers of the Earth.

These waves can cause significant damage to the foundations of buildings that do not comply with seismic standards, including cracks and horizontal displacements. Although they propagate at a speed of about 4 km/s, their intensity decreases with distance.

During a large earthquake, Love's waves are responsible for the horizontal movements felt by most people outside the immediate area of the epicentre. Their impact on the foundations of the structures is therefore crucial to take into account in the context of this thesis aimed at designing Japanese buildings that are more resistant to seismic tremors.

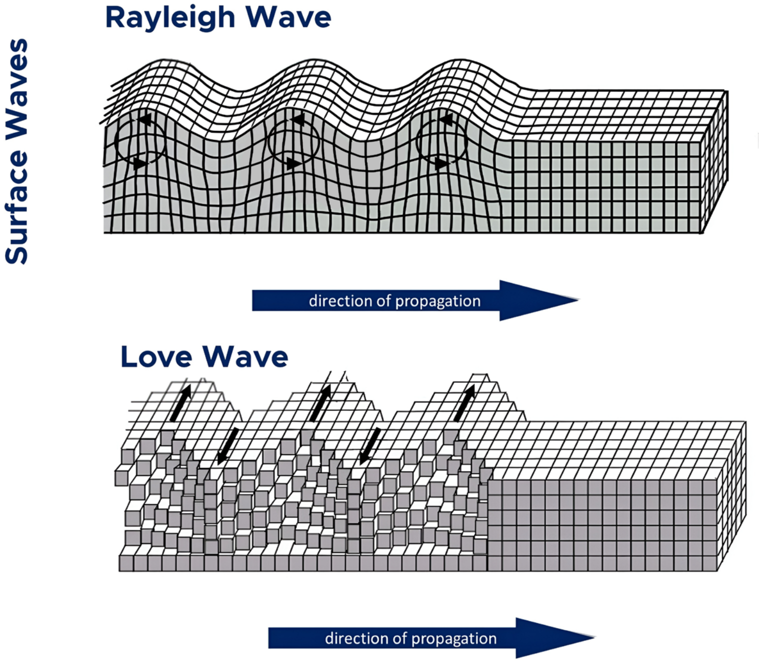


Figure 10: *IlustratioTriton, L., Earle, S., Bačić, M. B., Librić, L. L., Jurić Kaćunić, D. J., Saša Kovačević, M. S., & wikimedia. (4 C.E., July 23). Overview_Seismic_Waves. Wikimedia. https://upload.wikimedia.org/wikipedia/commons/0/07/Overview_Seismic_Waves.jpg*

---

[12] *Love wave. (n.d.). https://www.eri.u-tokyo.ac.jp/people/knishida/eng/Seismology/Love_wave.html*

SECTION 1.3: DRY STONE MASONRY IN JAPANESE ARCHITECTURE.

A. HISTORICAL AND GEOGRAPHICAL CONTEXT OF MASONRY CONSTRUCTION.

Masonry construction is an ancient practice that can be found in many cultures around the world. The genesis of the building technique called “Ishigaki” dates back to the “Sengoku” period (1467-1573). This technique, closely linked to the construction of fortified castles, was justified by the numerous territorial wars that took place on the island at that time. Initially used to build retaining walls, the first traces of this technique were found in the mountains, where it was employed to reinforce strategic areas in castles.

Over time, this technique gradually spread to the rest of the nation, giving architectural treasure such as the castle of Azuchi, erected in 1573. This illustrates both the rise of so-called “modern” castles and the beginning of the so-called “Azuchi Momoyama” period (1573-1603), which allowed the unification of Japan.

The development and multiplication of castles at this time favoured a rapid evolution of dry-stone construction. However, from 1615 onwards, several shogunate decrees, such as the “Ikkoku Ichijōrei”, imposed regulation and reduced the number of castles in the country.

From that date on, the construction of new castles and even the reconstruction of existing castles were prohibited. This led to a decline, or even abandonment, of the various dry stone construction techniques. It was not until the 1930s that these buildings experienced a new craze, also allowing for a revival of interest in “Ishigaki” techniques (Young & Young, 2014, pp. 100–105).

It is also important to note that many castles were dismantled or destroyed between 1873 and World War II. Leading to the disappearance of the testimonies of the “Ishigaki” know-how. Thus, the current knowledge, although numerous, may not represent the capabilities of the time.

B. WHAT IS A 石垣 (ISHIGAKI)”WALL.

A “石垣 (Ishigaki)” wall, literally “stone wall” in Japanese, as explained in the book of (Turnbull, 2009) is a dry masonry technique used in Japanese architecture, especially for fortifications. This method is characterised by assembling stones without mortar or binder, which is supported by an embankment of earth and rubble several meters high (Figure 11).

Unlike traditional fortifications, which consisted mainly of wooden palisades or packed earth surrounded by a moat, the Ishigaki technique emerged during the Azuchi–Momoyama period (1573 to 1603). This development is a direct response to the introduction of firearms in Japan. The main goal of this technique was to create a stronger, gun-resistant base, unlike traditional wooden or earthen fortifications. This sturdy foundation provided better support for wooden structures built on top of it, such as watchtowers or dungeons. Ishigaki was also used to construct gates, ditches surrounding the castle, and the foundations of the keeps.

Generally built with local stones such as andesite, granite, quartz porphyry and gneiss, this technique was favoured for its ease of work. The castles mainly used andesite and granite for their surrounding walls. These constructions are distinguished by their inclination, which varies according to the height of the wall: the greater the height, the less steep the inclination.

According to the article (J.A.A.A.N.U.S, 2001),[13] the book “KENROKU” by Ogyuu Sorai (1727) describes three main forms of castle walls:

Narashi: 45-degree tilt, only the top stone is vertical.

Second type: 50-degree tilt, the top 20% is vertical.

Third type: Inclination of about 80 degrees, the wall slopes in a concave curve, with the top 25% vertical.

If the period Azuchi-Momoyama marks the emergence of the Ishigaki technique; it was during the Edo period that this construction method reached its peak. The successive innovations of master masons transformed Ishigaki from a simple defensive technique into an art capable of producing imposing and elegant structures. To understand the evolution of these stone walls, it is essential to explore in more detail the construction techniques and architectural principles that went into creating masterpieces like the walls of Osaka Castle and Himeji Castle.

---

[13] *System, J. A. A. A. N. U. (2001). JAANUS/ishigaki 石垣. Retrieved May 8, 2024, from https://www.aisf.or.jp/~jaanus/deta/i/ishigaki.htm*

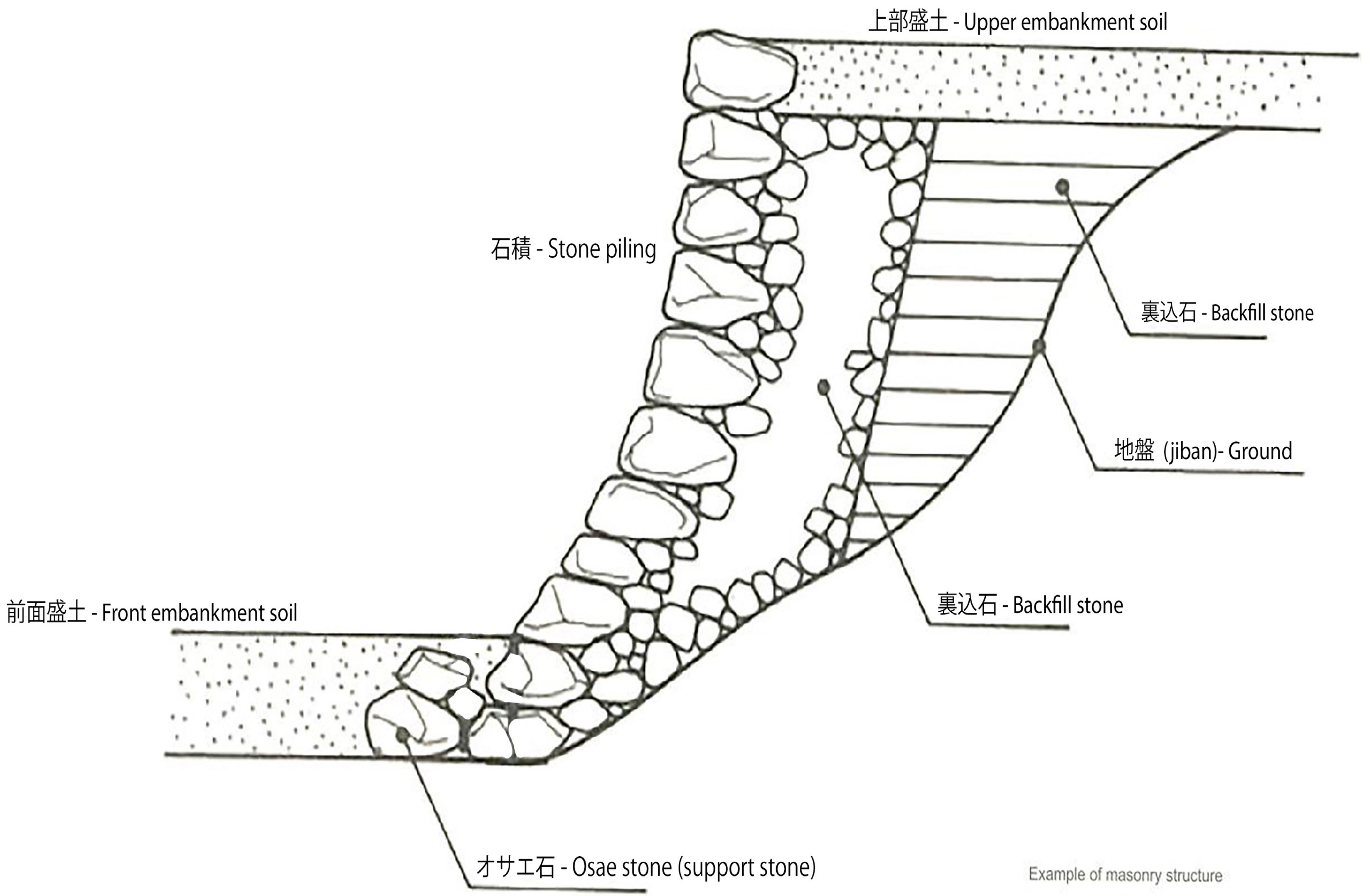


Figure 11: *Illustration of the structure of a Ishigaki wall adapted from Toshiakira. (2023, March 9). Kw-bunnka.com/自立しない! 我々は石垣を修復（なお）せるか. https://kw-bunnka.com/%E8%87%AA%E7%AB%8B%E3%81%97%E3%81%AA%E3%81%84%EF%BC%81%EF%BC%88%E2%85%B0%EF%BC%89/*

C. The different styles of Japanese “Ishigaki” stone walls.

Between 1573 and 1615, over a period of about forty years, the dry-stone construction technique underwent significant advances both in the cutting of the stones and in their assembly. These developments were closely linked to what the authors of the book “The Art of Japanese Architecture” (Young & Young, 2014) call “castle culture”.

Initially, walls built using the “Ishigaki” method[14] often featured a disorderly stack of stones of different shapes, which the Japanese called “Ransekizumi” (Figure 12). The “Gobousumi” technique was also one of the first cutting techniques used, which consisted of cutting large stones in the shape of burdocks to integrate them into the set of stacked stones (Figure 13).

With the rise of castle construction, several stone-cutting techniques began to be used, and more fitted superimpositions filled with small stones could be observed. The process of “natural face masonry,” also called “Nozurahagi,” (Figure 14) symbolises this method evolution, which met more military requirements. The sparsely worked stones appeared to be stacked randomly, but in reality, this technique produced solid walls that supported the ramparts while effectively draining water during heavy rains.

The stone wall construction technique “Uchikomihagi” (Figure 15) is the most commonly used for castle enclosures. Each stone surface is roughly cut to form the rock lines that can still be seen today.

Finally, we come to the most advanced construction techniques, such as the “Kirikomihagi”, where the individual stones are carefully chiselled and fitted in straight lines in order to create a regular and smooth facing surface (Figure 16). Or the “Kikkouzumi” technique, which, like the technique mentioned above, is very meticulous, but is distinguished by being an arrangement of almost hexagonal stones.

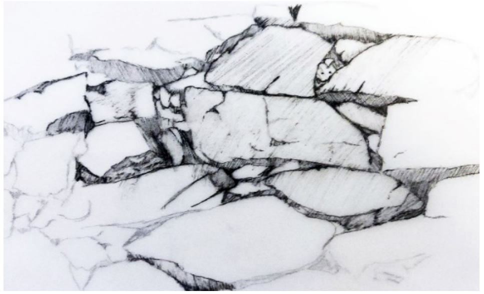


Figure 12: *Sketch illustrating the so-called «Ransekisumi» process used for the Matsumotojou fort in Nagano.[Original Drawing©].*

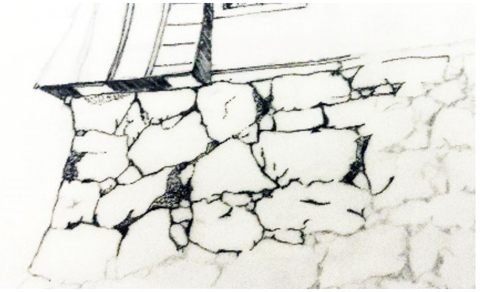


Figure 13: *Sketch illustrating the so-called «Gobousumi» process. [Original Drawing©]*

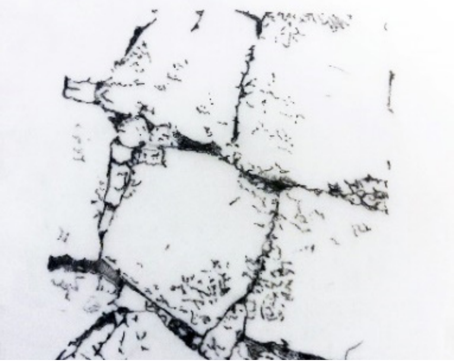


Figure 14: *Sketch illustrating the so-called «Uchikomihagi» process used for the Matsumotojou fort in Nagano. [Original Drawing©].*

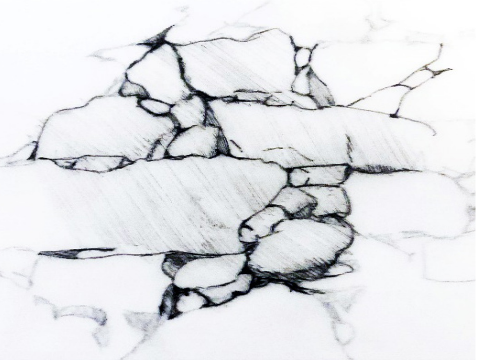


Figure 15: *Sketch from illustrating the so-called «Nozurahagi».[Original Drawing©]*

Figure 16: *Sketch from based on the Edojou Tenshudai fort in Tokyo to illustrate the process of laying the walls “Kirikomihagi”.[Original drawing©]*

SECTION1.4: WHAT IS THE FORM OF MASONRY TODAY IN JAPAN?

A. WHAT ARE THE MASONRY TECHNIQUES THAT WERE USED AFTER THE EDO ERA江戸時代 (1603 TO 1868)?

After the decree of 1615, the previously mentioned building techniques were abandoned or rarely used during the Edo period. In addition, the arrival of the Meiji Emperor in 1867 did not favour the development or reuse of these dry masonry techniques. The emperor, eager to modernise the Japan of his time, opened his country to Western architecture and foreign materials, creating a style known as “giyōfū” (擬洋風建築), or the pseudo-Western style. This terminology includes two types of constructions. The first type concerns buildings with Western shapes but structured with traditional Japanese frameworks. (Young & Young, 2014). The second type concerns buildings whose appearance and the techniques used are Western.

During the 1870s and 1880s, Japan was barely open to the world, and building craftsmen were mainly carpenters. As a result, it wasn’t easy to find qualified personnel for masonry construction. These hybrid structures, with a Western appearance but built according to Japanese processes, clearly mark this transition. The Ōura Church in Nagasaki, built in 1864[15], which uses timber ribbed vaults for the structure, is a good example of this early type of architecture.

The Western architects Waters, Chastel de Boinville and Conder for their part, designed the first buildings of the second type. Tatsuno Kingo was the first Japanese architect to build in this style with the Bank of Japan, built in Tokyo between 1890 and 1896. (Cluzel, 2018)

After the war, new concrete and steel structures were widely employed. In the case of masonry, since it is considered fragile during seismic tremors, it is frequently reinforced in two ways. The first consists of surrounding the wall with a steel or reinforced concrete frame, making the masonry a non-load-bearing partition. The second method called reinforced masonry, is similar to reinforced concrete walls and allows the wall to be used as a load-bearing member.

B. THE STRENGTHS AND WEAKNESSES OF EACH TECHNIQUE OF CURRENT MASONRY CONSTRUCTION TECHNIQUES IN RELATION TO SEISMIC CONDITIONS.

Thus, although these techniques make masonry more resistant to earthquakes, it is important to set their limits. Indeed, despite their different designs, these types of construction suffer from the seismic tremors they undergo. In the case of architectures using concrete or steel frames, studies by (Dias-Oliveira & al., 2022) or (Di Sarno & Wu, 2020) show that vibrations that propagate at different speeds in the frame and masonry create violent bending or even shear forces, which can cause cracks and even collapse of the masonry.

As far as concrete and reinforced masonry is concerned, (Gertin, 2014) thesis shows that even if their resistance to earthquakes is better, their inability to dissipate seismic waves exposes them to fractures and damage that can weaken the entire wall. In short, despite the improvements made to these two types of construction, their lack of ductility (the property of bodies that can be stretched without breaking) makes them unable to effectively dissipate earthquaked waves.

This problem is pushing researchers to consider possible optimisations for these types of construction and even to look for new ways of building using blocks that are better adapted to seismic constraints.

---

[15] Cluzel, J. S. (2018). The European Influence in Japanese Architecture (1860-1930). EHNE. Retrieved April 20, 2023, from https://ehne.fr/fr/encyclopedie/th%C3%A9matiques/les-arts-en-europe/l%E2%80%99art-de-l%E2%80%99europe-%C3%A0-l%E2%80%99%C3%A9preuve-de-%C2%AB-l%E2%80%99autre-%C2%BB/

l%E2%80%99influence-europ%C3%A9enne-dans-l%E2%80%99architecture-japonaise-1860-1930

C. TRENDS AND INTERESTS IN RELATION TO DRY MASONRY.

Modern masonry construction techniques have limitations, especially regarding environmental impact, which cannot be ignored in the current context of diminishing resources and global warming. Faced with these challenges, some Japanese architects and artists are turning to traditional, more sustainable and environmentally friendly techniques, such as “Ishizumi” (石積み).

Ishizumi (石積み) is a variant of the Ishigaki (石垣) technique, both using dry stones, i.e. without mortar or binder, to create walls and foundations. However, Ishizumi is distinguished by its use in the construction of rice terraces, where smaller, uncut stones, usually of a size and weight that can be handled by a single worker, are used, making it much more accessible to creators.

In addition, as highlighted in the article by (Uchida, 2015), the Ishizumi walls, thanks to their construction method, provide a habitat for many unique plant species, thus helping to preserve the surrounding biodiversity.

Thus, the approach of (Abundance, 2023)[16] is therefore in line with this research, thus allowing, by bringing this technique up to date, to preserve ancestral know-how threatened with disappearance and to promote an ecological approach to construction. This craze for more sustainable architecture rooted in heritage is arousing a growing interest among researchers and designers. It could herald a revival of the “Ishigaki” know-how that has marked Japanese culture for four centuries.

The architectural firm AATISMO, for example, is already integrating these techniques into its projects. Their “Stone Wall” bench[17], made of Ishizumi, perfectly illustrates this emerging trend. This structure, built entirely of dry stone, showcases the creative potential and possibilities offered by traditional Japanese techniques to meet contemporary challenges.

---

[16] *Abundance, Z. =. (2022, December 29). Is stone wall a sustainable architectural choice? Ask traditional Japanese masons. zero = abundance. https://www.interactiongreen.com/japanese-stone-wall/*

[17] *Nakamori, D. (2023, February 7). AATISMO revives traditional dry stone wall construction for this sustainable bench in japan. Designboom | Architecture & Design Magazine. https://www.designboom.com/design/aatismo-traditional-dry-stone-wall-construction-sustainable-bench-japan-02-07-2023/*

CHAPTER 2: EXPLORING VISUAL PROGRAMMING AND PHYSICAL SIMULATION

INTRODUCTION TO THE CHAPTER OVERVIEW:

As introduced at the beginning of this thesis, this chapter, which focuses more on the computational aspect of the research question, is composed of four subsections. Like the previous chapter, these subsections may be further divided into smaller parts if the topics require more detailed exploration.

The first two sections will start by introducing and defining what visual programming is, followed by a discussion of the different approaches taken by other researchers, which, like in this thesis, aim to analyse the behaviour of masonry walls under earthquake conditions.

Given that simulation is a key aspect of this research, the third and fourth subsections will delve into the field of computer simulation. They will define simulation, compare its various uses, and review some of the mathematical principles that underpin it. This will allow for an evaluation and verification of the realism of these simulations, which will be further examined in Chapter 3.

SECTION2.1: VISUAL PROGRAMMING OR PARAMETRIC DESIGN.

A. WHAT CAN IT BRING TO THE DESIGNER AND HOW TO MAKE THIS TOOL ACCESSIBLE?

Although visual programming and parametric design are two concepts often related, it is important to differentiate between them. Visual programming, as defined (Miroliubov, 2018, p.1), *“is a style of programming where the user uses graphical elements, which represent functions, operators, or variables, and usually connects them via lines or arrows, forming relationships. Visual programming languages (VPLs) can be classified into icon, diagram, and form-based languages.”*

As for parametric design according to (de Boissieu, A, 2022, p. 3), it “is based on the design and modelling of parametric systems. A parametric system is a combination of clear rules and constraints in a specific order.“.

Although visual programming in architecture often involves aspects of parametric design, the reverse is not always true. However, the combination of these two concepts can greatly benefit designers, such as AATISMO’s architects, by allowing them to better comprehend, manipulate and appropriate simple simulations performed on their computers.

Indeed, visual programming, (Figure 17)which, thanks to its graphic use, allows programming novices to understand the relationships between the different elements of a program more intuitively than traditional text-based coding languages. This makes simulations with this type of language more accessible and facilitates potentially faster prototyping.

Combined with the parametric design, this offers several notable advantages. This approach provides great flexibility and adaptability, allowing for the creation of easily editable templates. It also ensures accuracy and efficiency through the establishment of clear and precise constraints. Finally, parametric design promotes the automation of repetitive and complex tasks, thus optimising the work of designers.

This approach is similar to that of (Funari & al., 2021), who sought a way to make earthquake-resistant design more accessible through visual programming. This team looked for a way to reduce the computing power needed by using the upper-bound theorem, allowing software such as Grasshopper for Rhino to make the process easier.

Grasshopper, which, as defined (Costantino & al., 2022), “is a plug-in integrated into the Rhinoceros software, developed by Robert McNeel & Associates, USA. This plug-in consists of a programming language for the creation of geometries visualised through the Rhino software.”

By combining these two concepts, designers can leverage the benefits of each, making their projects more accessible, flexible, accurate, and efficient. Thus, by applying these qualities to the research carried out in this thesis, it is possible to better understand the behaviour of Ishigaki walls, with the aim of optimising their conservation and appropriation by architects or designers.

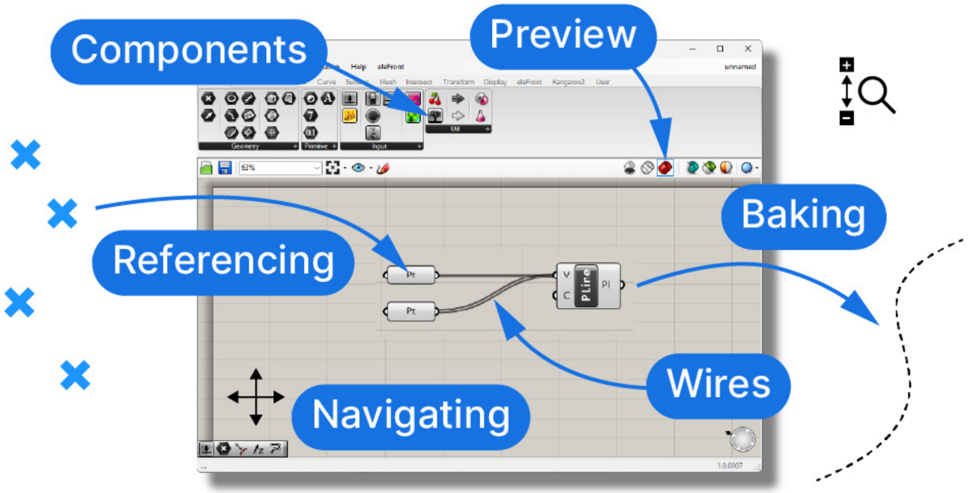


Figure 17: *Image briefly illustrating the Grasshopper interface in Rhinoceros 3D software, by Tait, T. (2024, February 21). Mastering the Grasshopper interface: A Beginner’s guide. Hopific. https://hopific.com/the-grasshopper-interface-a-beginners-guide/*

SECTION2.2: TWO DIFFERENT APPROACHES USED BY RESEARCHERS TO SOLVE THE COMPLEX DESIGN PROBLEM OF EARTHQUAKE-RESISTANT DRY MASONRY.

Thus, we can distinguish two ways to use visual programming to optimise masonry walls against seismic tremors.

The first considers the entire masonry building, which leads to a focus on the structure's overall shape and optimisation of its overall appearance.

The second way is to try to conceive of the masonry building as a superposition of units, which leads to focusing on the geometry of the blocks and, therefore, on the optimisation of the latter.

We will expand on them in the following subsections.

A. Approach 1: Optimisation of the geometry of brick structures for seismic conditions.

The first approach is found in various studies. The master's thesis of (Ding, 2016) can be a first example. This research comes in the wake of the earthquakes in the Groningen region. The author uses visual programming and the "Rhino-Vaults" plug-in to study and propose building geometries that can withstand earthquakes.

Another study, conducted by (Grewal & al., 2019), also uses visual programming in response to a seismic tremor. The authors analyse the propagation of seismic waves in the building using a different methodology than (Ding, 2016). They combine data transmitted by a succession of plug-ins, such as "Quelea", "Culebra", "Karamba", and "Strand",[18] in order to analyse the movement of seismic waves in the structure. The team then uses the data collected to give the building a shape and then check its resistance.

The research of (Sheth & Fida,2020) partially shares the methodology used by (Ding,2016) to design arches of different sizes using the "Rhino Vaults" plug-in. Despite this, their goals being to design the latter in dry masonry, the research turned to the optimal shape of the blocks according to the size of the arch. By this desire, it is therefore closer to the second approach that we develop below.

B. Approach 2: Approach the problem through block geometry.

The second approach, focusing on the design of the blocks, is close to the field of study envisaged in the framework of the research following this work.

Despite the lack of seismic or structural analysis during this study, the research conducted by (Yenice & Park, 2019) on the geometries of stone blocks caught my attention. Inspired by the stone assemblages erected by the Incas on Machu Picchu, the researchers propose mud bricks that can be superimposed without mortar and resist earthquakes.

This document also allowed me to discover a project carried out by the studio "Emerging object"[19] which has a similar approach to (Yenice & Park, 2019) (Figure 18), but which differs in their realisation given that the tower in question is made of 3D printed blocks.

Another approach that caught my attention is that of researchers (Goyal & Agarwal, 2017) who, in order to propose anti-seismic constructions adapted to Indian conditions, propose a masonry system composed of blocks of earth interlocked by recycled tyre slats. This wall design gives visco-elastic interlocking allowing the constructions to resist earthquakes.

Figure 18: *Image showing on of the block prototype made by Yenice, Y., & Park, D. (2019b, January 1). V-INCA - designing a smart geometric configuration for dry masonry wall. eCAADe Proceedings. https://doi.org/10.52842/conf.ecaade.2019.2.515*

---

[18] *Programs to add functions to the "Grasshopper" software and self-service on the Food4Rhino website. (n. d.). Food4Rhino. https://www.food4rhino.com/en*

[19] *Quake Column | Emerging Objects. (Ed.). http://emergingobjects.com/project/quake-column/*

SECTION2.3: PHYSICAL SIMULATION BETWEEN SCIENCE AND VIDEO GAMES.

As explained by (Goldsman & al., 2009), modern computer simulation has its roots in the Manhattan Project, it experienced rapid growth between 1945 and 1970 thanks to the creation of the first electronic computers and the application of the Monte Carlo method, which (Ledra & al., 2016) define as a method to calculate a numerical value using random processes, developed by Ulam and von Neumann. In addition, the work of many researchers, such as Geoffrey Gordon, who introduced the General Purpose Simulation System (GPSS) at IBM to simplify the modelling of complex systems, has contributed to this evolution. Simulation programs have continued to develop with the rise of computer science over the years, gradually laying the foundation for today's physics simulations.

According to the (CEA, n.d.), "*numerical simulation refers to the process by which one or more programs are executed on one or more computers in order to represent a physical phenomenon. Scientific numerical simulations are based on the implementation of theoretical models. They are, therefore, an adaptation of mathematical models to the numerical means. They are used to study the functioning and properties of a system and to predict its evolution.*"

The site also explains that numerical simulation was designed primarily for scientific purposes to accurately predict the movements of a specific object of study, the growing access of the general public to ever-increasing computing capabilities has made it possible to democratise these techniques. Used in a simplified form, the mathematical methods used by scientists allow video game players to observe physical behaviours in real-time and understand their interaction with the environment. Used his "simplified methods" to allow video game engines to display faster simulations at the cost of lower accuracy.

Thus, we can distinguish two main uses of physical simulation today:

1. ***Scientific simulators:*** Designed for research, they focus on precision and fidelity to the laws of physics, often requiring significant computing resources.
2. ***Physics Engines for Video Games:*** Optimised for real-time performance and interactivity, they prioritise smoothness, visual realism and stability, sometimes at the expense of absolute physical precision.

To gain a deeper understanding of how these programs are designed and how they simulate physics, it is important to grasp the different mathematical methods used to achieve this. This will subsequently allow us to understand the foundations of these programs and the complexity that lies behind the approaches presented in the following chapter. This mathematical exploration will also help later in the researche to verify the simulated models to better understand certain errors they might produce.

A. SCIENTIFIC SIMULATION AND ITS DIFFERENT METHODS.

To reduce the complexity of problems, whether in science or in the field of construction, many simulation methods have been developed. These techniques make it possible to obtain precise simulations, with a certain amount of computational time, depending on the tools available. In architecture and civil engineering, different methods are used. Here are three examples of methods among many others:

1. ***Finite element methods (FEM):*** which (Logan, 2007) defines as follows "*The finite element method (FEM) is a numerical method for solving problems in engineering and mathematical physics. [...] It divides a complex system into smaller interconnected elements (finite elements)*". As described in the paper, this process, called discretisation, enables the modelling of complex geometries, loads, and material properties, simulating their behaviour under various conditions. As described in the paper, this process, called discretisation, enables the modelling of complex geometries, loads, and material properties, simulating their behaviour under various conditions. As described in the paper, discretisation provides simulations that are particularly effective for structural analysis and heat transfer.
2. ***Computational fluid dynamics (CFD):*** Another approach to simulation, based on individual particles, is explained (Bouhela & Arezki, 2022) in their presentation. Computational fluid dynamics is the science of predicting fluid flow characteristics, heat transfer, mass transfer, and chemical reactions. This discipline applies to various fields such as aerodynamics, hydrodynamics, combustion, and sports. It allows researchers to perform simulations that are sometimes impossible to conduct in the laboratory, and at a reduced cost compared to experimental measurements.
3. ***Discrete element analysis (DEM):*** This approach, in turn, is a mix of the two previous methods. As defined (Bićanić, 2004), this simulation includes "*different techniques suitable for simulating the dynamic behaviour of systems composed of multiple rigid bodies, simply deformable (pseudo-rigid) or fully deformable, of simplified or arbitrary shapes, subjected to continuous changes in contact status and variable contact forces, which in turn influence the subsequent movement of bodies*". To illustrate this definition, this method is particularly suitable for simulating bodies composed of many particles, making it particularly useful for simulating soil erosion or the stability of a slope.

In conclusion, these methods significantly reduce the time needed to solve complex problems in science and construction through their precision. Although they require time, computing power, and advanced knowledge, they enable researchers and architects to improve their work and gain a deeper understanding of their projects. But are, at this cost, less accessible to people having limited access to the three previous.

B. PHYSICS SIMULATION IN VIDEO GAMES.

As explained above, simulations for video games have a high computing speed as their main objective. They aim to optimise scientific methods in order to offer simplified calculations allowing a coherent simulation in real time. To do this, video game developers use specialised “physics engines” that (Valencia-García & al.,2016) define as physics simulation programs that “include support programs, libraries, and interpreted language, among others, to help develop and unite different parts of a project.”

And as we can read in the book of (Millington, 2010), these simulators use a particular vocabulary that defines very precise intersections and simulations but we can highlight 2 main families:

PARTICLE SIMULATION: Particle simulations typically model for sets of individual particles, each with its own position, velocity, and mass. This method is ideal for simulating fluids, granular materials, or clothing. Although they allow for a certain precision, they are very demanding in terms of calculation, especially for a great number of particles, and the management of interactions can become complex.

RIGID BODY SIMULATION: Non-deformable entities, ideal for realistic movements and interactions between solid objects, allow for high computational efficiency, allowing many objects to be managed with less expensive calculations. However, they cannot model deformations or fractures and are less accurate for small-scale interactions or fluid phenomena.

These two families of methods are utilised in various physics engines used in today’s video games. Each physics engine then uses its own techniques and strategies to accelerate these physical simulations. These differences can be demonstrated by the variation in performance between different physics engines, as explained by (Erez & al.,2015) through these two examples:

PHYSX: Developed by NVIDIA, PhysX is a physics engine widely used in video games (Figure 19). It’s designed to provide optimal performance and stability, making it ideal for gaming. However, to achieve this stability, PhysX compromises on physical accuracy. For example, researchers have found that it ignores Coriolis forces, meaning it can’t always faithfully simulate certain types of motion.

*HAVOK :*Another popular physics engine in the video game industry. Like PhysX, it also ignores Coriolis forces, which can reduce its accuracy for some simulations. In addition, in the researchers’ tests, it did not support planar geometries natively, requiring workarounds to create floor surfaces. Despite this, Havok is well-known for its stability optimisations, making it a great choice for video games where performance is more important than exact physical accuracy.

This preliminary understanding of the use of a physics simulator and its applications in various fields now allows us to address the fundamental mathematical foundations on which the simple physics simulators employed in this research are based.

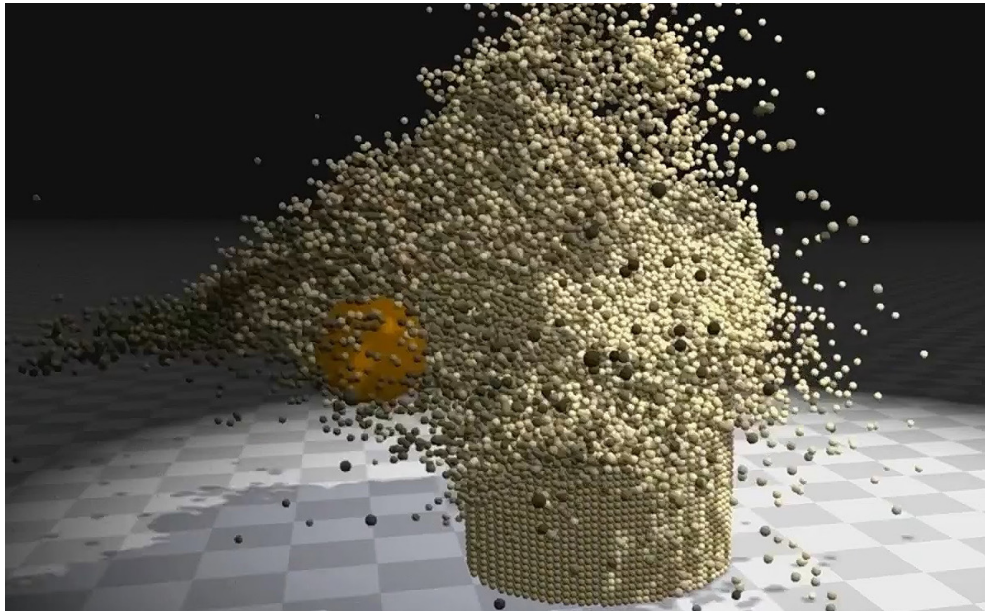


Figure 19: *Image showing “physic engine “ as PhysX simulate colision in video game. Image from Papadopoulos, J. (2014, December 12). New NVIDIA video shows off GameWorks PhysX FleX features. DSOGaming. https://www.dsogaming.com/videotrailer-news/new-nvidia-video-shows-off-gameworks-physx-flex-features/*

SECTION2.4: MATHEMATICAL BASIS USE TO CALCULATE THE PHYSICAL BEHAVIOUR OF A WALL, ISHIGAKI DURING AN EARTHQUAKE.

This thesis aims to create a tool capable of simulating in a semi-realistic way the behaviour of the blocks composing an “Ishigaki” type wall using visual programming. To achieve this goal, a thorough understanding of the physical principles governing this type of simulation is essential. Thus, the explanations that follow will allow us to understand the calculations that will be included in this thesis in order to verify and simulate the oscillatory movements of granite blocks during an earthquake.

For the sake of progressiveness, we will base ourselves on the explanations of the book written by (柴田[Akinori], 2014) and the book of (Millington, 2010). This will allow us to develop a simplified model by considering each block as a mass undergoing a simple harmonic motion during a seismic tremor. This model will then be refined by incorporating more parameters and degrees of freedom for a more realistic simulation.

A. Motion in Space and the First Two Newtown Laws.

1. Important concepts :

Understanding the movement of objects in space is fundamental to analysing the behaviour of physical systems. Based on the book of (Walker & Resnick, 2018) we will try to explain the concepts discussed in this section and then explain Newtown’s two laws.

- ***Velocity:*** Simply put, velocity describes how fast an object is moving and in what direction. This distinction is essential in physics, as it allows us to understand the speed of a movement and its orientation in space.
- ***Speed:*** An object’s speed is the rate at which its position changes with respect to time. In opposition to velocity, speed doesn’t have a direction. It is usually measured in meters per second (m/s).
- ***Acceleration:*** The acceleration of an object is the rate of change in its speed with respect to time. It shows how the velocity changes over times. It is measured in meters per square second (m/s^2). Positive acceleration indicates an increase in speed, while negative acceleration indicates a decrease in speed (deceleration).

2. Newton’s First Law :

Newton’s first law states that an object at rest remains at rest, and an object in motion continues to move at a constant speed in a straight line, unless an external force is applied to it. In other words, an object resists changes in its state of motion. This resistance to change is called inertia. Take, for example, a ball placed on a table that remains motionless because no horizontal force is exerted on it. If you push the ball, you apply an external force that sets it in motion.

3. Newton’s second law :

Newton’s second law quantifies the relationship between the force applied to an object and its acceleration. It states that the net force acting on an object is equal to the product of its mass and acceleration:

$$\boldsymbol{F} = \boldsymbol{m} \times \boldsymbol{a}$$

- $\boldsymbol{F}$ is the net force (in N)
- $\boldsymbol{m}$ is the mass of the object (in kg)
- $\boldsymbol{a}$ is the acceleration of the object (in m/s^2)

To illustrate this formula, imagine that if you push a 10 kg ball with a force of 20 N then your ball will accelerate to 2 m/s^2 (20 N/10 kg = 2 m/s^2) due to the force you applied on it.

B. HOOKE'S LAWS AND RELATION IN SPACE.

Hooke'se law describes the relationship between the force applied to an elastic material and the resulting deformation. It states that the deformation of an elastic material is directly proportional to the force applied, as long as the strength of the material is not exceeded.

Mathematically, Hooke's law is expressed by the following formula:

$$F = k \times x$$

- F is the applied force (in Newtons, N)
- k is the stiffness constant of the material (in Newtons per meter, N/m)
- x is the deformation of the material (in meters, m)

The negative sign indicates that the elastic restoring force opposes the deformation.

To illustrate this concept, imagine a sphere made of soft rubber. When you press the sphere with your finger, you apply a force (F) that distorts it (x). Hooke's Law states that the harder you press, the more the sphere deforms.

The stiffness constant (k) of the rubber determines the sphere's resistance to deformation. A stiffer rubber will have a higher stiffness constant, meaning it will require more force to deform.

When you remove your finger, the elastic restoring force (F) returns the sphere to its original shape, as long as the deformation has not exceeded the rubber's elastic limit. If you press too hard, the sphere can be permanently warped.

This law is fundamental to understanding the behaviour of elastic materials and has many applications in physics and engineering. For example, it is used to calculate the force exerted by a compressed or stretched spring and to analyse the deformation of structures under load.

These basic laws of physics form the foundation for delving into more complex calculations and concepts in the next chapter and in this master's thesis research.

C. EARTHQUAKE SIMULATION AND HARMONIC MOTION.

1. SIMPLE HARMONIC MOTION: A FIRST APPROACH.

Based on the knowledge of the previous chapter, we will illustrate the concept that will be used during this chapter by studying the movement of a mass attached to a spring. Although simplified, this model makes it possible to understand the fundamental concepts of oscillation and to lay the foundations of a simulation that is closer to reality but also more complex.

In this first step, we make some assumptions to simplify the calculation. The mass is, therefore, only back and forth, creating a system with a single degree of freedom. We ignore the effects of gravity, damping, and friction.

For the time being, we are only interested in the oscillation of the mass over time under the influence of the spring, which compresses and relaxes indefinitely without being stressed.

This simple model is based on Newton's second law (F=ma), or **Force (F) = Mass (m) x Acceleration (a)** which establishes a relationship between the force applied to an object, its mass, and the resulting accelerations...

Having established this correlation, we can formulate the following equation $mx'' + kx = 0$ which can also be written $ma + kx = 0$, which now considers the hard spring force represented by (kx). As seen in Hooke's law laws, K expresses the stiffness of an object, as in this case, the stiffness of the spring expressed in Newtons per meter (N/m) and x is the position of the mass in relation to its equilibrium position expressed in meters. (m).

Since we are interested in the position of mass through time, the solution of the equation **$ma+kx=0$** is a sinusoidal function **that takes the following form:**

$$x(t) = A \sin(\sqrt{k/m}\, t + \phi)$$

This will allow us to determine the coordinates of the points and draw the oscillation of mass over time. Thus, although abrupt at first glance, the formula can be translated as such:

- **$x(t)$:** the position of the mass at time t.
- **A:** amplitude of the oscillation (maximum displacement).
- **sin():** a sine function, which describes the oscillatory nature of motion.
- **$\sqrt{k/m}$:** angular frequency (ω) of the system, which determines the speed of oscillations.
- **t:** time.
- **ϕ:** phase constant, which determines the initial position of the mass.

This first step, based on the rudimentary model of simple harmonic motion, allows us to understand the fundamental factors that govern the behaviour of a mass-spring system. This knowledge will be essential to approach the next step, where we will integrate additional factors, such as damping and external forces, to arrive at a more realistic simulation and a more complex equation of motion.

2. Simple harmonic movement with damping: a complementary approach.

In reality, a freely vibrating mass does not do so indefinitely, because the initial energy that caused the movement of the spring dissipates over time. This results in the oscillation of the mass gradually decreasing in amplitude and finally stopping completely. This energy loss is called damping and must be integrated into the formula seen above $ma+kx=0$ giving it the form $mx'' + cx' + kx = 0$.

Even though it is based on the formula seen before, it can be useful to examine the meaning of its components to understand it better.:

mx'': represents the inertial force.

- ***m*** is the mass of the object (kg).
- ***x''*** previously denoted a is the acceleration of the object (m/s^2).
- ***mx''*** has the Newton (N) as a unit, because 1N = 1 kg × m/s^2.

cx' **: represents the damping force.**

- ***c*** is the damping coefficient (N s/m).
- ***x'*** is the speed of the object (m/s).
- ***cx'*** also has the Newton (N) as its unit.

kx: represents the force of the spring.

- ***k*** is the spring's return constant (N/m).
- ***x*** is the displacement of the object relative to its equilibrium position (m).
- ***kx*** has the Newton (N) as its unit.

The new variable introduced in this formula, damping (c) can result from various factors such as material properties or friction.

To simplify the calculations, these different types of damping are combined under the term “viscous damping”. Often represented by a piston that moves in a cylinder filled with liquid. Each time the plunger moves, a force will act to oppose its movement, much like the resistance you feel when you push an object through honey. Thus, the damping coefficient defined by the total amount of damping taken into account represents the “thickness” of the fluid included in the piston.

So depending on the total amount of depreciation, the way to solve this equation will be different. This is because if the system is under-damped, meaning that the damping is relatively total is less than 1, it will oscillate, and the amplitude of each oscillation will decrease until it stops like a pendulum that swings from side to side, gradually losing energy until it comes to a standstill.

If the damping is stronger, any wobble will be entirely suppressed by the damping, creating an over-damping system. As if, using the analogy of the pendulum, the pendulum no longer evolves in the air, but in the water.

Finally, a critically damped system is an extreme case of the under-dumped phenomenon explained before that have enough damping to suppress vibrations without wobbles. In this case, if considered, you catch the pendulum in the middle of its course, stopping it abruptly.

In each of these cases, a different function defines the displacement of the system, obtained by solving the equation of motion. These functions describe how the position of the mass changes over time, taking into account the damping effect. Nevertheless, in order not to weigh down this already heavy and unfamiliar part, these formulas will not be described in this part of the brief.

In practice, determining the damping coefficient requires laboratory experiments. However, due to a lack of time and resources, the coefficients used in this thesis will be based on the results of study carried out by other researchers.

3. Simple harmonic motion with damping and multiple levels of freedom: a final approach.

Designing earthquake-resistant structures is a complex task due to seismic tremor unpredictability. To ensure buildings' stability against seismic forces, engineers must use techniques that allow them to understand each floor's dynamic behaviour.

Although more complex calculations have not been performed in this thesis due to a lack of the necessary foundational knowledge, it is essential to understand the underlying principles to better grasp the limitations of the single-degree-of-freedom models presented so far. These models can only explain the movement of a uniform mass subjected to shaking, without accounting for the interactions between different parts of the structure.

To model the motion of a multi-story building more realistically, each floor can be imagined as a mass connected to the others by springs, each with its own stiffness (k). By complicating the model in this way, relationships are created between the different masses, allowing for the simulation of the movements of each floor based on its interactions with the others.

As explained in Shibata's book (柴田[Akinori], 2014, pp. 53–57), matrix calculations[20] , can be used to account for these interactions between the floors. These calculations enable the effects of each equation of motion on the others to be integrated, thus providing more precise modelling of the overall dynamics of the structure.

In theory, it is therefore possible to calculate the interactions between the floors of a large building, with each floor adding an additional degree of freedom. However, as the number of degrees of freedom increases, the system becomes increasingly complex.

To manage this growing intricacy, engineers can use numerical techniques, such as the finite element method, which have been introduced in the previous section. These techniques help simulate and determine the movements of the floors relative to each other, providing an overall view of the building's behaviour under different scenarios.

---

[20] *The web site (Intro to Matrices (Article) | Matrices | Khan Academy, n.d.) provides a clear, easy-to-understand definition of matrices. It defines a matrix as «a rectangular arrangement of numbers into rows and columns». This basic definition let us understand the arrangement of a matrix is an array of numbers or in our case of formula, structured to facilitate mathematical calculation and analysis.*

CHAPTER 3: METHODOLOGY AND CORPUS.

INTRODUCTION TO THE CHAPTER OVERVIEW:

As explained in the introduction to this dissertation, this chapter builds on the knowledge gained in the last two chapters to begin a research process aimed at answering the following question: “How can a visual programming tool be used to simulate the behaviour of Ishigaki walls during earthquakes?”

This chapter will begin by presenting the methodology put in place to frame the research carried out as part of this dissertation.

This section, constituting the corpus of this dissertation, will be organised into three main stages: firstly, the beginnings of the research will be outlined, followed by the identification of the limitations and possibilities of the tools used during this research. Finally, the initial exploration phase aimed at creating more specialised tools for this research will be presented.

The eleven phases of the research will be presented chronologically. For each stage, the objectives will be detailed, the actions taken to achieve them will be described, and the conclusions drawn from each phase will be discussed in order to prepare the next stages of the research.

METHODOLOGY:

This research chapter outlines the work conducted between October 2023 and July 2024. As explained in the introduction, the primary objective was to create software to optimise the geometry of Ishigaki wall blocks to enhance their seismic resistance, thereby contributing to the preservation of Japanese heritage. However, due to my lack of knowledge about what the creation of such a program entails, I redirected my efforts toward establishing the necessary foundations for the future development of this software.

Therefore, the following methodology aims to address the question posed at the beginning of this thesis: “How can a visual programming tool be used to simulate the behaviour of Ishigaki walls during seismic events?”

The motivation behind this question stems from the desire to preserve Japan’s architectural heritage, which is at risk from the major earthquakes that frequently strike the archipelago. The goal is to provide designers and craftsmen with a simulation tool based on a user-friendly interface, such as visual programming, to assist them in this task (Funari & al., 2021, p.3) .

To achieve this objective, this research draws upon the state-of-the-art presented in the previous two chapters, as well as the guidance of the professors who supervised this research.

Given my very limited background in traditional Japanese architecture and virtual simulation, the methodology chosen for this thesis is a project-based learning approach. This approach allowed me to address my knowledge gaps through close supervision by my professors. To mitigate the irregular pace that this approach can cause, bi-weekly meetings were established to ensure steady progress and to structure my research pace.

To address the theoretical gaps identified at the beginning of this thesis, an experimental approach was adopted, relying on empirical tests. The goal was to conduct research based on the observation of phenomena at each stage, in order to explore, adapt, and refine the research according to the results obtained in previous phases.

Thus, the methodology applied in this thesis can be considered similar to that described by (Yenice & Park, 2019) in their study on the geometry of earthquake-resistant blocks, and by (Ding, 2016), who explored the capabilities and limitations of Grasshopper under the supervision of his professors, even though his goal was to improve the resistance of a structure by modifying its overall shape.

This methodology has allowed me to acquire the basic concepts used to conduct this research through exercises supervised by my professors, enabling it to reach its current state

SECTION 3.1: DEVELOPMENT OF A CODE ALLOWING THE SIMULATION OF AN “ISHIGAKI” WALL.

A. Subsection 3.1.1: First stage in research to simulate the behaviour of a wall.

INTRODUCTION TO THE FIRST STAGE OF RESEARCH.

During this step, the main objective was to understand two important aspects of this simulation. First, it was require to digest the basic physical principles that guide a computational physics simulator. Secondly, it was essential to comprehend the movements of an earthquake and to transcribe them using Grasshopper. To achieve these objectives, two exercises were carried out. The goal was to help me understand the fundamentals of simulation and the mathematics necessary for this thesis. The first involved a double pendulum, and the second a platform whose frequency and amplitude could be determined.

The double pendulum consists of two pendulums attached end to end by a spring between them. This configuration allows us to comprehend the interactions between two masses and the chaotic movements they can generate. By adding a spring connecting the pendulums, it is possible to understand a potential elastic interaction between the masses.

Regarding the creation of the platform, this exercise made it feasible to reproduce the seismic conditions in the form of a controllable simulation. It was used to experiment diverse methods of motion generation through Grasshopper. This laid the groundwork for building a realistic earthquake simulation and creating a basic program to test the future simulation under different frequencies. This process also highlighted the limitations of the software and the various plugins that will be tested later.

These two exercises made it possible to mobilise and grasp the principles explained in the state-of-the-art and favoured the development of simplified simulations. These fundamental exercises will pave the way for more complex simulations that will increasingly mimic the complex principles described in the state-of-the-art.

STAGE 1: FIRST STAGE OF THE RESEARCH - CREATION OF A DOUBLE PENDULUM. (04/11/2023 TO 10/12/2023):

INTRODUCTION:

As indicated above, the first stage of this investigation involves understanding the movements of the future blocks of the simulated Ishigaki wall through the double pendulum simulation exercise. This experiment, by simulating the interaction between modelled masses, aided us to comprehend the interactions between dry masonry blocks during an earthquake.

Additionally, as mentioned previously, attaching a spring between the pendulums helps to illustrate the importance of spring stiffness in our future simulation. Then, the knowledge gained through this stage of the research will be beneficial for understanding and then demonstrating how energy dissipation occurs within the Ishigaki wall during an earthquake.

This simulation aims to begin exploring the implications of the ”equations of motion” based on the formulas presented in section 2.4 of this thesis. By applying these formulas to the simple case of the double pendulum, I could start to comprehend the application of the mathematical equations discussed in the state-of-the-art, such as the harmonic equation $mx'' + cx' + kx = 0$ and its variables. Here, m represents the mass, c the damping between the two solids in contact, and k the spring force between the two pendulums.

To create this simple model, the integrated physics simulator in Grasshopper, called Kangaroo (Piker, 2013), was used, as I had prior experience with it. Moreover, this plugin can easily simulate simple interactive physical systems. Kangaroo facilitates an intuitive understanding of the interactions between the various variables and forces at play. It allows for real-time visualisation and manipulation of forces, providing a practical overview of the system’s dynamic behaviours.

STEPS COMPLETED :

Thus, the method implemented can be described as follows:

1. ***Creating the Pendulums:*** Two solids represented as cubes were created and placed side by side. These cubes serve as the masses of the pendulums in the simulation.

2. ***Center Point Positioning:*** Points were placed at the centre of each cube to serve as references and to connect the masses to their future support. These central points are crucial for the modelling process and then analysis that will be conducted during this exercise.

3. ***Placement of the Upper Points:*** Two points were added with the same x and y coordinates as those created in the previous step, but with higher z coordinates. These points will be used in the next step of this research.

4. ***Creating the Strings:*** Using these new points along with those established in step 2, two strings were created, allowing us to leverage Kangaroo's elasticity capabilities. The strings act as connectors between the pivot points (created in the previous step) and the masses, enabling pendulum-like motion.

5. ***Adding Elastic Force*:** Introducing a spring to act as an elastic force between the pendulums allows us to understand how adjusting the damping between the two volumes affects their motion. By increasing the damping, we observe that the volumes come to a stop more quickly.

6. ***Application of Gravity:*** A force of gravity was added to induce the movement of the pendulums, as it is essential to simulate the natural swinging motion of the pendulums.

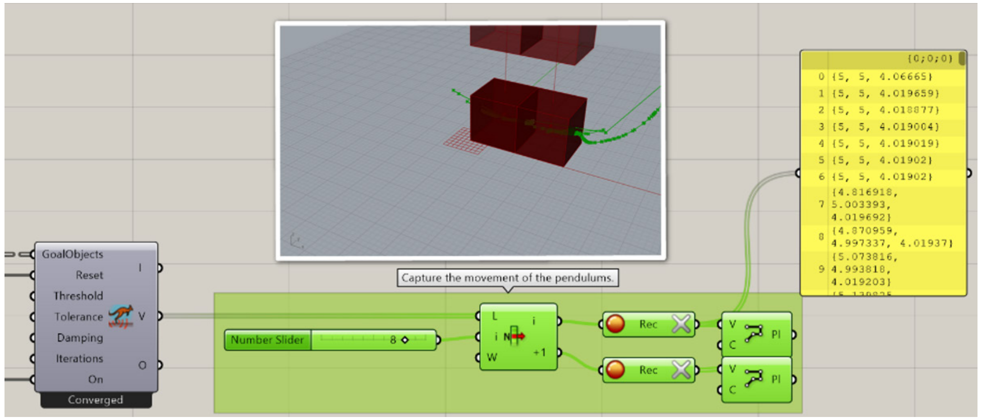
7. ***Interaction Management:*** In the Grasshopper design chain, each s was kept accessible through sliders, allowing to easily manage the interactions between the pendulums, as contacts, of the stiffness of the spring. This setup enables us to adjust these variables and observe how they influence the behaviour of the pendulums.

8. ***Simulation with the Solver:*** In Grasshopper, to perform a simulation, it is usually necessary to connect the created chain to a solver. The solver is a calculation tool that generates simulations. In our case, we connect the solver to our chain to create a pendulum motion simulation.

9. ***Motion Tracing:*** The movement of the pendulums was recorded to create a curve, helping us to track and visualise the differences in behaviour during experimentation, as shown in (Figure 20).

DISCUSSION AND CONCLUSION:

This basic double pendulum simulation, as you see in (Figure 20) has laid the foundation for future simulations and provided us with a fundamental understanding of the challenges in modelling the behaviour of an "Ishigaki" wall under earthquake conditions. This initial phase has enabled us to grasp the first principles of simulating chaotic behaviour, which mimics the complex interactions between the blocks of a dry-stone masonry wall. This exercise paves the way for developing more sophisticated models and deepening our comprehension of the variables involved. Moreover, this stage has highlighted both the strengths and limitations of simulation tools like Kangaroo in Grasshopper, underscoring the need to explore more advanced simulation techniques in future research.



```
                  {0;0;0}
0 {5, 5, 4.06665}
1 {5, 5, 4.019659}
2 {5, 5, 4.018877}
3 {5, 5, 4.019004}
4 {5, 5, 4.019019}
5 {5, 5, 4.01902}
6 {5, 5, 4.01902}
  {4.816918,
7 5.003393,
  4.019692}
8 {4.870959,
  4.997337, 4.01937}
  {5.073816,
9 4.993818,
  4.019203}
```

Figure 20: *Picture showing the final step of the double pendulum using Kangaroos and a chain to record its movement [Original Image©].*

STAGE 2:DEVELOPMENT OF A PROGRAM TO SIMULATE A CONSTANT OSCILLATION (11/12/2023 TO 05/01/2024)

INTRODUCTION:

After completing the initial stage of research, the second stage will focus on creating a highly simplified earthquake simulation using Grasshopper. The primary objective of this exercise is to develop a cyclical movement that can mimic earthquake vibration.

To create this simulation, it is essential to understand the mechanics of an earthquake and reference the different waves that compose it, as discussed in section1.2. It's important to think about how to simulate the complex movement of every type of wave covered in the literature review. Indeed, as discussed earlier, each wave has its own behaviour: P-waves involve compression and expansion movements, S-waves create transverse motion in the ground, Love waves move with a left-to-right motion, and Rayleigh waves exhibit a complex movement combining longitudinal and transverse motions within an elliptical path.

Given the complexity of these movements, it has been decided to create a simplified simulation that produces oscillations along the X, Y, and Z axes. This straightforward simulation method allows a platform to move along all axes while controlling the frequency of each, reflecting simplified characteristics of the four types of waves mentioned earlier. By adjusting the intensity of these movements, the various earthquake scenarios can be explored.

This simulation were carried out using resources like the (McNeel Forum, n.d) and explanatory videos to overcome technical challenges with Grasshopper and ensure a better understanding of this kind of simulation. These resources provided valuable insights and solutions, helping me comprehend the software's complexities and improve my simulation techniques.

This initial stage is expected to facilitate the comprehension of how to simulate more complex scenarios in the future and establish a foundation for future tests. By mastering the basics of earthquake simulation, I will progressively tackle more intricate models that incorporate additional variables and complexities.

STEPS COMPLETED :

Then the method pursued during this exercise can be summarised as follows:

1. ***Create a surface representing the ground during an earthquake:*** Start by creating a surface that simulates the behaviour of the ground during an earthquake.

2. ***Divide the surface into multiple points:*** Dividing this surface into a grid of points will allow you to control the shape of the surface later in the simulation.

3. ***Create a flat surface:*** For this, we base our work on the tutorial by (Daniel Christev, 2016), which introduces a movable attraction point on the surface. This point allows the created points to move away from it, creating the impression of a wave. However, in our case, wanting to maintain a flat surface for our next simulations, we multiply by 0 the values that would allow the oscillation of the surface

4. ***Create an interactive timer:*** To simulate motion, you need to create a countdown timer that controls the speed of the movement. Since the version of Rhinoceros 3d version 8, that we were using does not natively support the creation of timers, we have translated into the Python programming language the component developed by (Oster, 2020) from the (McNeel Forum, n.d). This component allows you to adjust the countdown speed, which will control the frequency of movements and the intensity of the simulated earthquake.

5. ***Simulate wave propagation:*** To simulate the motion of waves through the ground, we establish a cyclic oscillation employing two distinct formulas, based on the tutorial by (Daniel Christev, 2016). The first formula generates a cycle that returns to zero after a certain time interval, thus simulating the repetition of seismic waves. The second formula is a sine function that creates the actual oscillation, representing the undulatory movement of the ground during an earthquake.

6. ***Create a cycle:*** Still following the tutorial by (Daniel Christev, 2016), we convert the countdown from the "interactive timer" developed earlier using the formula $2\pi(yx \% y)$. ***x*** represents the passage of time, modulated by the "interactive timer".

- ***y*** represents the maximum value interval after which a return to zero happens.
- ***yx*** represents the multiplication of the two input values.
- The modulo (% y) applied to ***yx*** always results in a value between 0 and ***1***, thus producing a repetitive cycle.
- The factor 2π converts this result into an angular value. By determining **y**, the frequency of the cycle is set, and this cycle occurs more or less quickly depending on ***x***.

7. ***Create an oscillation using the formula (Asin(x + y)):*** To create an oscillation of the surface symbolising the ground , we use the sine formula Asin(x + y) , which we link to the various parts created earlier. Here's how to understand it:

- ***A*** represents the amplitude of the oscillation .
- ***x***, connected to the flat surface we created earlier, allows it to integrate the oscillation that our component produce.
- ***y*** is connected to the previous equation, allowing the creation of a cycle. By receiving this data, we can create an oscillatory movement.

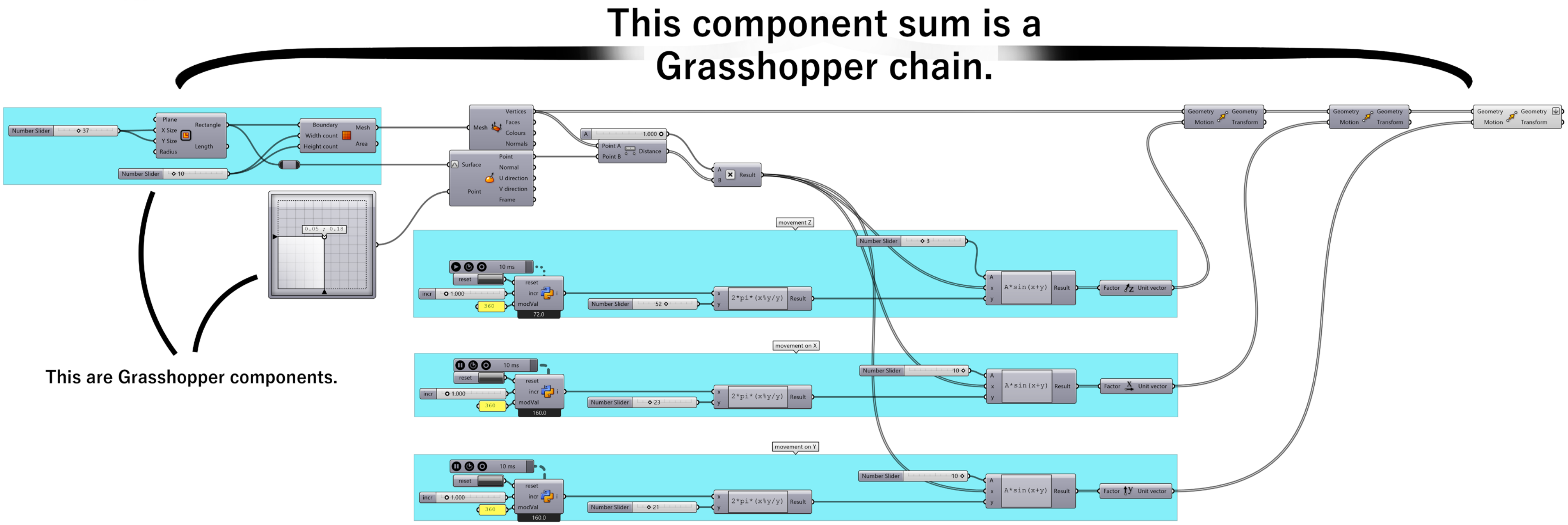
8. ***A vector and a movement:*** To produce a motion in Grasshopper, we attach the chain to a Grasshopper component, producing a vector, and then to another component, generating a movement.

9. ***Complexification:*** By duplicating this chain several times and connecting them at their Grasshopper movement components, it allows us to create movements in multiple directions. In our case, we have created a platform oscillating on the X, Y, and Z vectors.

DISCUSSION AND CONCLUSION:

To conclude, this second stage of research was an interesting first step into earthquake simulation, because the changes faced helped me understand how to simulate earthquakes in Grasshopper. As a novice in mathematics, resources like the (McNeel Forum, n.d) and explanatory videos were essential for overcoming technical challenges with Grasshopper and ensuring the simulation's accuracy and effectiveness. However, even though these resources helped me develop the Grasshopper chain presented in (Figure 21), it was important to comprehend the significance of each formula and its use to improve this chain and produce more realistic simulations. This phase also forced me to learn a little about programming to understand the components made by (Oster, 2020) to make my own.

Completing this second stage of research, which focused on the creation of a basic simulation of a seismic tremor, will facilitate our comprehension of how to simulate more elaborate scenarios in the future while establishing the foundation for future tests and more complex simulations.


This component sum is a Grasshopper chain.

This are Grasshopper components.

Figure 21: *Image showing the grasshopper shain made during this satge of research for simulating earth queake[Original Image ©].*

B. Possibility and Limitation of Visual Programming to Simulate an Earthquake Based on the Discovery of the Flex Hopper Plug-in.

STAGE 3: SETTING CRITERIA FOR EVALUATING VISUAL PROGRAMMING PLUG-INS AND SOFTWARE IN THE STATE-THE-ART FOR EARTHQUAKE SIMULATION.

INTRODUCTION:

Having established a fundamental understanding of earthquake simulation through the preliminary research stage, this phase will focus on exploring other visual programming techniques used by researchers, as outlined in the state-of-the-art. The primary objective is to assess the possibility and constraints of these tools in simulating the structural behaviour of traditional Ishigaki walls, as mentioned at the outset of this thesis. This involves investigating whether the methods used by researchers, highlighted in the state-of-the-art, can be effectively adapted and applied to our specific goals. The aim is to evaluate the potential and limitations of the software and plug-in they employed for simulating the structural behaviour of their case studies.

Indeed, as other academics have explored, visual programming environments possess some capabilities for simulating physics. Plug-ins developed by researchers can simulate particle trajectories or optimise shapes. When utilised correctly, as the researchers mentioned in section 2.2 of this thesis have done, these tools allow for intuitive manipulation of parameters and provide real-time feedback for the case study examined in Grasshopper.

However, even if, in their cases, the strategies applied were appropriate for the purpose of this phase, it remains essential to assess their suitability for accurately modelling the dynamic interactions and material behaviours inherent to our case. Thus, the various plugins discussed in the literature will be tested to explore their capabilities and uses in Grasshopper. These numerous tests will help us understand the strengths and limitations of each plugin and better comprehend the approaches of different researchers. Moreover, it will aid in clarifying the objectives of this research and the methods we wish to employ for developing the future simulation of this thesis. This will enable us to make an informed choice about the plugin that will be used during this project.

Nevertheless, it is already possible to establish some criteria for evaluation based on what we have learned in the previous stage using Kangaroo to create the double pendulum and the simplified earthquake simulation. In the context of our research, we need to ensure our simulation meets the following criteria:

1. ***Collision Management:*** As outlined in the initial stage of our study, it is crucial to have a simulator capable of accurately simulating collisions between multiple geometries. Ideally, it should efficiently handle a multitude of collisions in a non-static configuration; as our plan is to simulate the interactions between many blocks, it's important that we can reproduce in a bigger scale the experiment of the double pendulum.

2. ***Real-Time Visualization:*** As observed in the initial phase of the research with the double pendulum, it is more intuitive to visualise the consequences of actions while manipulating different variables. This capability allows users to instantly observe interactions and movements, facilitating a more comprehensive understanding.

3. ***Parametric Flexibility:*** The simulation must offer flexibility to easily modify parameters, allowing for the exploration of different scenarios and the ability to adapt and correct the simulation if needed or to explore different scenarios. This helps to test various hypotheses and optimise the simulations.

4. ***Full Parameterization:*** For future research that may require more advanced automated simulations, it has been decided that geometries will only be created through visual programming. Any step that involves modelling a shape manually will, therefore, be discarded.

STEPS COMPLETED :

After explaining these criteria, we test the following five plug-ins to determine whether they meet them: RhinoVault, Quelea, Culebra, Karamba, and Strand7.

1. RhinoVault

The first version of RhinoVault developed by (Rippmann, 2022) as it has been mentioned section 2.2, have been employed by (Ding, 2016) and (Sheth & Fida, 2020). However, this version is no longer compatible with version 8 of Rhinoceros 3D, driving us to test the capacity of this plug-in by using its successor, RhinoVAULT 2, developed this time by (Block Research Group, 2024).

This plugin is designed to create and optimise funicular structures. Its main objective is to optimise the geometry submitted by the user to achieve funicular forms.

Nevertheless, despite offering real-time simulation and some flexibility, RhinoVAULT 2 does not fully meet our criteria. Specifically, it treats geometry as a single entity and does not incorporate collision management between multiple geometries, which is essential for our research. Since the primary goal of this thesis is different from the capabilities provided by RhinoVAULT 2, this plugin has been discarded from further manipulation in this research.

2. Quelea

Used by (Grewal & al., 2019), this physics simulation plugin developed by (lxfschr, 2022), allows for the simple analysis of the motion of a lot of particles within a space or geometry. Often utilised for simulating crowds or swarms, this component offers real-time visualisation and a certain degree of flexibility. However, during the tests, it was observed that although particles can interact with a specified surface or geometry, they do not collide with each other. Given that the aim of this simulation is to model collisions between geometries, this plugin has been deemed unsuitable and will not be used in this research.

3. Culebra.NET

Also used by (Grewal & al., 2019), Culebra.NET made by (Quinones, 2022) is designed to integrate particle simulations into Grasshopper. Similar in some ways to the software we have previously discussed, Culebra.NET uses particles to create and manipulate trajectories and flows, enabling the simulation of complex and dynamic motions in a parametric design environment by interacting with specific surfaces or geometries. However, like Quelea, the particles in Culebra.NET do not seem to interact with each other, indicating that collisions between them are not taken into account. Despite offering real-time visualisation, a good parametric flexibility and a possible capability for full automatisation, similar to the previous plugin, Culebra.NET has been deemed unsuitable for this research.

4. Karamba

Another software used by (Grewal & al., 2019), Karamba3D is developed by the enterprise of the same name (Karamba, 2024). This tool is designed for real-time physical simulations of complex structures, such as buildings, and is highly suitable for civil engineering applications. Karamba3D allows for the real-time visualisation of stresses applied to slabs, columns, and beams.

Similar in some aspects to RhinoVault2, Karamba3D enables the creation of complex simulations involving different geometries by applying forces and constraints to each and visualising the consequences in real-time. However, like the other plugins we've examined, it does not support the visualisation of random collisions, as we experienced with the double pendulum at the beginning of this research.

Since it does not take real-time collisions into account, this plugin, while highly interesting in many respects, was not selected for this study.

5. Strand7

Finally, Strand7, used by (Grewal & al., 2019), and developed by the company of the same name (Strand7, 2020), is a standalone program independent of Rhino3D, primarily utilised for force and stress simulations in civil engineering. It can import 3D models created in Rhinoceros 3D, allowing users to test different geometries by applying forces and constraints. This makes it quite similar in functionality to the Karamba plug-in mentioned earlier and, therefore, shares some similar limitations.

Although Strand7 can simulate static elements in real-time, its requirement to export geometry outside of Rhino3D results in limited parametric flexibility. Moreover, like Karamba, Strand7 does not account for collisions between moving objects. Consequently, Strand7 was not selected as a simulation tool for this research.

DISCUSSION AND CONCLUSION:

By testing the five preceding software programs, we have gained valuable insights into the complexities involved in optimising geometry for earthquake simulations, as explored by (Grewal & al., 2019) (Figure 22) in their research. Additionally, these investigations have helped us better understand the specific type of simulation software needed for this research. Based on these insights, we can incorporate the following features to the criteria already exposed:

1. **Integration into Rhino3D:** During the testing of the Strand7 software, it was found that it offers file compatibility that allows, in some instances, for easy import of models created in Rhino3D. Indeed, as this software supports surfaces, meshes, and curves, but not points, it is possible that, its limitation can be a constraint for future scenarios.
2. **Dictate the Movement of Geometries Relative to Themselves and Surfaces :** The software should enable a user to dictate the movements of geometries relative to themselves and surfaces. Such functionality is necessary for creating accurate simulations where specific patterns of motion. The aim is to provide the ability to the user to explore different scenarios.
3. **Define Interactions Between Geometries and S*urfaces:*** The software should allow the users to determine the interactions between geometries and surfaces. By offering the choice to the user to specify how objects collide, slide, or bounce off each other, as well as any friction or adhesion properties involved, it will give the user the possibility to create a simulation that will correspond to their own case study.

In this section, the following software were evaluated, including RhinoVault, Quelea, Culebra, Karamba3D, and Strand7, to assess their capacity to simulate the structural behaviour of traditional Ishigaki walls under an earthquake. This examination revealed that while each tool offers some advantages, they are all not usable for dynamic collision as we have experimented in the previous steps. Therefore, these tests allowed us to set a list of criteria that will help us to choose software that will correspond to the needs of this research. This software should then provide seamless integration with Rhino3D, give control over geometry movements, and define interactions between geometries and surfaces. These criteria will guide our selection of the most appropriate tool for future simulations in this thesis.

That's why, in parallel with the following stages of the study, a new plugin will be explored to fit all the precedent criteria and start simulating an Ishigaki wall and its interaction with the earthquake that will be simulated.

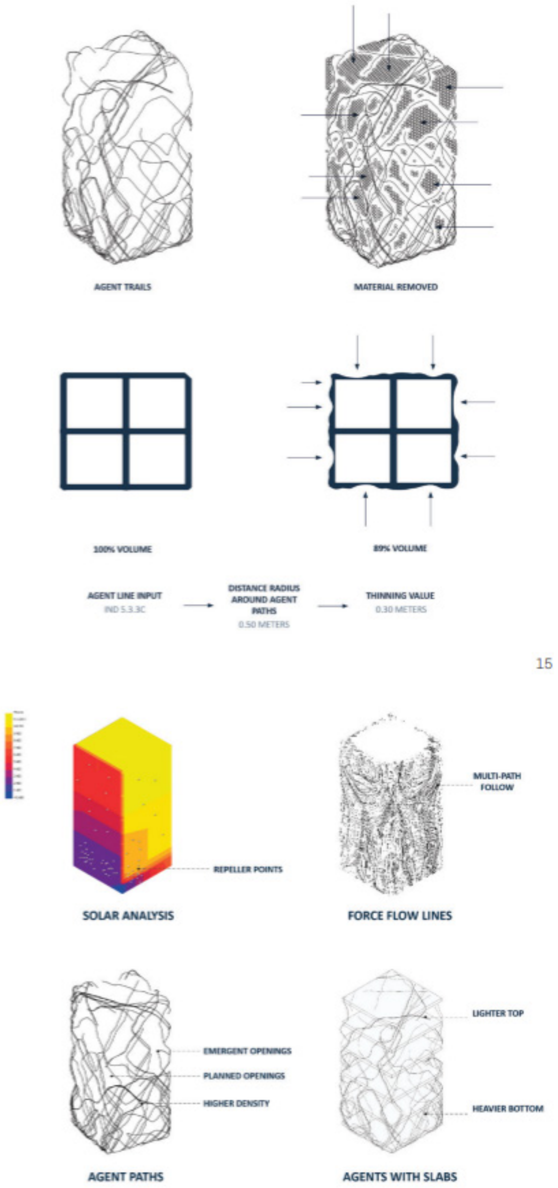


Figure 22: *Image from the publication of (Grewal et al., 2019) showing how they used the different plugin tested in this stage of research to improve the structure of a building. image from Grewal, N., Escallon, M., Chaudhary, A., & Hramyka, A. (2019b, January 1). INFRASONIC. Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). https://doi.org/10.52842/conf.acadia.2019.234*

STAGE 4: IS IT POSSIBLE TO CREATE A REAL EARTHQUAKE SIMULATION USING GRASSHOPPER?: (13/12/2023 TO 12/01/2024)

INTRODUCTION:

During the previous stages, we explored the complexities of simulating an earthquake and the chaotic behaviours it involves. We also tested the simulation capabilities of various plug-ins used by other researchers.

Building on the foundations laid in the first part of the research, this exercise focuses on creating a more realistic seismic simulation. The objective is to understand the behaviour of Ishigaki walls during an earthquake in order to preserve these traditional structures and ensure their longevity.

Therefore, we will leverage the skills and knowledge acquired in the previous part to develop a more accurate earthquake simulation using real data collected from past earthquakes. Ideally, the goal of this stage of research is to compare the simulated movement of an Ishigaki dry masonry with the attitude of a real wall during a seismic event.

To do this, we will employ the seismograph curves from the (気象庁 Japan Meteorological Agency, n.d.-a) as shown in (Figures 7 and 8) in section 1.1. Thus, the seismographs recording ground motion on the north/south, up/down and east/west axes will be repositioned on their software equivalents, i.e. the X, Y and Z axes. The aim is to use the data received in Grasshopper to generate a three-dimensional movement that can approach that of an actual earthquake.

However, at the time of this research, I did not yet have access to the data necessary to carry out this more realistic simulation. To address this gap, we decided to create a curve representing a progressive oscillation, allowing us to develop a Grasshopper chain capable of translating the curves from a seismogram into three-dimensional movements. Although these curves do not represent an actual earthquake, their use is intended to tackle the challenges posed by such a simulation and to resolve potential issues that may arise.

STEPS COMPLETED :

Thus, we can summarise the method employed as follows:

1. ***Creation of Curves:*** As previously mentioned, at the time of conducting these tests, I did not yet know how to access seismic data from different earthquakes. Therefore, I created three curves representing the East/West, North/South, and Up/Down seismograms to progress in the research and tackle the development of a more realistic program.

2. ***Placement of Curves on Their Axes:*** The aim is to position each curve on its appropriate axis. For example, in this simulation, we can place the East/West curve on the Y axis and the North/South curve on the X axis, horizontally. The Up/Down curve will be placed vertically on the two aforementioned axes, representing in both cases the Z fluctuations of a potential earthquake.

3. ***Extrusion of Curves Along the X-Axis:*** The curves are then extruded perpendicularly, which means that a surface is created following the movement of the curves and extends perpendicularly to them. So, for horizontal axes, the 'extruded' surface will be vertical, and for vertical axes, the extruded surface will be horizontal. During this stage, we take care to extrude enough of the surfaces created from each curve so that those positioned on the X-axis cross each other, and the same applies to the extrusion of curves on the Y-axis.

4. ***Intersection of Surfaces:*** The aim of this stage is to make Grasshopper understand that the two extruded surfaces created earlier from each axis intersect. However, several different approaches can be adopted to adapt to each situation's unique case.

5. ***Create a curve passing through the intersections of the two extrusions:*** We use the intersections detected earlier to create a curve oscillating around the X and Y axes. This curve will then be used to simulate the movement of an earthquake. However, depending on the curves used initially, correction points may be necessary.

   - ***Bug fixing: Decomposing the curve to eliminate potential noise:*** Depending on the quality or density of the curves used, anomalies can occur, such as points superimposed at the same coordinates, breaks in the continuity of the curve, or the creation of multiple intermittent curves. One method of dealing with these problems is to break down the curve into one or more lists of points and then sort these points according to their spatial coordinates, thereby eliminating inconsistencies.

   - ***Bug correction: Creation of a new curve and possible adjustments:*** From the previous step, it is possible to create a new curve or recover the one generated in step 3. However, it may still be necessary to smooth the recovered curve to eliminate any remaining minor bugs.

6. ***Motion animation:*** The resulting X and Y axis curves are then used to create an animation. By re-using the "stopwatch" component from the first earthquake simulation, we can coordinate movement on both axes, producing a simultaneous animation.

7. ***Create two reference surfaces:*** Two flat surfaces are positioned horizontally at coordinates (0, 0, 0), perpendicular to the X and Y axes. These two surfaces will serve as references for collisions with the two curves representing movement on each axis created in step 5 (Figure 23).

8. ***Intersection of the paths with the surfaces:*** The path created in step 5 intersects the surfaces created in step 7.

9. ***Extract intersection points:*** The intersection points between the path and the surfaces are extracted. This produces a point moving in Z and Y on the surface perpendicular to the X axis, with coordinates (0,0,0), and a point moving in X and Z on the surface perpendicular to the Y axis, also with coordinates (0,0,0). These two points, moving in the planes mentioned above, can cross each other in order to reproduce the movements of an earthquake as faithfully as possible.

10. ***Drawing a line between two points with a predefined centre:*** The aim is to connect the points we extracted earlier with a line, so that we can roughly estimate the displacement of the ground we are trying to simulate.

11. ***Create a centre point between the two surfaces:*** From the line we created earlier, we generate a centre point which will be used in the next step.

12. ***Attach a surface to the point:*** A surface is attached to the central point to simulate the approximate movement of the ground during an earthquake, providing a visual representation of the displacement in three dimensions.

DISCUSSION AND CONCLUSION:

In this section, in the absence of real seismic data, we have chosen to create fictitious curves to advance our research. This method has enabled us to gain a better understanding of the recording of seismic phenomena and their representation in modelling. It will also facilitate the integration of real seismographic data into our future research.

One of the main challenges of this stage was to develop a method for coordinating simulated seismic movements along the East/West, North/South and Top/Bottom axes, in order to create a three-dimensional representation of seismic movements. While this approach is instructive, it is crucial to recognise the limitations of the chain developed. By drawing a line between two oscillating points in X and Y, as described in step 10, we have found that this method can attenuate earthquake motions in certain axes. However, it is limited in its ability to represent extreme motions that may occur outside its range, which may reduce the accuracy of the simulations.

Despite these limitations, the approach adopted is in line with the objective of creating a Grasshopper chain capable of seismic approximations (Figure 24), as expressed in the introduction to this thesis. The knowledge acquired at this stage of the research will be essential for future study to develop a more realistic earthquake simulation, in particular by integrating real data provided by the Japanese Meteorological Agency. Ultimately, these improvements will enable simulations to be better aligned with reality and provide designers with a tool that can help them design Ishigaki-type earthquake walls.

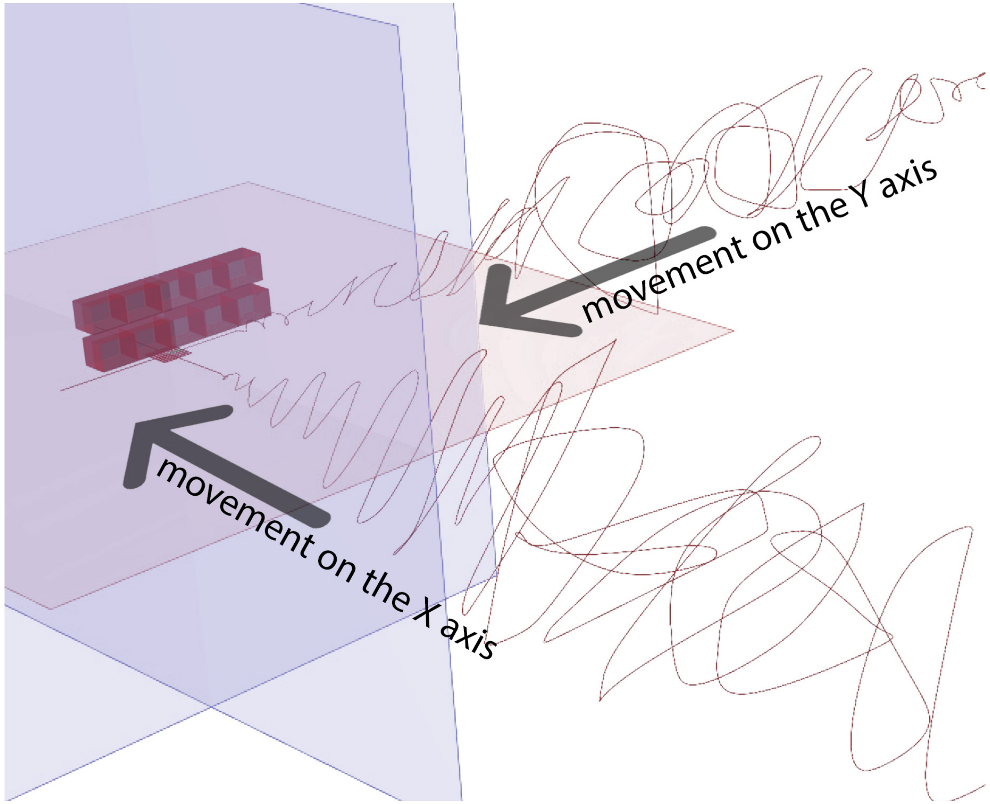


Figure 23: *Image showing the positioning of the curves on the X, Y, and Z axes used for the simulation and the surfaces perpendicular to both axes. [Original Image ©]*

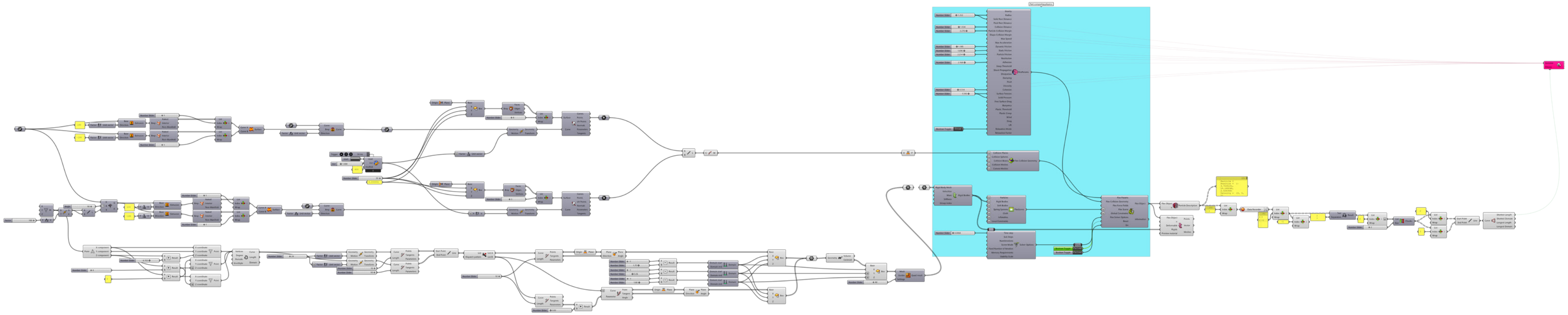


Figure 24: *Image showing the Grasshopper chain created during this stage of the research.[Original Image ©]*

STAGE 5 :DISCOVERING FLEXHOPPER AND ITS LIMITATIONS AND ALTERNATIVES .(13/01/2024 TO 12/02/2024)

INTRODUCTION:

In the previous phase, our objective was to develop a realistic earthquake simulation model. For this, we searched for an alternative plug-in to the solutions tested at the beginning of this second phase of research. It was crucial to find a physics simulator capable of meeting the following seven criteria:

1. Integrate seamlessly with Rhino3D.
2. Offer precise control over geometric movements.
3. Define interactions between geometries and surfaces.
4. Accurately simulate multiple collisions.
5. Provide real-time visualisation.
6. Offer parametric flexibility.
7. Full Parameterisation.

The goal is to subsequently combine the earthquake simulation with a program simulating the physics of Ishigaki walls. This approach aims to gradually improve the realism of the simulation in order to test its fidelity and draw relevant conclusions for the writing of this dissertation.

For this purpose, the Flexhopper plug-in, developed by (Heinz Benjamin, 2019) was chosen. This plug-in, based on particle simulation with assigned constraints and properties, met most of the criteria listed above.

The discovery of this plug-in and the research related to comprehending its functionality allowed for a better understanding of how to simulate the physics of an object through a computer, which opens up new perspectives for this work and for future research. Indeed, the plug-in created by (Heinz Benjamin, 2019) is based on a simulator developed by Nvidia, called Flex. As explained in section 2.3, the particle-based "physic engine" as Flex, are often used in video games to simulate the physics of a multitude of geometry in real-time.

This plug-in made it possible to begin experimenting with the physical simulation of an Ishigaki wall through a simple simulation, composed of a surface representing the ground and a dozen blocks that stack and rest on it.

STEPS COMPLETED :

This first simulation step can be summarised by the following methodology:

1. ***Wall Modelling:*** The wall modelling was executed using Rhino and Grasshopper to create a simplified section of the Ishigaki walls. The model consists of 5 layers, each composed of 5 blocks, effectively representing the architectural essence of the original structure.

2. ***Flexhopper integration:*** FlexHopper, the physics simulation plug-in developed by (Heinz Benjamin, 2019)(Figure 30), was incorporated to manage the physical interactions between the blocks. This required understanding the simulator's various capacities and basic functionalities, as well as learning how its different components operate.

3. ***Creation of meshes:*** Using the 25 blocks initially generated, meshes were formed around each one to transform them into rigid bodies. This process was carried out using Grasshopper, where each block was enveloped in a dense mesh to accurately represent its contours. This conversion step transformed the geometric models into physical entities capable of interacting with each other within the simulation.

4. ***Creation of Rigid Bodies:*** The previously generated meshes were then turned into rigid bodies employing a component provided by the Flexhopper plug-in called "rigid bodies" as showed in (Figure 25). These rigid bodies are essential for the solver to process and simulate their interactions accurately.

5. ***Creation of a Surface symbolising the Ground:*** Creating a surface to represent the ground was facilitated by Grasshopper, which allows for the easy generation of large surfaces based on the horizontal x and y axes. This surface serves as the foundational plane for the simulation.

6. ***Creation of a collision geometry:*** The previously created surface, designed to represent the ground on which the Ishigaki wall's blocks rest, was assigned as a "collision geometry" using a FlexHopper component named "Flex collision geometry" as shown in (Figure 26). This assignment allows the surface to act as a solid entity capable of colliding and interacting with the newly created rigid bodies.

7. ***Creation of a Scene:*** A scene represents an environment where physical interactions occur among the various geometries it contains. In the case of Flexhopper, the component called "FlexScene"(Figure 27) is used to create this environment by grouping together all the geometries that will interact with each other during the simulation. We then attach our "rigid bodies" to this component.

8. ***Linking the Scene to the FlexHopper Solver:*** The FlexHopper solver, (Figure 28) as explained during the creation of the double pendulum, is a component that calculates interactions between different objects within the simulation. In our case, a connection was established between the scene and its composing geometries to visualise their interactions in real-time.

9. ***Attribution of Properties to Particles:*** To ensure a realistic simulation, FlexHopper allows its component “Flexparams” (Figure 29) to assign the desired properties to various geometries within the simulation through one of its components connected to the solver. These properties include mass, stiffness, bonding between particles, friction coefficients, and gravitational forces, all contributing to a realistic response to applied forces. The main challenge was calibrating these parameters to prevent non-physical behaviours such as interpenetrations or blockages.

However, despite its strengths, Flexhopper has limitations in managing a big number of objects, as it is not designed as a “physics engine” using “rigid bodies’ to simulate collisions. It then has to use a large number of particles for each block or rigid body that can quickly make the simulation heavy and difficult to handle, forcing us to reduce the number of blocks and the number of particles assigned to each block[21]. It also needs to be noted that the plugin doesn’t specify units for its component ‘flex params,’ leaving the user to infer the strength of the constraint being applied to the structure.

Consequently, to mitigate this effect, the following step was added to the methodology:

10. ***Mesh Reduction and Particle Magnification:*** Reduce the mesh surrounding blocks and increase the size of the particles surrounding them.

The simulations that followed allowed us to visualise the initial interactions, but they were not realistic. Indeed, once simulated, the blocks would slide on the surface and only simulate contact with it after several seconds, seeming to be pushed by a pressure on the X-axis. Not understanding this problem and not finding a solution, we questioned the use of Grasshopper and Rhino.

During the time needed to solve this issue, other software, with integrated physics simulators and visual programming languages, such as Blender and Unity, were considered and tested to see if they could provide a more reliable and efficient alternative to the Flexhopper simulator in Grasshopper.

Blender and “Sverchok”:

Blender, an open-source 3D modelling software, integrates a powerful physics engine (Bullet Physics) and a visual programming system “Sverchok,” the equivalent of Grasshopper for Blender. Although interesting for both reasons, an approach using this software has revealed prohibitive limitations for this project. The initial, goal as mentioned in the thesis introduction, was to create precise geometries for future studies to optimise block geometry for seismic designs.

However, during this short exploration of “Sverchok”, it became apparent that the precise modelling and automation process of shape search required to manually generate a geometry in the early stages of design. The software did not meet the ‘full parametrisation’ criteria discussed at the beginning of this stage. Since no solution was found to bypass the initial manual step within the time allocated for its investigation, it was decided that the software would be discarded for this research.

Unity and “Visual scripting”:

Unity, a cross-platform game engine, offers a powerful physics engine (PhysX) and a visual scripting system. However, “visual scripting”. As with Blender, the need to go through the 3D modelling interface to produce objects during the visual programming process created the same problems, affecting the continuation of this evaluation. Because it does not correspond to the criteria mentioned initially, this software has also been discarded for this study.

---

[21] *Problem already mentioned in the state-of-the-art section 2.3, in the part addressing the physics engine based on particle simulation page 33 of this master thesis.*

DISCUSSION AND CONCLUSION:

In this section, we aimed to start to develop a realistic simulation model of Ishigaki walls using the FlexHopper plug-in developed by (Heinz Benjamin, 2019), as it met the criteria we established during the testing of various software and plug-ins in the state-of-the-art.

FlexHopper, which exploits Nvidia's Flex physics engine, allowed for seamless integration with Rhino3D, precise geometric control, interaction definition, accurate collision handling, real-time visualisation, parametric flexibility and possible capability for full automatisation.

However, during the initial utilisation of this software, we encountered challenges, particularly in managing a large number of objects and achieving a realistic physical simulation. This required adjustments to mesh density and particle interactions, especially with the collision surface representing the ground, which still needed significant improvement.

In addition to this, unexpected behaviours such as block sliding led us to explore alternative tools like Blender and Unity. While these tools offered similar functionalities to Grasshopper, they did not provide a complete and straightforward parameterisation of the creation approach. Indeed, they demanded manual modelling at the start of the experimentation process. Consequently, neither was suitable for our goal of achieving a more parametric design, and thus they were not selected for further investigation in this study. However, the lessons learned from these experiences will help refine simulation methodologies to enhance realism and precision while highlighting the complexity of simulating chaotic physical interactions, required by the objective of this research.

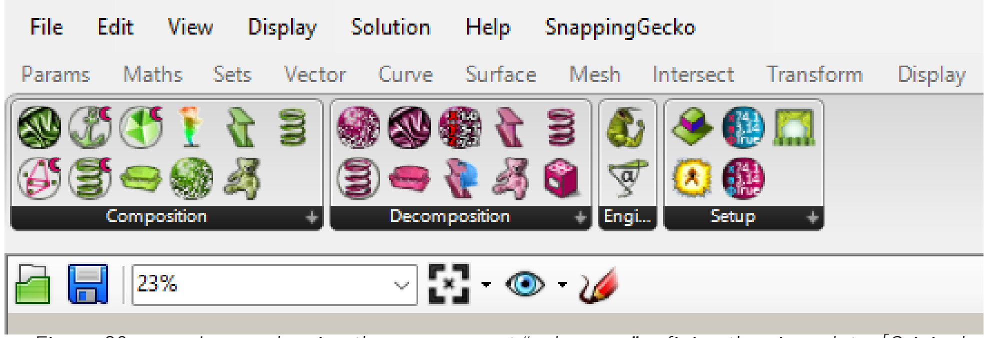


Figure 30: *Image showing the componnent "galapagos" refining the given data. [Original Image©].*

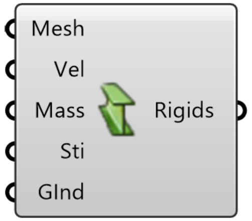


Figure 25: *Image showing the component Flexhopper called "Rigid Bodies". [Original image ©]*

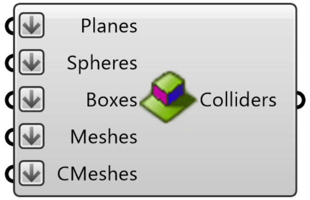


Figure 26: *Image showing the component Flexhopper called "Flex collision geometry".[Original Image ©]*

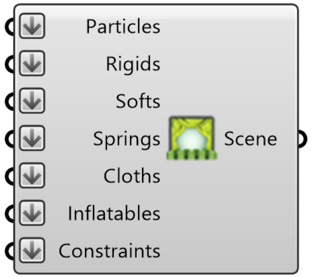


Figure 27: *Image showing the component Flexhopper called "FlexScene". [Original Image ©]*

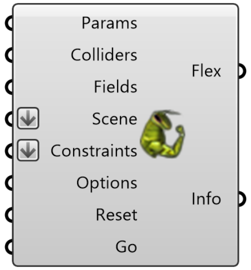


Figure 28: *Image showing the component Flexhopper call "Flexengine". [Original Image ©]*

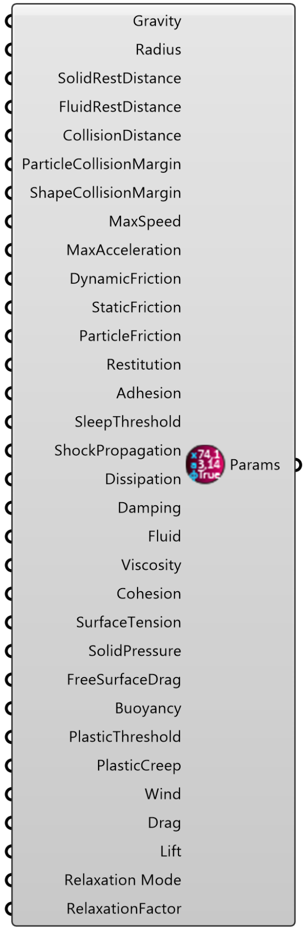


Figure 29: *Image showing the component Flexhopper call "FlexParams". [Original Image ©]*

STAGE 6: UNDERSTANDING AND BEGINNING OF THE OPTIMISATION OF PHYSICS RELATED TO THE BLOCKS GIVEN BY THE FLEX HOPPER PLUG-IN. (13/02/2024 TO 12/03/2024)

INTRODUCTION:

After an initial interaction with the FlexHopper software, which was inconclusive due to several challenges in its ability to simulate a great number of volumes and physical simulation problems that made the simulation unrealistic, we decided to explore other options.

We investigated software like Blender and Unity, which have integrated physics simulators and their own visual programming languages. However, these options were set aside because they relied on initial manual modelling, preventing the possibility of full automation in the future.

As a result, the following weeks were focused on gaining a deeper understanding of the FlexHopper plug-in to resolve the previously encountered issues. This involved conducting more in-depth research based on tutorials provided by FlexHopper's creator, Heinz Benjamin (Heinz, n.d.), which helped us understand the different levels of interaction between particles. Additionally, we learned how to utilise more advanced aspects of this plug-in, allowing us to address the problems faced in previous weeks while paving the way for more realistic simulations.

STEPS COMPLETED :

To do this, the following method has been adopted:

1. ***Transformation of the Mesh into Rigid Body:*** This process enables the Grasshopper component to define the vertices (points that make up the mesh) as centres of specific spheres. This step is crucial as it allows the detection of collisions between geometries. When the spheres enter the perimeter of a sphere of another geometry, they indicate to the computer whether a collision occurs. Thus, the surfaces of the geometries are covered with spheres that facilitate interaction between different geometries.

2. ***Placement of the Blocks:*** The rigid blocks are spaced based on the mesh thickness. A denser mesh requires careful attention to prevent the spheres overlapping between them because of the densification of verticles from causing extreme movements. To avoid this, it is essential to space the spheres so that they slightly touch each other without provoking undesirable interactions.

3. ***Constraints Applied to Rigid Bodies:*** During this stage, the particles are connected in a more or less restrictive manner. Flexhopper allows us to control the stiffness of our geometry. In this research, which uses stone blocks, the stiffness is set to the maximum to best replicate the physical properties of the materials.

4. ***Assigning Constraints to the Scene and the Created Rigid Bodies:*** Grasshopper uses the "Flex Params" component from Flexhopper (Figure 29) to manage several constraints. These constraints include the size of the spheres, the weight of the particles, and how they interact with each other by modifying parameters like damping and cohesion.

5. ***Revision of Constraints:*** The constraints of the "Flex Parameter from Value" plugin can be adjusted using sliders. However, it is crucial to understand the limits of each constraint to avoid inappropriate settings that could compromise the simulation.

6. ***Attempt to Resolve the Problems Encountered During the First Stages:*** I attempted to solve the issues that made the simulation unrealistic by manipulating the various available variables. These efforts included adjusting different parameters to better match the physical reality of the simulated objects.

7. ***Review of Tutorials and Documentation Related to This Plugin:*** After failing to resolve the problem by merely adjusting the constraints of the simulation space, I decided to consult the tutorials provided by the developer. This helped me better comprehend how the Flex simulator developed by Nvidia works.

8. ***Attempt to Work with Extreme Values:*** After gaining a better understanding of the software, I considered using extreme values to solve the problems of the physical simulation. We then multiplied the recommended limits by a hundred. However, this approach did not solve the persistent problem of sliding on the surface intended to represent the ground.

9. ***Resolution of the Simulation Issue:*** Failing to find a solution by simply increasing the strength of the constraints, we found a solution thanks to the recent updates of Flexhopper. (Heinz Benjamin, 2019) corrected the slipping issue by creating the "Flex Solver Option" as visible in the component. By adjusting the "Stability Scale" variable, we were able to configure the simulation to eliminate slipping. In the context of this study, the value "0.412" resolved this issue.

After successfully resolving the sliding matter encountered over the past few weeks, the next step was to maximise the realism of the simulation. Given the numerous constraints that can be applied to the geometry and the wide range of values available for the simulation, it was decided to use tools like Galapagos. As explained by its designer (Rutten, 2013), Galapagos is a plug-in that employs advanced algorithms to optimise complex designs.

By integrating this plug-in with Grasshopper, it became possible to test thousands of potential configurations to find the one that creates the most realistic simulation of the blocks modelled.

To achieve this objective, the following methodology was adopted:

1. ***Creation of a Data Collection Chain:*** The objective is to establish a chain that gathers data from the Flexhopper solver (Figure 32). While the solver transmits the coordinates of the blocks over time, it also sends additional data in text form. Therefore, it's essential to filter this information to retain only the differences between the starting coordinates and those collected at the end of the simulation.

2. ***Selection of Three Particles per Block:*** By choosing three particles on every block, we can precisely track the movement in the modelling space of each block during various iterations. This allows us to better understand how each block behaves in space.

3. ***Creation of a Chain to Record Particle Movement:*** The goal is to filter the information calculated by the solver and organise it to provide Galapagos with data that can be used to define optimisation objectives.

4. ***Creation of a Curve from Recorded Points:*** This curve will serve as a unit for Galapagos to analyse what is produced during the simulation, progressively selecting the best options. The curve represents the path taken by the particles and helps evaluate the efficiency of each simulation.

5. ***Adjustment of Simulation Time:*** Since Galapagos cannot directly adjust the iteration time, we must allow Flexhopper to transition from the initial state to the solution as quickly as possible. By using the "Flex Solver Option" component, we instruct it to show the simulation only after 300 calculations by the solver. This allows us to quickly move from the original state to the final state without delay, enabling iterations to occur simultaneously with Galapagos's calculations.

6. ***Connecting Grasshopper to Variables and Simulation Results:*** To enable Galapagos to function effectively, we attach it to variables such as friction and restitution and evaluate the stability of the blocks. We also link it to components that calculate the length of each curve created by the blocks or rigid bodies as they move through space (Figure 31). The goal is to determine that the iteration generating the least movement between the end and the beginning of the simulation is the optimal solution. This iterative process ensures that the simulation parameters are finely tuned for maximum stability of the blocks.

7. ***Managing Extreme Values:*** If, during computations, Galapagos indicates that a variable is approaching one of the slider's extremes, the range of numbers the slider can reach can be manually expanded. Then the test is rerun while marking the ultimate result of each variable. This allows the exploration of other values to ensure the reliability of the solutions.

8. ***Refinement of Core Values:*** When Galapagos consistently produces the same result after five iterations, the precision of the sliders it is connected to is increased, and the range of the slider is reduced between the minimum and maximum final results recorded during the last five tests. This refines the values that yield the best result to determine the optimal solution.

DISCUSSION AND CONCLUSION:

In this stage of research, we focused on resolving issues encountered with the physical simulation generated by Flexhopper during the previous stage, namely the sliding of blocks on the surface without an apparent reason and reducing the simulation load to prevent crashes.

To achieve this, we conducted an in-depth study on the components and competencies of the plug-in, drawing on tutorials by Heinz Benjamin (Heinz, n.d.). This helped us gain a better understanding not only of how this specific simulator works but also of physical simulators for video games in general. The knowledge we obtained allowed us to exploit Flexhopper's capabilities effectively. By using the "Flex Solver Option" component, we were able to adjust the "Stability Scale" variable to eliminate the inexplicable sliding problems. Following this, the integration of Galapagos (Rutten, 2013), into the process of exploring the variables controlling the physical interactions of the wall allowed us to progressively refine our research and define the values that allow the most realistic movement possible.

The insights obtained enabled us to refine our approach, transform the meshes into rigid bodies, optimise collision detection, and manage constraints effectively to replicate the physical behaviour of a stone wall visually.

This stage allowed us to achieve a convincing simulation of stone blocks stacking in a static space. The next stage of the study will involve applying seismic pressures to the simulation created during this stage.

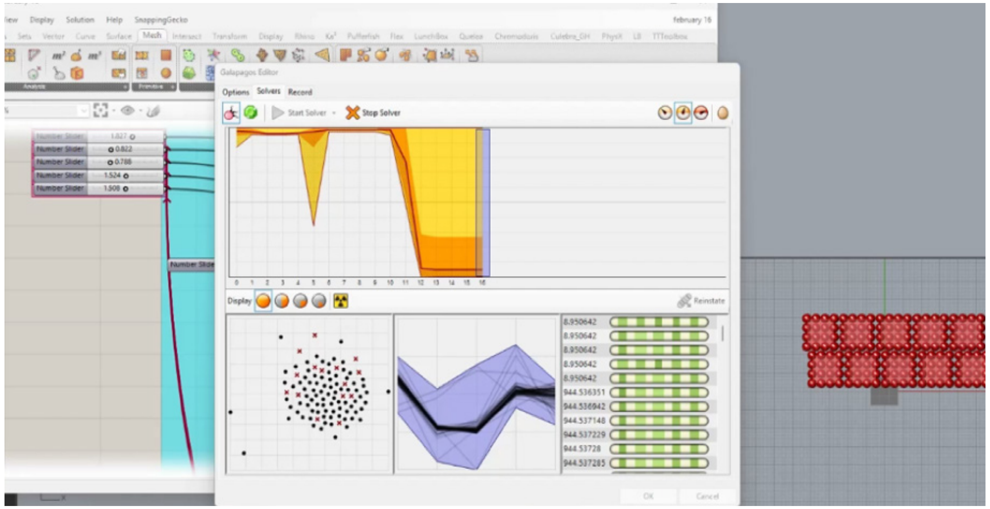


Figure 31: *Image showing all the Galapagos components working in the simulation developed during this stage of the research.*

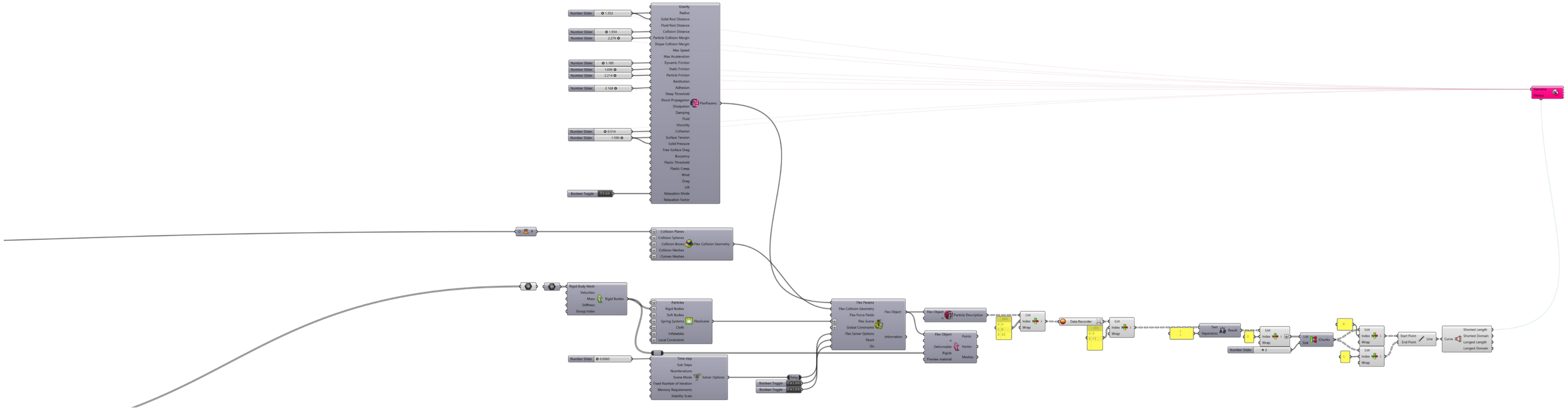


Figure 32: *Image showing the chain recodring the data used in the satgge of research [Original Image©].*

STAGE 7: COMBINING FLEX HOPPER PLUG-IN PHYSICS AND REALISTIC EARTHQUAKE SIMULATION. (13/03/2024 TO 26/03/2024)

INTRODUCTION:

In the previous stages of our study, we developed a program that partially simulates the motions of an earthquake and addressed the challenges related to the physical simulation of modelled blocks using Flexhopper. We tackled issues such as block sliding and optimised the simulation's performance to ensure its capability to help solve the question of this thesis.

This stage of research builds on the work completed over the past months. We aim to incorporate the Grasshopper chain, which produces an animation that mimics earthquake movements, with the Flexhopper-based chain, which simulates the physical behaviour of stone walls. By combining these two systems, we strive to create a comprehensive simulation model that can represent the dynamic interactions between seismic forces and structural components.

The integration of these two parts marks the first attempt to simulate a wall under earthquake pressures, providing a foundation to address the central question of this thesis: "How can a visual programming tool be used to simulate the behaviour of Ishigaki walls during seismic events?" This research will explore the capabilities offered by the Grasshopper chains developed and examine their limitations and potential challenges.

STEPS COMPLETED:

The search stages can be broken down as follows:

1. ***Linking Animation and Simulation:*** Flexhopper, is a physics simulator capable of simulating the collision of multiple moving objects, allows the integration of a chain that mimics earthquake movements by attaching it to the face linked to the "Flex Collision Geometry" component.
2. ***Launching the Simulation:*** Once the two chains are connected, they are tested. We begin by initiating the physical calculations performed by the Flexhopper solver, represented by the "Flex Engine" component (Figure 28). This allows us to observe physics being applied to the simulation's blocks, which are initially stationary. Then, we start the animation that imitates the earthquake by activating the countdown produced by the Python component developed in Part 1 of the research.
3. ***Observing the Created Simulation:*** After the simulation is created, we can witness that it seems to neglect the friction generated by horizontal movements on the "Flex Collision Geometry" surface, which is supposed to symbolise the ground, with the volumes intended to represent the stone blocks of the Ishigaki wall.

To solve this problem, several approaches have been tried, ranging from the most conventional solutions to more indirect methods that get around the friction problem while preserving collision capability, which is essential for simulating horizontal movements. This research is crucial, because without a combination of these two strengths, it would be impossible to simulate correctly the interactions between a simulated earthquake and the modelled bock of the Ishigaki wall.

The following steps have been taken to address this issue:

1. ***Finding a Solution by Adjusting the FlexHopper Parameters:*** The first attempt involved modifying the FlexHopper parameters to create friction between the "collision geometry" and the "rigid bodies" using the "Flex Parameter from Value" component. As explained in the tutorials made by (Benjamin F., 2018b), we tried increasing the value controlling the "adhesion" to the surface. However, this did not solve the friction problem, which led us to consider another approach.

2. ***Bypassing the Friction Problem by Using a "Rigid Body" as the New Ground:*** **To bypass the friction problem, a surface defined as a "Rigid Body"** was created. This surface, in the shape of a slab, is placed between the horizontal surface (collision geometry), which previously represented the ground, and the "rigid bodies" meant to constitute the wall blocks. The motion of the collision geometry can be controlled, thus allowing the desired friction to be introduced.

3. ***Modifying the Geometry of the "Collision Geometry" Representing the Ground:*** For the "Rigid Body" located between the volumes representing the blocks and the "Collision Geometry" to follow the trajectory dictated by the chain imitating earthquake movements, it was decided to replace the flat surface with an open-top container to enclose the aforementioned "Rigid Body."

4. ***Simulation Movement Tests:*** A new test was conducted to observe whether the addition of this intermediary layer allowed friction to be created during the horizontal movements of the "collision geometry." During the test, it was found that the blocks followed the movement of the surface when it moved horizontally, indicating that the friction problem was accounted for. However, the "Rigid Body" employed as an intermediary layer tended to pass through the new geometry used as a "collision body," causing errors in the simulation. Furthermore, when the particles were spaced at a distance equal to their diameter, the "rigid bodies" gradually slid through the "Rigid Body" intended to represent the new ground.

5. ***Resolving Permeability Issues of the "Rigid Body" Serving as the Intermediary Layer:*** To solve the permeability issue, a tighter mesh was tested, positioning the particles at a distance equal to their radius. This was done to improve the "Rigid Body's" ability to act as a less porous surface.

6. ***Resolving Movement Issues of the "Rigid Body" Serving as the Intermediary Layer:*** To correct the deviation of the "Rigid Body" allowing friction, a Grasshopper chain was developed to frame it. Thanks to the tutorial video of (Benjamin F., 2018) dedicated to fluid management, we built a frame composed of four connected faces, centered on the central point of the "collision geometry." This frame was added as "collision geometry," which constrained the intermediary layer to follow the motions dictated by the Grasshopper chain imitating those of an earthquake.

7. ***Movement Tests with Frame:*** A new simulation was launched using the frame developed in the previous step. It was observed that the "Rigid Body" used as an intermediary layer was less likely to pass through the frame created earlier, thus maintaining a more faithful trajectory (Figure 33). It was also observed that the permeability problem was resolved due to the densification of the mesh of the geometry representing the ground. However, it was noted that the latter tended to detach from the "collision geometry" during abrupt vertical movements, thereby skewing the simulation.

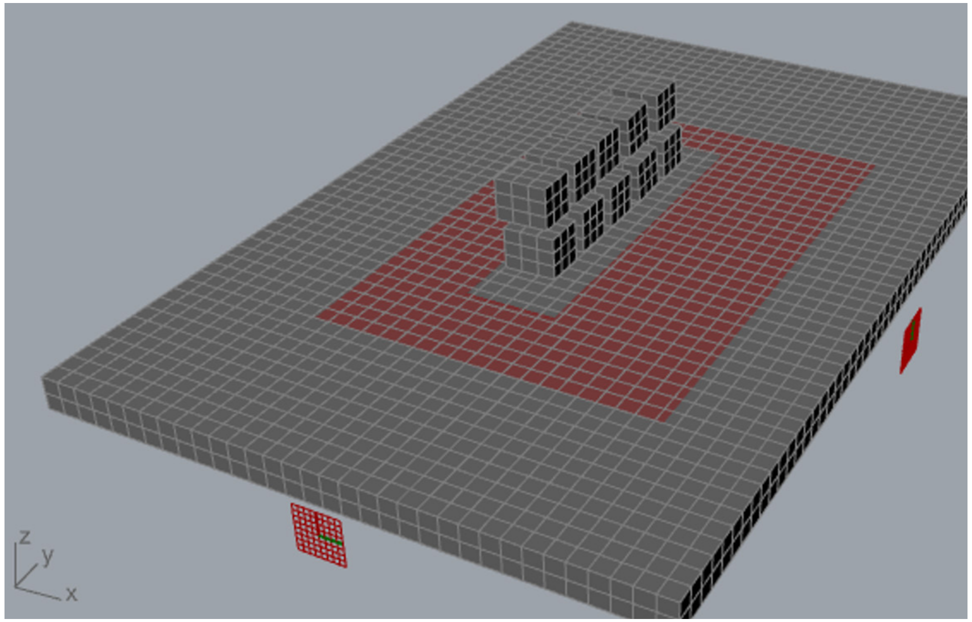


Figure 33: *Image showing the final forme of the simulayion developped during this stage of research with the blocks standing one «the new ground» made of an other rigid body [Original Image©].*

DISCUSSION AND CONCLUSION:

In this stage of research, a program was developed that integrates the work previously done by combining the chain that simulates an earthquake with the physical simulation offered by Flexhopper.

During the first test, challenges were encountered in simulating friction between the “collision geometry” and the “Rigid bodies.” Since this problem could not be solved by parameter revisions, such as surface adhesion, a new approach was considered.

To address this friction problem, we created an intermediary layer composed of a “Rigid Body” to simulate friction with the ground during horizontal movements. Additionally, adjustments were made to the geometry of the “collision body” so it could act as a receptacle for the “Rigid Body.” However, in subsequent tests, we observed other issues, including a certain porosity in the new geometry of the “collision body” and the “Rigid Body” meant to represent the new ground, requiring further corrections.

Consequently, we densified the mesh of the “Rigid Body” and adopted a new approach using faces as the “collision body” to frame the new ground.

These measures improved the accuracy of the simulation but also revealed new issues, such as the detachment of the “Rigid Body” intended to symbolise the new ground during abrupt vertical movements.

Given these factors, it is possible to conclude that in the current state of the simulation developed in Grasshopper, it is not possible to accurately represent the behaviour of an Ishigaki wall subjected to an earthquake. However, this finding has helped define the present limitations of the visual simulation and explore other methods to analyse the resistance of an Ishigaki wall against earthquakes.

STAGE 8:HOW TO ANALYSE THE SIMULATION IN ORDER TO VERIFY IT MATHEMATICALLY? (27/03/2024 TO 13/04/2024)

INTRODUCTION:

After the previous stage of the research, it was decided to continue with the work in spite of the result of the previous stage of the study. Although, the simulation does not faithfully reproduce the movements of an earthquake, which makes it impossible to realistically simulate the behaviour of an Ishigaki wall under such pressure. However, it is still possible to simulate the behaviour of a wall subjected to vibrations of different frequencies utilising the chain described below.

It was therefore decided to continue the research in order to provide a more complete understanding of the accuracy that Grasshopper and the plug-in Flexhopper can offer thanks to the chain developed, as well as to deepen my knowledge of seismic construction with a view to continuing this research after this master thesis. Alongside this, it was also considered important to continue exploring other ways of simulating an earthquake using Grasshopper's capabilities in Rhinoceros 3D.

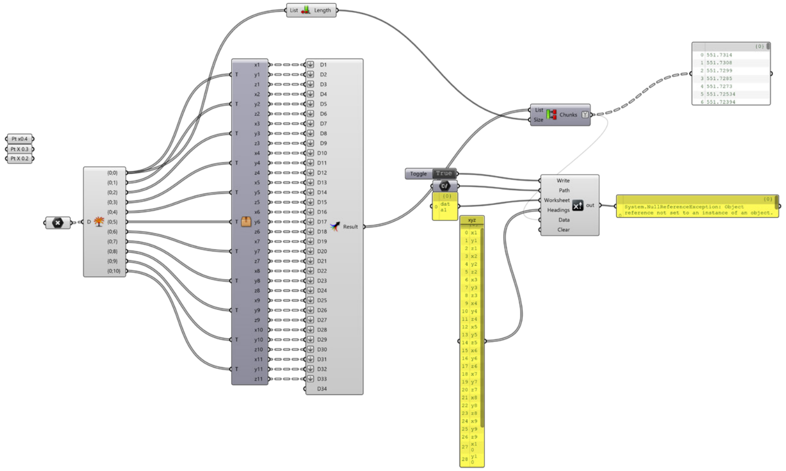
Consequently, the aim of this stage of the research was to produce a chain able to record the movements of the wall blocks modelled at different frequencies representing different seismic pressures. The aim of this exercise is to provide the data needed to create graphical representations for analysing the behaviour of the wall and, subsequently, to check by calculation the degree of realism of the simulations carried out.

STEPS COMPLETED:

To achieve this objective, the following method was put in place:

1. ***Reusing Knowledge Acquired During Part 1*****:** To successfully implement the chain developed during the stage 2 of this investigation, the initial approach of creating a realistic earthquake was replaced by a chain that reproduces continuous oscillations, similar to what was created during Part 1 of this research. This transition builds on previously acquired knowledge and aims to leverage regular oscillations to enhance the simulations.
2. ***Choice of Axis for Simulation:*** To allow for a mathematical analysis, the simulation is performed successively on each of the X, Y, and Z axes of the simulation space. This systematic approach enables the evaluation of block behaviour under different pressures and scenarios.
3. ***Adjusting Components to Create Precise Oscillations:*** For this part, we adjust the speed of the oscillation by calculating how long it takes for the platform to complete a round trip over the 8 meters of amplitude available to it. This allows us to calibrate the simulation to achieve precise oscillations that reflect the anticipated seismic conditions.
4. ***Data Retrieval from the Solver:*** Thanks to the skills developed during the research phase using Galapagos, it was possible to partially reuse the chain that records block movements during the simulation, allowing the recorded data to be used in the following steps.
5. ***Improving the Previously Developed Data Recording Chain*****:** The chain created to utilise Galapagos was not able to record the data it received. Therefore, it was necessary to add this functionality using a Grasshopper component called "Data Recorder." This component allows the collected information to be stored for later evaluation (Figure 35).
6. ***Isolation of Collected Data for Each Block:*** Once the data is collected, it is necessary to sort the coordinates of the points to trace the movement of each block along the X, Y, and Z axes (Figure 34). A Grasshopper chain was developed to separate the coordinates of every block during the simulation, thus ensuring the future analysis of the recorded movements.
7. ***Data Retrieval and Export to Excel:*** The isolated data for each block was retrieved and sent to an Excel spreadsheet. To accomplish this task, it was decided to use the component from the LunchBox plugin developed by (Miller, 2024), named "Excel Write". This component automates the process of transferring data to Excel, allowing for more efficient organisation and more reliable copying of the data in the Excel sheet.

8. ***Creation of Graphs to Visualise Block Movements:*** Based on the Excel tables created previously, graphs were developed to represent block motions along each axis (X, Y, Z). These graphs express how each block moves under different seismic pressures, allowing for a detailed analysis of its behaviour.



```
{0}
0 551.7314
1 551.7308
2 551.7299
3 551.7285
4 551.7273
5 551.72534
6 551.72394
```

```
{0}
0 System.NullReferenceException: Object
  reference not set to an instance of an object.
```

Figure 34: *Image showing the chain separating the data in purpose to send it to an exel cheat [Original Image©].*

DISCUSSION AND CONCLUSION:

In this stage of research, we have focused on exploiting the capabilities of the Grasshopper chain developed so far to gain a deeper understanding of its limitations and to test its capabilities. Although the current model does not perfectly reproduce the dynamics of earthquakes on Ishigaki walls, it effectively simulates the behaviour of the walls under different vibrational frequencies.

To this end, we used the skills acquired in this thesis to create a Grasshopper chain capable of recording movements on various axes and at multiple frequencies. This allows us to collect the position of each block during tests carried out successively on the X, Y and Z axes of the simulation space. We then automated the sending of the data using the LunchBox plug-in component, developed by (Miller, 2024), called "Excel Write."

This component can be used to create Excel tables containing the coordinates of the blocks recorded during the simulation and to derive graphs that provide information on the behaviour of the blocks under different seismic pressures. These tables can then be used to check the realism of the simulations carried out.

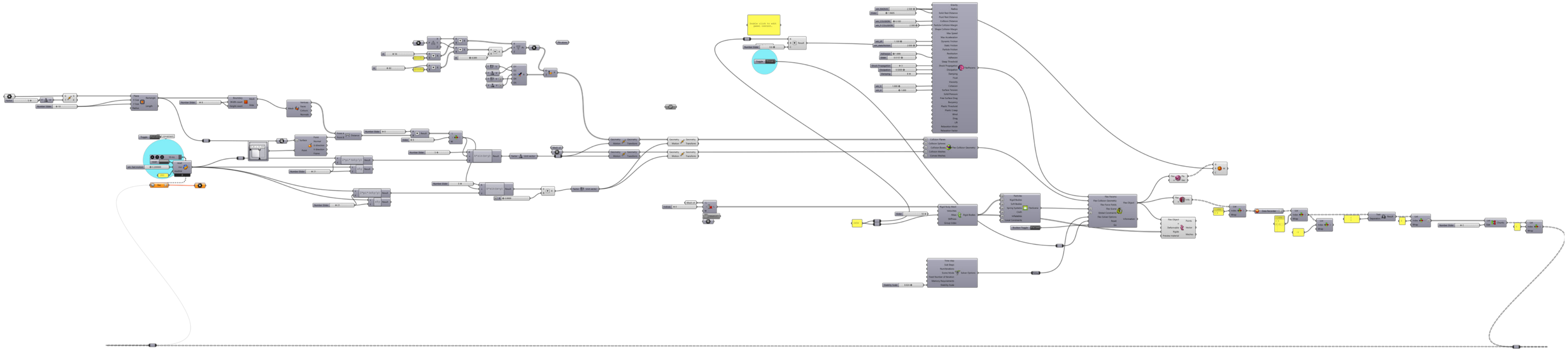


Figure 35: *Image showing the chain Grasshopper to create the recorded oscillation tests in purpose to send it to an Excel sheet [Original Image©].*

STAGE 9: RESEARCH AND MATHEMATICAL UNDERSTANDING (13/04/2024 TO 05/05/2024)

INTRODUCTION:

In the previous stage, we collected data on the behaviour of the blocks during simulation on different axes and at different vibration frequencies. The aim of this section is therefore to use this data, the accompanying graphs, and the knowledge developed during section 2.4 of this dissertation to assess whether the physical simulation developed can be improved to produce realistic earthquake simulations.

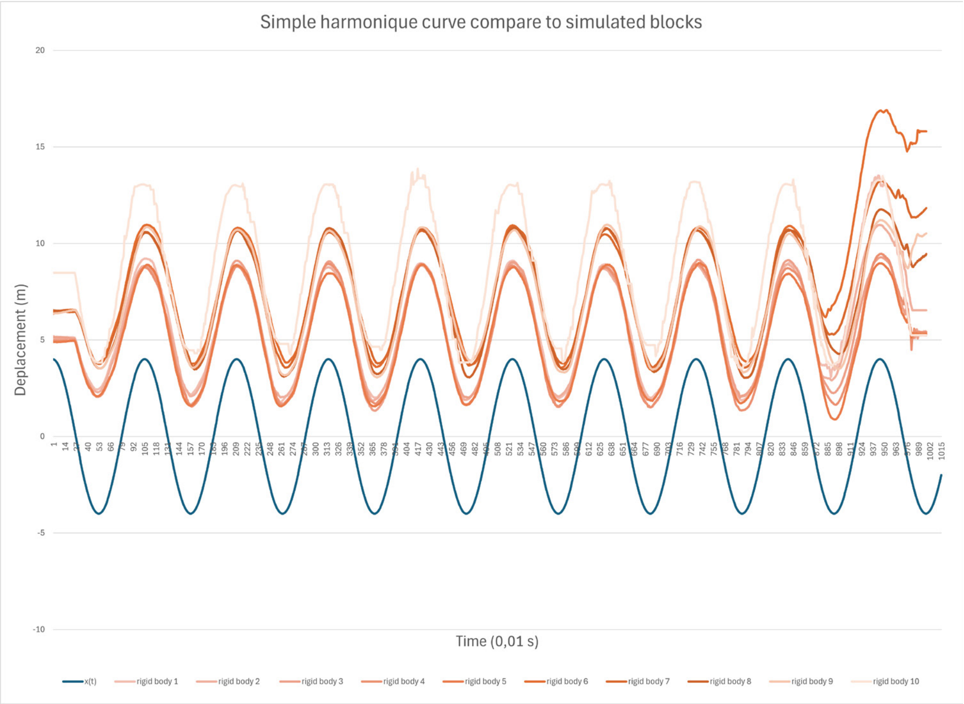


Figure 36: *Image showing the colected data of the simulation in orange compared to the harmonique motion calculated in blue. [Original Image©]*

STEPS COMPLETED :

Choice of reference graph: To compare the simulated data with the calculated displacements, we selected a scenario simulating a wall 5 blocks long by 2 blocks high, subjected to constant vibrations at a speed of 25 m/s perpendicular to its axis as shown in (Figure 37). This choice is explained by the fact that, unlike higher walls which crumble easily in the simulation, the smaller size of this wall enables it to wobble without collapsing, allowing extended analysis of its movements under the effect of shaking.

Collecting the necessary data: Before we start the calculations, we collect the following additional data from the simulation:

- The block is located at a height of 2 m.
- Its width is 2.1 m.
- Its length is 2.27 m.
- Its height is 1.87 m.
- The amplitude of the platform is 4 m.
- The initial phase is 0 rad.
- The period of the simulated curves is 1050 milliseconds.

Assuming that the simulated blocks are made of granite, we gather the necessary, though approximate, data to solve the various equations discussed in this section. Here is the information on granite collected:

- According to (Fouques, 2018), granite has a density of 2.66 g/cm^3 = 2660 kg/ m^3
- The website (JPE, 2010) indicates that the damping coefficient of this stone is less than 0.01.
- Research by (Yang & Hu, 2018) reveals that the modulus of elasticity, or Young's modulus, of granite is 25 MPa, or 25×10^6 N/m^2.

Based on this initial data, we estimate that the weight of the block is around 23,712.01 kg.

Solving a simple harmonic equation: Based on the previous data, we can estimate the position of the blocks using a simple harmonic formula of the form $mx''+kx=0$. This first step of calculation allows us to check if the data in the graphic corresponds to a possible real movement.

We calculate the angular frequency by noting that on the graph, it takes the block 1050 milliseconds to complete one cycle. Using the formula $\omega=2\pi$ /Temps , we obtain the result 5.983rad/s.

Then we apply the formula: $x(t)=A\cos(\omega t+\varphi)$

- ***A*** is the maximum amplitude of the movement, which is 4 m.
- ***ω*** is the angular frequency, measured in radians per second, which is 5.983rad/s
- ***φ*** is the initial phase, which is 0 rad.
- ***t*** is the time, measured in seconds.

This gives us the formula : $x(t)=4\cos(5.983t)$, which will allow us to draw the blue curve shown in (Figure 36).

Graphing and comparison with the simulation: The results obtained using the simple harmonic formula are then compared to the wave motion produced by the simulation. Thanks to the similarity between these two curves, this comparison makes it possible to verify the accuracy and reliability of the simulated model.

Solving the harmonic equation with damping: As seen in section 2.4 of this thesis, this equation is a harmonic formula of the form mx”+kx=0, to which we add a damping term, which gives the equation mx”+cx’+kx=. To solve this equation, we continue to rely on (柴田[Akinori], 2014), which breaks down the process into several steps using previously collected data.

We start by calculating the inertia of the blocks using the following dimensions:

$$I=\frac{(b\times h)^3}{12}$$

$$I=\frac{(2.27m\times 2.1m)^3}{12}=9.02\ \mathrm{m}^4$$

Next, we calculate the stiffness (k) using the formula below, which takes into account Young’s modulus (E), the moment of inertia (I), and the height above the ground of the block (h):

$$k=\frac{3EI}{h^3}$$

$$k=\frac{3\times(2.5\times10^{11}N/m^2)\times9.02m^4}{(2m)^3}=8.46302\times10^5=846302\ \mathrm{N/n}$$

Calculate critical damping coefficient (C) based on the following formula and using the stiffness (k), the damping coefficient (ζ) and the mass(m).

$$C=2\times\zeta\sqrt{k\times m}$$

$$C=2\times0.01\sqrt{846302\ N/m\times23712kg}=1419.6\ \mathrm{Ns/m}$$

Next, we calculate the natural frequency (ωn) using the formula below and taking into account the mass (m) and stiffness (k) of the block.

$$\omega_n=\sqrt{\frac{\text{stiffness (k)}}{mass}}$$

$$\omega_n=\sqrt{\frac{846302\ N/m}{23712\ kg}}=5.98\mathrm{rad/s}$$

We then determine the critical damping factor (h) using data from (JPE, 2010), as well as the frequency (ω) and mass (m) of the block.

$$h=\frac{c}{2\times\omega\times m}$$

$$h=\frac{1419.6\ Ns/m}{2\times5.987\ rad/s\times23712kg}=0.005$$

Finally, based on the previous results, we use the following equation to calculate the displacement of our block:

$$y=e^{-h\omega t}\left(d_0\,cosh\sqrt{h^2-1\omega t}+\frac{v_0+h\omega\,d_0}{\sqrt{4-h^2\omega}}sin\,h\sqrt{h^2-1\omega t}\right)$$

However, given that the initial displacement d_0, is 0 radian, we can simplify the expression, allowing us to calculate the position of the block while accounting for the damping effect:

$$y=e^{-h\omega t}\left(\frac{v^0}{\sqrt{1-h^2\omega}}\times sin\sqrt{1-h^2}\times\omega t\right)$$

$$y=e^{-0.005\times5.98\times time}\left(\frac{25ms}{\sqrt{1-0.005^2\times5.98}}\times sin\sqrt{1-0.005^2}\times5.89\times time\right)$$

9. ***Creating a graph and comparing it with the simulation:*** The results obtained from the equation are used to create a graph comparing the calculated behaviour to that of the simulated blocks (Figure 38). As shown by the blue curves representing the movement of the blocks while accounting for damping, the calculated movement is similar to that simulated in Grasshopper.

DISCUSSION AND CONCLUSION:

This stage has allowed us to test the results obtained during the previous steps based on engineering data such as that provided by the research of (Yang & Hu, 2018).

This allows us to utilise the data collected during the simulations carried out (mass, size, volume, displacement of the block) as well as that gathered by other researchers to test our understanding of the simulations and the results obtained. We, therefore, carried out calculations to determine the frequency of the simulation, its behaviour without damping and its behaviour with damping. The graphs created from these calculations, by their similarity to those of the simulation, give us hope that the chain developed may be useful for simple tests. However, we must remain cautious, as the movement of dry masonry walls may turn out to be more complex than simulated and calculated. It will, therefore, be required to pursue the research begun during this dissertation.

Although this stage of research has taught us a lot, it will be important to carry out laboratory tests for future study to get complementary data to the one obtained in this stage. At the same time, it will be necessary to continue to learn from the work of other teams, such as (Hashimoto & al., 2021). This will enable us to get values and behaviour that are approximate, but consistent with real observations.

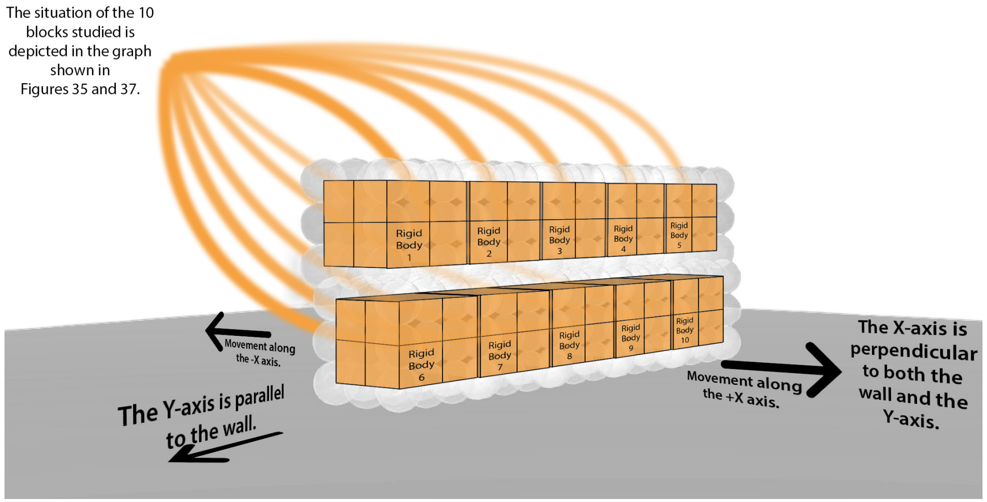


Figure 37: *Diagram illustrating the data recorded during this stage of the research. The diagram shows 10 blocks that have been recorded under simulated pressure along the X-axis. [Original Image©].*

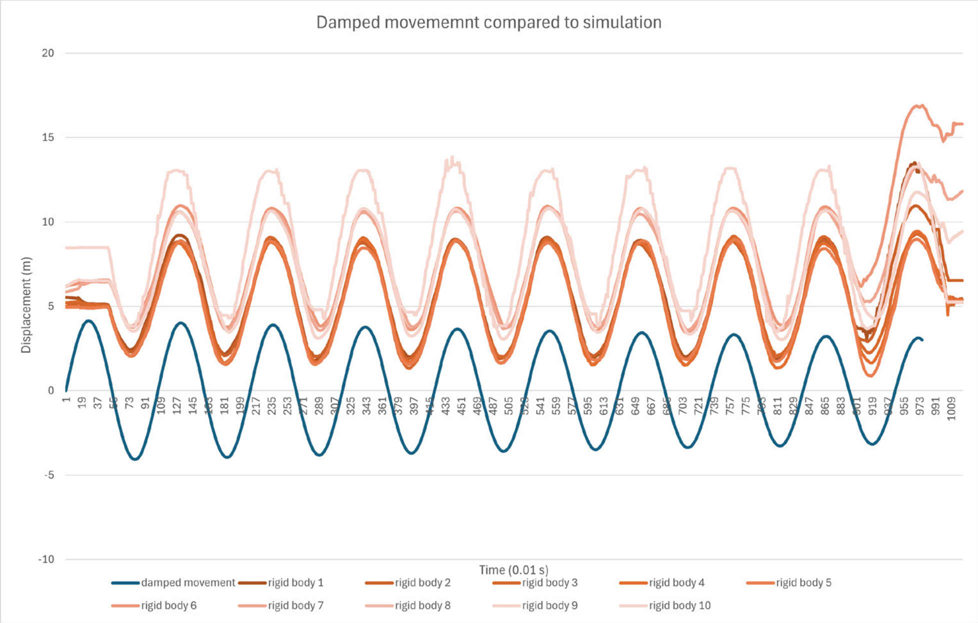


Figure 38: *Image showing the colected data of the simulation in orange compared to the harmonique motion with dumping calculated in blue. [Original image©]*

C. USING THE KNOWLEDGE FROM THE PREVIOUS STEPS TO CREATE A MORE SPECIALISED SIMULATOR.

STAGE 10: LOOKING FOR AN ALTERNATIVE TO FLEX HOPPER IN THE PHYSX ECOSYSTEM DEVELOPED BY NVIDIA. (06/05/2024 TO 13/05/2024)

INTRODUCTION:

Faced with the limitations outlined in the previous stages regarding earthquake simulation, a parallel study was conducted to evaluate the realism of the simulation. The aim was to find a way to overcome the restrictions imposed by the FlexHopper plugin, particularly the lack of support for friction between “collision bodies” and “rigid bodies,” as well as the computational heaviness caused by using a large number of particles.

Due to these constraints, it became crucial to find an alternative to create more realistic, fast, and powerful simulations.

STEPS COMPLETED:

In this context, the Grasshopper plugin PhysX. Gh, developed by (Kao & al., 2019) (Figure 39), was tested according to the following procedure:

- ***Preparation:*** PhysX. Gh was installed in Grasshopper, followed by a thorough review of the documentation to understand its utilisation and capabilities.
- ***Model Creation:*** Sections of Ishigaki walls were modelled in 3D using Grasshopper. These models served as the basis for simulation experiments, providing a realistic representation of the structures under study.
- ***Simulation Attempt:*** An attempt was made to set up a scene to simulate seismic forces. However, it was discovered that PhysX. Gh could not assign predefined movements to an object in the scene, which prevented the creation of realistic earthquake simulations.

Despite these limitations, PhysX. Gh remains promising, particularly because it is based on the PhysX physics simulator, which has been fully open source since 2018 and has received major updates since 2022 (Wikipedia contributors, 2024). These updates have allowed for the incorporation of new specialised simulators for more advanced physical simulations, and the performance has been improved to be faster and more accurate (Moravanszky, 2022).

PhysX has also been integrated into the NVIDIA Omniverse platform (NVIDIA Omniverse, n.d.), offering great capabilities in terms of customisation and simulation, as well as partnerships with major 3D modelling platforms like Rhinoceros. Intrigued by these capabilities, I decided to test the Omniverse software to understand its capabilities and limitations.

The test can be summarised as follows:

- ***Installation on Laptop:*** Despite NVIDIA’s recommendations to install Omniverse on a “workstation” using components from the firm, an installation attempt was made on my laptop which is equipped with an RTX 2060 graphics card from 2019. However, after installation, the application did not function properly, with the modelling window remaining black.
- ***Installation on Desktop Computer:*** During my stay at the Kyoto Institute of Technology, I had access to non-professional computers equipped with RTX 4090[22] graphics cards from 2022, which were the most powerful non-professional graphics cards at the time of writing this thesis, and close to the professional cards recommended for testing the software.

---

[22] *A more detailed comparison of the performance of the two graphics cards cited in the first points of this stage of research can be made on the manufacturer’s website: Compare GeForce RTX and GTX Graphics Cards series. (n.d.). NVIDIA. Retrieved June 14, 2024, from https://www.nvidia.com/en-us/geforce/graphics-cards/compare/*

- ***Initial Interactions:*** Once launched, Omniverse offers a wide range of features, whether for creating realistic renders or physical simulations. It also includes visual programming capabilities. However, the same limitations encountered with Blender and Unity, the need for modelling in the initial stage of creation, prevent the complete parameterisation of the experiment.

- ***Linking Rhino with Omniverse:*** The Omniverse plugin was installed in Grasshopper to facilitate the transfer of geometric data. This integration aimed to leverage the advanced simulation capabilities of Omniverse.

- ***Execution of Simulation:*** Geometries were exported from Grasshopper to Omniverse, followed by an attempt to simulate an earthquake. As with Blender and Unity, while it is possible to transmit geometries, it is not possible to interact with them via Rhinoceros 3D or Grasshopper.

DISCUSSION AND CONCLUSION:

Execution of Simulation: Geometries were exported from Grasshopper to Omniverse, followed by an attempt to simulate an earthquake. As with Blender and Unity, while it is possible to transmit geometries, it is not feasible to interact with them via Rhinoceros 3D or Grasshopper.

This software, despite its strength and versatility, was therefore not selected. Indeed, it is only usable by the most powerful computers and requires components that, due to their cost, are less widespread than other more affordable components. Moreover, it presents the same limitations as the programming languages of other software showcased in this study, making the complete parameterisation of the software complicated.

However, this test allowed us to better understand the objectives that this master thesis aims to achieve, by first making the software accessible to most people without component constraints. To this end, it was decided to continue the research to find different ways to answer the question: “How can a visual programming tool be used to simulate the behaviour of Ishigaki walls during seismic events?”

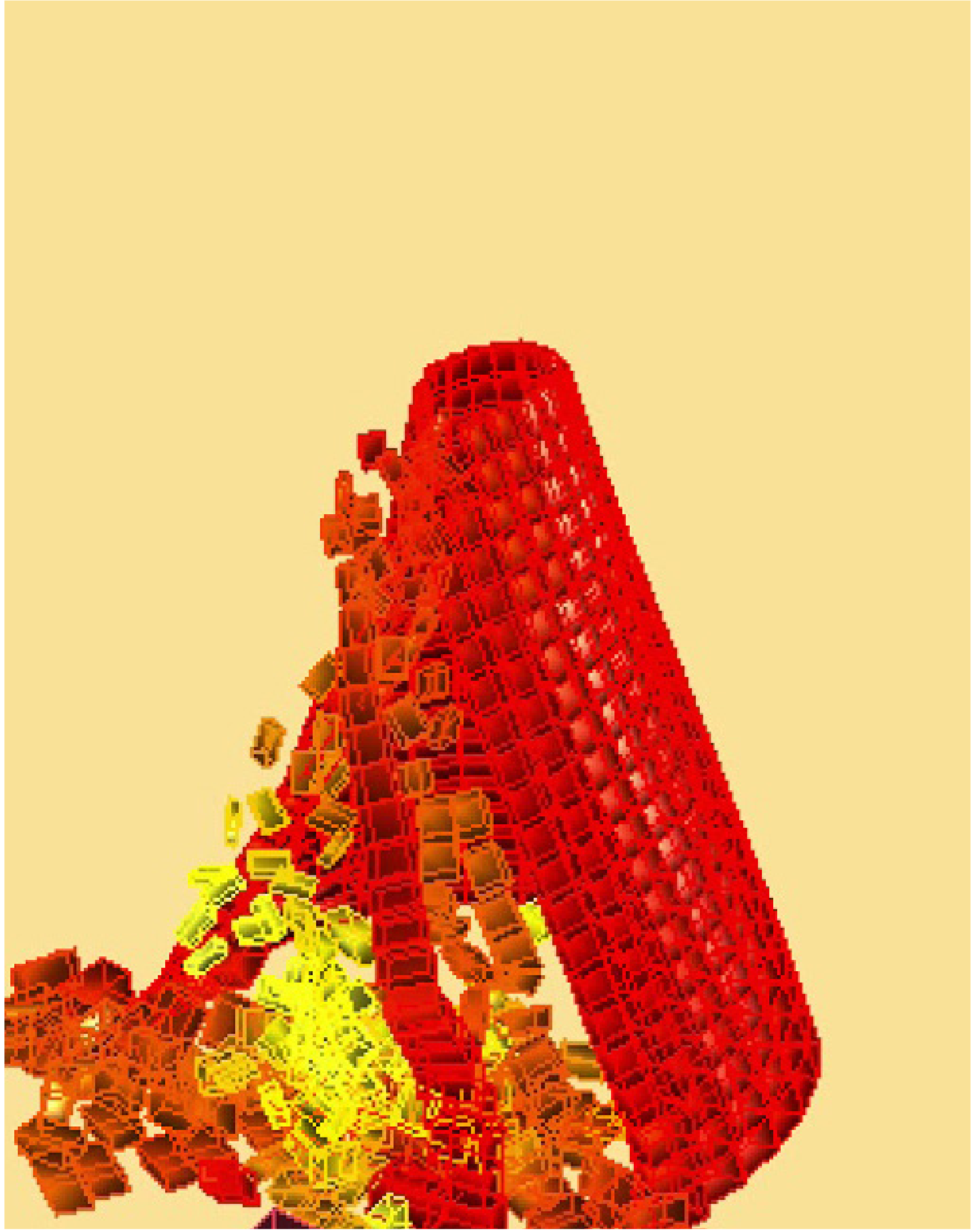


Figure 39: *Image showing the use of PhysX.GH that can simulate numerous “rigid body” but is not able to simulate an earthquake. Image from Kao, G. T. C. K., Nguyen, L. N., & The Asian Coders. (2019a, January 8). PHYSX.GH. Food4rhino. https://github.com/TheAsianCoders/PhysX.GH/blob/master/README.md*

STAGE 11: DEVELOPMENT OF A SPECIALISED SOLVER. (01/06/2024 TO 26/06/2024).

INTRODUCTION:

After numerous experimentation stages that have helped to better understand the issues of this thesis, while identifying the challenges of using a real-time simulator corresponding to the criteria outlined at the beginning of this study, it was decided to start developing our own specialised plug-in.

This final research phase aims to create a specialised plug-in that meets the criteria that have guided this research. It was decided to use the capabilities of the PhysX physics simulator produced by Nvidia, for creating a specialises in real-time simulation of rigid bodies undergoing an earthquake. This specialisation will allow for optimising the speed of the simulation and limiting the computational power required.

STEPS COMPLETED:

As this is still ongoing research and will continue next year, it is possible to trace the steps already completed, which are as follows:

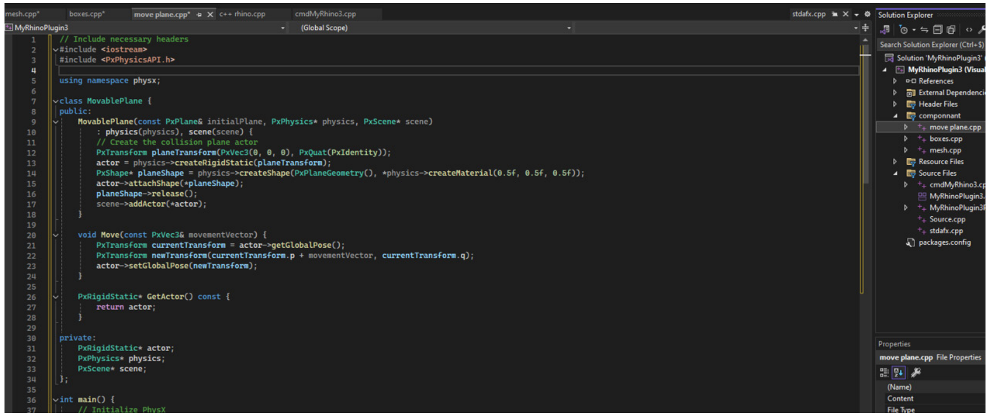
- **Learning how to create a plug-in for Grasshopper:** To learn how to build a Grasshopper plug-in, we referred to tutorial videos like those by (ParametricCamp, 2022) or (ProArchitect, 2023).
- **Understanding how Visual Studio works:** Visual Studio is a software that (Microsoft, 2024) defines as “a creative launch pad you can use to edit, debug, and build code, and then publish an app.” This software has also enhanced compatibility with Rhinoceros, offering presets to link the two software applications during plug-in development to correct possible errors.
- **Choice of programming language:** There are several programming languages, each with its own characteristics. In this programming endeavour, C++ was selected because it has the advantage of being the same language as PhysX, which will later allow for using the language without needing to create a translation for each term.
- **Integration of the PhysX library into the programming environment:** Use of VCPKG, which (Microsoft, n.d.) defines as a “cross-platform C/C++ package manager,” enabling the integration of a list of terms linked to specific commands of programs like PhysX, thus simplifying the programming of the plug-in by using a vocabulary recognised by the software (Figure 40).

DISCUSSION AND CONCLUSION:

During this last research step, I have learned the basics of developing a plug-in dedicated to being incorporated into Grasshopper. For this, it was necessary to start learning new software and a new programming language, as well as the processes developers utilise to accomplish their tasks.

This investigation phase marks an important step for this research. Thanks to the understanding acquired through the literature review and the experiences gained during this third chapter, I am now able to start creating a tool that no longer relies on the work of others but instead draws on the knowledge gathered during this research to address the question posed at the beginning of this thesis.

Thus, thanks to all this, it is now possible to conclude this study.



```
// Include necessary headers
#include <iostream>
#include <PxPhysicsAPI.h>

using namespace physx;

class MovablePlane {
public:
    MovablePlane(const PxPlane& initialPlane, PxPhysics* physics, PxScene* scene)
        : physics(physics), scene(scene) {
        // Create the collision plane actor
        PxTransform planeTransform(PxVec3(0, 0, 0), PxQuat(PxIdentity));
        actor = physics->createRigidStatic(planeTransform);
        PxShape* planeShape = physics->createShape(PxPlaneGeometry(), *physics->createMaterial(0.5f, 0.5f, 0.5f));
        actor->attachShape(*planeShape);
        planeShape->release();
        scene->addActor(*actor);
    }

    void Move(const PxVec3& movementVector) {
        PxTransform currentTransform = actor->getGlobalPose();
        PxTransform newTransform(currentTransform.p + movementVector, currentTransform.q);
        actor->setGlobalPose(newTransform);
    }

    PxRigidStatic* GetActor() const {
        return actor;
    }

private:
    PxRigidStatic* actor;
    PxPhysics* physics;
    PxScene* scene;
};

int main() {
    // Initialize PhysX
```

Figure 40: *Image showing the visual studio interface and the first lines of code being created. [Original image©]*

CHAPTER 4: CONCLUSION AND OPENING.

CONCLUSION

This study aimed to initiate research to design a simulation tool using visual programming to optimise Japanese Ishigaki walls. At the intersection of various concepts, this study required a concise definition of the ideas addressed and was successively tackled in the literature review.

The thesis began by specifying the geographical area studied and identifying significant earthquakes in its history, leading to an analysis of the influence of these events on Japanese architecture. This approach explored existing research on using visual programming, the different physical simulators used by academics, and the mathematical foundations underpinning them.

With this knowledge, the first physical simulations were developed, consisting of two interdependent parts: one simulating the physical behaviour of the walls, the other modelling the effects of earthquakes. After exploring several approaches, the characteristics of the future program were defined as follows:

- Seamless integration with Rhino3D.
- Precise control over geometric movements.
- Definition of interactions between geometries and surfaces.
- Accurate simulation of multiple collisions.
- Real-time visualisation.
- Parametric flexibility.
- Complete parameterisation.

To meet these needs, the software Grasshopper and Flexhopper, a particle physics simulation plug-in developed by (HeinzBenjamin, 2019), were chosen. However, the constraints associated with Flexhopper revealed that it was impossible, in the current state of the developed Grasshopper chains, to realistically simulate the complex interactions between an earthquake and the blocks of an Ishigaki wall.

Despite these limitations, research continued to assess whether the simulations created during this study could still contribute to a better understanding of a wall's movements under seismic pressure. Several ground movement scenarios at different frequencies were developed and recorded. The scenario exhibiting significant sinusoidal motion, due to its perpendicularity to the simulated wall, was selected for a detailed mathematical analysis, using harmonic equations with and without damping. These analyses provided better insight into the forces at play and helped evaluate the realism of the simulations.

In conclusion, it can be asserted that, in the current state of the research, realistic earthquake simulations remain out of reach. Nevertheless, it is possible to perform simplified realistic earthquake simulations by applying different oscillation scenarios to the modelled walls.

It is important to note, however, that the Flexhopper physics simulator imposes limitations on the number of blocks that can be simulated, due to the significant computational power required, making the program less accessible to designers with more modest hardware configurations. In response to these challenges, the possibility of employing another physics simulation engine was considered at the end of this study, however, this exploration didn't succeed. The adoption of the "PhysX" engine developed by Nvidia, to create a plug-in specialised in simulating "rigid bodies" subjected to earthquakes, paves the way for more realistic simulations of Ishigaki walls using visual programming.

Thus, although this thesis has revealed technical limitations, it has also laid the groundwork for promising future research, aiming to refine the tools necessary to realistically simulate the behaviour of Ishigaki walls during earthquakes, thereby contributing to the preservation of Japan's architectural heritage.

OPENING

This research aimed at stimulating the behaviour of masonry walls during earthquakes in Japan, it was possible to establish a solid knowledge base. This knowledge subsequently allowed the development of an empirical method, which, through numerous trials and errors, led to the creation of a physical simulator using existing plug-ins and visual programming capabilities. This simulator enabled the assessment of the simulation's realism, as explained in the conclusion.

The results obtained are promising but are limited by the physical simulator used. However, this research opens up many avenues for improvement in the simulation and analysis of dry masonry walls employing Grasshopper.

Therefore, during the doctoral research that will follow this master's thesis, the final step will involve programming a plug-in leveraging the capacities of the PhysX physics engine, specialised in the simulation of rigid bodies. This will allow novices in engineering and programming to visually understand the capabilities of the 3D model they are testing. The hope is that this will lead to advances in construction and the preservation of historical monuments in areas with significant seismic pressures, like Japan, contributing to the preservation and safety of the world's architectural heritage.

Once this plug-in is developed, it could be promising to integrate artificial intelligence and machine learning tactics to refine the simulations and more accurately predict the behaviour of Ishigaki walls under various seismic conditions. Additionally, exploring new augmented and virtual reality technologies could provide architects and creators with interactive and immersive means to visualise and adjust structures in real-time.

Furthermore, interdisciplinary collaboration between architecture, civil engineering, and computer science could lead to the design of innovative solutions that are adapted to contemporary needs and respectful of traditional techniques.

BIBLIOGRAPHY :

- 日本建築センタ[Japan Architecture Center]. (2016). THE BUILDING ST 日本建築センタ[Japan Architecture Center]. (2016). THE BUILDING STANDARD LAW OF JAPAN (May 2016) [Printed]. 日本建築センタ [Japan Architecture Center].

- Abe, K. (1979). Size of great earthquakes of 1837–1974 inferred from tsunami data. Journal of Geophysical Research Atmospheres, 84(B4), 1561–1568. https://doi.org/10.1029/jb084ib04p01561

- Abundance, Z. =. (2023, December 27). Is stone wall a sustainable architectural choice? Ask traditional Japanese masons. zero = abundance. https://www.interactiongreen.com/japanese-stone-wall/

- Ahn, JK. A., Park, D., & Yoo, J.-K. (2015). Estimation of damping ratio of rock mass for numerical simulation of blast induced vibration propagation. The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering. https://www.jstage.jst.go.jp/article/jgssp/2/45/2_KOR-34/_pdf

- Aki, K. A. (1966). generation and Propagation of G Waves From the Niigata earthquake of june 16, 1964.: Part 2.Estimation of earthquake moment, released energy, and stress-steain drop from the G waves spectrum. Bulletin of the Earthquake Research Institute, 44, 73–88. https://ds.irid.edu/seismo-archives/quakes/1964niigata/Aki1966b.pdf

- Aoyagi, Y., Kimura, H., & Mizoguchi, K. (2020). Seismic velocity structure at the southern termination of the 2016 Kumamoto Earthquake rupture, Japan. Earth, Planets and Space, 72(1). https://doi.org/10.1186/s40623-020-01276-1

- Benjamin F. (2018a, May 28). FlexHopper Workshop Part 2/6: Fluid Systems [Video]. YouTube. Retrieved April 1, 2024, from https://www.youtube.com/watch?v=A1j3211X9yM

- Benjamin F. (2018b, May 28). FlexHopper Workshop Part 5/6: Rigid Bodies & Shape Matching Constraints [Video]. YouTube. Retrieved May 6, 2024, from https://www.youtube.com/watch?v=fQ69agaAg60

- Bićanić, N. (2004). Discrete Element Methods. Encyclopedia of Computational Mechanics. https://doi.org/10.1002/0470091355.ecm006.pub2

- Biran, O., & Ziv, A. (2009). Micro-scale roughness effects on the friction coefficient of granite surfaces under varying levels of normal stress. In CRC Press eBooks (pp. 145–156). https://doi.org/10.1201/b10826-18

- Blanchard, N. B. (2018). Politiques et mesures de réaménagement urbain dans le Tôkyô de l'après-séisme de 1923. 経済論集, 43(2), 127–145. https://toyo.repo.nii.ac.jp/?action=repository_action_common_download&item_id=9817&item_no=1&attribute_id=22&file_no=1

- Block Research Group (ETH). (2024). RV2 [Software]. In Food4Rhino. https://www.food4rhino.com/en/app/rv2

- Bormann, P. (2012). Magnitude calibration formulas and tables, comments on their use and complementary data. GFZ German Research Centre for Geosciences, 1–19. https://doi.org/10.2312/gfz.nmsop-2_ds_3.1

- Bouhelal, A. B., & Arezki, S. A. (2022, June 22). Introduction à la CFD [Slide show; Numérique]. hal.science. https://hal.science/hal-04427690

- Brown, E. (2011, March 31). Japan earthquake science: Japan earthquake shifted Earth on its axis - Los Angeles Times. Los Angeles Times. https://www.latimes.com/science/la-sci-japan-quake-science-20110313-story.html

- Cea. (n.d.). La simulation numérique. CEA/Découvrir & Comprendre. Retrieved March 4, 2024, from https://www.cea.fr/comprendre/Pages/physique-chimie/simulation-numerique.aspx?Type=Chapitre&numero=1

- Clancey, G. (2006). Earthquake nation: The Cultural Politics of Japanese Seismicity, 1868-1930. Univ of California Press.

- Cluzel, J. S. (2018). L'influence européenne dans l'architecture japonaise (1860-1930). EHNE. Retrieved April 20, 2023, from https://ehne.fr/fr/encyclopedie/th%C3%A9matiques/les-arts-en-europe/l%E2%80%99art-de-l%E2%80%99europe-%C3%A0-l%E2%80%99%C3%A9preuve-de-%C2%AB-l%E2%80%99autre-%C2%BB/l%E2%80%99influence-europ%C3%A9enne-dans-l%E2%80%99architecture-japonaise-1860-1930

- Compare GeForce RTX and GTX Graphics Cards series. (n.d.). NVIDIA. Retrieved June 14, 2024, from https://www.nvidia.com/en-us/geforce/graphics-cards/compare/

- Contributeurs aux projets Wikimedia. (2024, April 14). Échelle de Shindo. https://fr.wikipedia.org/wiki/%C3%89chelle_de_Shindo

- Costantino, D., Grimaldi, A., & Pepe, M. (2022). 3D MODELLING OF BULDINGS AND URBAN AREAS USING GRASSHOPPER AND RHINOCERSOS. Geographia Technica, 17(1/2022), 167–176. https://doi.org/10.21163/gt_2022.171.13

- Daniel Christev. (2016, March 8). Grasshopper - Creating a wave simulation in Kangaroo [Video]. YouTube. Retrieved May 8, 2024, from https://www.youtube.com/watch?v=OhCwaoZs7zw

- De Boissieu, A. (2013). Modélisation paramétrique en conception architecturale : Caractérisation des opérations cognitives de conception pour une pédagogie. Modélisation Paramétrique En Conception Architecturale. https://hdl.handle.net/2268/253979

- Di Sarno, L., & Wu, J. (2020). Seismic assessment of existing steel frames with masonry infills. Journal of Constructional Steel Research, 169, 106040. https://doi.org/10.1016/j.jcsr.2020.106040

- Dias-Oliveira, J., Varum, H., Asteris, P. G., & Varum, H. (2022). On the Seismic Behavior of Masonry Infilled Frame Structures. Buildings, 12(8), 1146. https://doi.org/10.3390/buildings12081146

- Ding, L. D. (2016). BRICK-FANTASY: Integrating form-finding of brick shell structure into the design of new architecture in seism-affected Groningen. MSc Graduation. https://repository.tudelft.nl/islandora/object/uuid:e8c1ba0c-0c2f-4bb8-b94b-b821cb6de203/datastream/OBJ2/download

- Earthquake building codes in Japan. (2021, December 29). JAPAN PROPERTY CENTRAL K.K. Retrieved May 19, 2023, from https://japanpropertycentral.com/real-estate-faq/earthquake-building-codes-in-japan/

- Erez, T., Tassa, Y., & Todorov, E. (2015). Simulation tools for model-based robotics: Comparison of Bullet, Havok, MuJoCo, ODE and PhysX. IEEE. https://doi.org/10.1109/icra.2015.7139807

- experts comment on Japan earthquake and tsunami | Science Media Centre. (2011, March 11). https://www.sciencemediacentre.org/experts-comment-on-japan-earthquake-and-tsunami-2/

- Fouques, A. (2018, January 18). Granite - la matériauthèque. https://materiautheque-laplace.second-degre.ac-normandie.fr/spip.php?article28

- Fowler, C. M. R. (2005). The Solid Earth: An Introduction to Global Geophysics. Cambridge University Press.

- Gertin, Y. (2014). COMPORTEMENT SISMIQUE D'UN MUR EN MAÇONNERIEARMÉE ENTIÈREMENT REMPLI DE CO (C.-P. Lamarche, Interviewer). UNIVERSITÉ DE SHERBROOKE, Faculté De Génie, Département De Génie Civil.

- Goldsman, D., Nance, R. E., & Wilson, J. R. (2009). A brief history of simulation. Proceedings of the 2009 Winter Simulation Conference (WSC). https://doi.org/10.1109/wsc.2009.5429341

- Goyal, A. K., & Agarwal, P. K. (2017). Earthquake-Resistant Interlinked Block Masonry System with Energy Dissipator Viscoelastic Links. Practice Periodical on Structural Design and Construction, 22(3). https://doi.org/10.1061/(asce)sc.1943-5576.0000319

- Grewal, N., Escallon, M., Chaudhary, A., & Hramyka, A. (2019a). INFRASONIC. Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). https://doi.org/10.52842/conf.acadia.2019.234

- Grewal, N., Escallon, M., Chaudhary, A., & Hramyka, A. (2019b, January 1). INFRASONIC. Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). https://doi.org/10.52842/conf.acadia.2019.234

- Gutenberg, B., & Richter, C. F. (1936). Magnitude and energy of earthquakes. Science, 83(2147), 183–185. https://doi.org/10.1126/science.83.2147.183

- Hanks, T. C., & Kanamori, H. (1979). A moment magnitude scale. Journal of Geophysical Research, 84(B5), 2348–2350. https://doi.org/10.1029/jb084ib05p02348

- Hashimoto, T., Nakazawa, H., Ikemoto, T., & Miyajima, M. (2021). SEISMIC EVALUATION OF STONE WALL REINFORCEMENT TECHNOLOGY BY LARGE-SCALE SHAKING TABLE TEST. Doboku Gakkai Rombunshuu. A1, Kouzou, Jishin Kougaku, 77(3), 405–417. https://doi.org/10.2208/jscejseee.77.3_405

- Heinz, B. H. (n.d.). Benjamin F. https://www.youtube.com/@benjaminf.3760

- HeinzBenjamin. (2019). FlexHopper [Software]. In HeinzBenjamin/FlexCLI: FlexCLI (1.1.2). https://doi.org/10.5281/zenodo.3355744

- Hoxha, D. H. (2022). Génie Parasismique [Slide show; Digital]. Polytech Orléans University of Orleans Engineering School, orléans, Centre-Val de Loire, France. Module 2 : Parasismique et dynamique des structure.

- Inazaki, T., Ôta, Y., & Maruyama, S. (2014). The Largest and Longest Project in Japan—Spanning over 400 Years. Journal of Geography, 123(4), 401–433. https://doi.org/10.5026/jgeography.123.401

- Intro to matrices (article) | Matrices | Khan Academy. (n.d.). Khan Academy. Retrieved May 12, 2024, from https://www.khanacademy.org/math/precalculus/x9e81a4f98389efdf:matrices/x9e81a4f98389efdf:mat-intro/a/intro-to-matrices

- JAPAN PROPERTY CENTRAL K.K. (2024, April 14). Earthquake building codes in Japan. https://japanpropertycentral.com/real-estate-faq/earthquake-building-codes-in-japan/

- JPE. (2020, October 9). Structural damping properties of mechanical systems - JPE. https://www.jpe-innovations.com/precision-point/structural-damping-properties-mechanical-systems/

- Kanamori, H. (1977). The energy release in great earthquakes. Journal of Geophysical Research, 82(20), 2981–2987. https://doi.org/10.1029/jb082i020p02981

- Kanie, Y., & Kanie, Y. (2022). The 1923 Great Kanto earthquake on the Zushi-Kotsubo Coast, Sagami Bay: evidence of quake, tsunami and landslide after-effects. Journal of Geography, 131(3), 381–392. https://doi.org/10.5026/jgeography.131.381

- Kao, G. T. C. K., Nguyen, L. N., & The Asian Coders. (2019a, January 8). PHYSX.GH. Food4rhino. https://github.com/TheAsianCoders/PhysX.GH/blob/master/README.md

- Kao, G. T. C. K., Nguyen, L. N., & The Asian Coders. (2019b). PHYSX.GH (0.1) [Software]. https://github.com/TheAsianCoders/PhysX.GH/blob/master/README.md

- Karamba. (2024). Karamba3D [Software]. In Food4Rhino (3.1.4). https://www.food4rhino.com/en/app/karamba3d

- Kimura, G., Nakamura, Y., Shiraishi, K., Fujie, G., Kodaira, S., Tsuji, T., Fukuchi, R., & Yamaguchi, A. (2022). Nankai forearc structural and seismogenic segmentation caused by a magmatic intrusion off the Kii peninsula. Geochemistry, Geophysics, Geosystems, 23(8). https://doi.org/10.1029/2022gc010331

- Koutaki, G., Ando, S., Shirai, K., & Kishigami, T. (2022). ISHIGAKI Retrieval System using 3D shape matching and combinatorial optimization. International Journal of Computer Vision, 130(9), 2286–2304. https://doi.org/10.1007/s11263-022-01630-8

- Ledra, M., Rima, B., & Fatiha, F. (2016). La méthode Monté Carlo et ses applications. ResearchGate. https://www.researchgate.net/publication/310828308_La_methode_Monte_Carlo_et_ses_applications

- Logan, D. L. (2007). A first course in the finite element method. Thomson Learning.

- Love wave. (n.d.). https://www.eri.u-tokyo.ac.jp/people/knishida/eng/Seismology/Love_wave.html

- xfschr. (2022). Quelea - agent-based design for Grasshopper [Software]. In Food4Rhino (alpha 0.0.9). https://www.food4rhino.com/en/app/quelea-agent-based-design-grasshopper

- McNeel Forum. (n.d.). McNeel Forum. https://discourse.mcneel.com/

- Microsoft. (n.d.). Documentation vcpkg. Microsoft Learn. Retrieved August 4, 2024, from https://learn.microsoft.com/fr-fr/vcpkg/

- Microsoft. (2024). Visual Studio : IDE et Éditeur de Code pour les Développeurs de Logiciels et les Équipes [Software]. In Visual Studio. https://visualstudio.microsoft.com/fr/

- Miller, N. (2024). LunchBox [Software]. In Food4Rhino (2024.2.9.0). https://www.food4rhino.com/en/app/lunchbox

- Millington, I. (2010). Game Physics Engine Development: How to Build a Robust Commercial-Grade Physics Engine for your Game. CRC Press.

- Miroliubov, A. M. (2018). Visual Programming-An alternative way of developing software. Metropolita, 1. https://www.theseus.fi/bitstream/handle/10024/146332/Aleksandr_Miroliubov_Visual_Programming_Thesis.pdf?sequence=1

- Mitsui, N., & Hirahara, K. (2004). Simple Spring-mass Model Simulation of Earthquake Cycle along the Nankai Trough in Southwest Japan. Pure and Applied Geophysics, 161(11–12). https://doi.org/10.1007/s00024-004-2574-6

- Moravanszky, A. (2022, November 18). Open Source Simulation Expands with NVIDIA PhysX 5 Release | NVIDIA Technical Blog. NVIDIA Technical Blog. https://developer.nvidia.com/blog/open-source-simulation-expands-with-nvidia-physx-5-release/

- Mori, S., Fujioka, K., & Arima, M. (2010). Topographical and geological characteristics of the Sagami Trough: Development of five fault systems in the northern part of the Sagami Trough. Chigaku Zasshi/Chigaku Zasshi, 119(4), 585–614. https://doi.org/10.5026/jgeography.119.585

- Muguruma, H. M., Nishiyama, M. N., & Watanabe, F. W. (1995). Lessons Learned from the Kobe Earthquake A Japanese Perspective. SPECIAL REPORT. https://learningfromearthquakes.org/images/earthquakes/1995_Kobe_Japan/Lessons_Learned_from_the_Kobe_Earthquake_-_A_Japanese_Perspective-PCI.pdf

- Nanayama, F. (2020). Evidence of giant earthquakes and tsunamis of the seventeenth-century type along the southern Kuril subduction zone, eastern Hokkaido, northern Japan: a review. Special Publication - Geological Society of London/Geological Society, London, Special Publications, 501(1), 131–157. https://doi.org/10.1144/sp501-2019-99

- Nancy. (2022, March 16). Earthquake building codes and technology in Japan - blog. Blog. https://resources.realestate.co.jp/buy/earthquake-building-codes-and-technology-in-japan/

- NVIDIA Omniverse. (n.d.). NVIDIA. https://www.nvidia.com/fr-fr/omniverse/#nv-accordion-a0863daaee-item-17946d1ca6

- NVIDIA Omniverse Enterprise Systems. (n.d.). NVIDIA. https://www.nvidia.com/en-eu/omniverse/platform/enterprise-systems/
- Ohsumi, T. (2017). Investigation on the damage to Kumamoto Castle Stone Wall related to the 2016 Kumamoto earthquakes. Lowland Technology International, 19, 175–184. http://cot.unhas.ac.id/journals/index.php/ialt_lti/article/view/515
- Oster, J. O. [Joseph_Oster]. (2020, August 19). Timer for button [Online forum post]. McNeel Forum. https://discourse.mcneel.com/t/timer-for-button/107366
- Papadopoulos, J. (2014, December 12). New NVIDIA video shows off GameWorks PhysX FleX features. DSOGaming. https://www.dsogaming.com/videotrailer-news/new-nvidia-video-shows-off-gameworks-physx-flex-features/
- ParametricCamp. (2022, March 2). 5.3 Development Setup of a Grasshopper Plug-in - Advanced Development in Grasshopper [Video]. YouTube. Retrieved March 16, 2024, from https://www.youtube.com/watch?v=xS2AbtpP2E0
- Piker, D. (2013). Kangaroo: Form Finding with Computational Physics. Architectural Design, 83(2), 136–137. https://doi.org/10.1002/ad.1569
- ProArchitect. (2023, October 26). Create a Grasshopper C# Plug-in in 10 minutes (Rhino 3D) [Video]. YouTube. Retrieved May 19, 2024, from https://www.youtube.com/watch?v=bwlDdgvHPVw
- Quinones, L. (2022). Culebra [Software]. In Food4Rhino (1.0). https://www.food4rhino.com/en/app/culebra
- Rayleigh, L. (1885). On Waves Propagated along the Plane Surface of an Elastic Solid. Proceedings of the London Mathematical Society, s1-17(1), 4–11. https://doi.org/10.1112/plms/s1-17.1.4
- Rippmann, M. (2022). RhinoVAULT [Software]. In Food4Rhino. https://www.food4rhino.com/en/app/rhinovault
- Satake, K. (2015). Geological and historical evidence of irregular recurrent earthquakes in Japan. Philosophical Transactions of the Royal Society A, 373(2053), 20140375. https://doi.org/10.1098/rsta.2014.0375
- Sheth, U. S., & Fida, A. F. (2020). Funicular Structures using Topological Assemblies. CAADRIA, 1, 75–84. http://papers.cumincad.org/cgi-bin/works/paper/caadria2020_072
- Strand7. (2020). Strand7 - Finite Element analysis (R3.1.4) [Software]. https://www.strand7.com/
- Tait, T. (2024, February 21). Mastering the Grasshopper Interface: A Beginner's guide. Hopific. https://hopific.com/the-grasshopper-interface-a-beginners-guide/
- Takeda, K., & Inaba, K. (2022). The damage and reconstruction of the Kumamoto earthquake: an analysis on the impact of changes in expenditures with multi-regional input–output table for Kumamoto Prefecture. Journal of Economic Structures, 11(1). https://doi.org/10.1186/s40008-022-00276-6
- Toshiakira. (2023, March 9). Kw-bunnka.com/自立しない!: [self-supporting]. 我々は石垣を修復(なお)せるか[Can We Repair the Stone Walls?]. https://kw-bunnka.com/%E8%87%AA%E7%AB%8B%E3%81%97%E3%81%AA%E3%81%84%EF%BC%81%EF%BC%88%E2%85%B0%EF%BC%89/
- Triton, L., Earle, S., Bačić, M. B., Librić, L. L., Jurić Kaćunić, D. J., Saša Kovačević, M. S., & wikimedia. (4 C.E., July 23). Overview_Seismic_Waves. Wikimedia. https://upload.wikimedia.org/wikipedia/commons/0/07/Overview_Seismic_Waves.jpg
- Uchida, T. (2015). Ecological role of natural stone masonry in rice terraces on plant species diversity. Nihon Ryokka Kogakkaishi/Nihon Ryokka Kōgakkaishi, 41(1), 267–270. https://doi.org/10.7211/jjsrt.41.267
- Understanding the fundamentals of earthquake signal sensing networks | Analog Devices. (n.d.). https://www.analog.com/en/resources/analog-dialogue/articles/understanding-the-fundamentals-of-earthquake-signal-sensing-networks.html
- Valencia-García, R., Lagos-Ortiz, K., Alcaraz-Mármol, G., Del Cioppo, J., & Vera-Lucio, N. (2016). Technologies and Innovation: Second International Conference, CITI 2016, Guayaquil, Ecuador, November 23-25, 2016, Proceedings. Springer.
- Walker, J., & Resnick, R. (2018). Halliday and Resnick Fundamentals of Physics.
- Wikipedia contributors. (2024). PhysX. In Wikipedia. Retrieved August 4, 2024, from https://en.wikipedia.org/wiki/PhysX
- Xie, Z., Cai, Y., Wang, C., Yoshioka, S., & Tanaka, M. (2019). Fault stress inversion reveals seismogenic asperity of the 2011 Mw 9.0 Tohoku-Oki earthquake. Scientific Reports, 9(1). https://doi.org/10.1038/s41598-019-47992-x

- Yang, S., & Hu, B. (2018). Creep and Long-Term permeability of a red sandstone subjected to cyclic loading after thermal treatments. Rock Mechanics and Rock Engineering, 51(10), 2981–3004. https://doi.org/10.1007/s00603-018-1528-8

- Yenice, Y., & Park, D. (2019a). V-INCA - Designing a smart geometric configuration for dry masonry wall. eCAADe Proceedings. https://doi.org/10.52842/conf.ecaade.2019.2.515

- Yenice, Y., & Park, D. (2019b, January 1). V-INCA - designing a smart geometric configuration for dry masonry wall. eCAADe Proceedings. https://doi.org/10.52842/conf.ecaade.2019.2.515

- Young, D. Y., & Young, M. Y. (2014). The Art of Japanese Architecture. Tuttle Publishing.

- 内閣府 [Cabinet office, Government of Japan]. (2013). 平成25年版 防災白書|附属資料1　平成23年(2011年)東北地方太平洋沖地震の概要：防災情報のページ - 内閣府: [White Paper on Disaster Prevention 2013|Annex 1: Overview of the 2011 Tohoku-Pacific Ocean earthquake : Disaster Prevention Information Page - Cabinet Office, Government of Japan]. In Cabinet Office. Government of Japan. Retrieved November 8, 2023, from https://www.bousai.go.jp/kaigirep/hakusho/h25/honbun/index.htm

- 川越蔵造りの町並みを散策しようー歴史からおすすめスポットまでご紹介!: [Take a stroll through the Kawagoe warehouses - from history to recommended spots!]. (2024, April 22). 埼玉りそな銀行 [Saitama Resona Bank]. https://www.saitamaresona.co.jp/mikke/local/local_0001.html

- 柴田[Akinori], 柴. (2014). 最新耐震構造解析: [Latest Seismic Structural Analysis] (3rd ed.) [Printed]. 森北[Morikita].

- 気象庁 [Japan Meteorological Agency]. (n.d.). 気象庁 | 強震波形(熊本県熊本地方の地震): [JMA | Strong-Motion Waveforms (Earthquake in Kumamoto Region, Kumamoto Prefecture)]. Retrieved January 17, 2024, from https://www.data.jma.go.jp/svd/eqev/data/kyoshin/jishin/1604160125_kumamoto/index2.html

- 気象庁 [Japan Meteorological Agency]. (n.d.-a). 2016/4/14 21:26:38 熊本県益城町惣領: [2016/4/14 21:26:38 Location, Sorio, Mashiki Town]. https://www.data.jma.go.jp/eqev/data/kyoshin/jishin/1604142126_kumamoto/wave/Q414EEB2.png

- 気象庁 [Japan Meteorological Agency]. (n.d.-b). 2016/04/16/ 01:24:50 熊本県益城町: [2016/04/16/ 01:24:50 Mashiki Town, Kumamoto, Japan]. https://www.data.jma.go.jp/eqev/data/kyoshin/jishin/1604160125_kumamoto/wave/Q416EEB001.png

- 気象庁 [Japan Meteorological Agency]. (n.d.-c). 気象庁 [Japan Meteorological Agency]. Retrieved April 12, 2024, from https://www.jma.go.jp/jma/en/Activities/inttable.html

- 気象庁 [Japan Meteorological Agency]. (2011). REPORT ON THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE BY JAPAN METEOROLOGICAL AGENCY. In 気象庁 [Japan Meteorological Agency] (ISSN 0447−3868). Retrieved December 24, 2023, from https://www.jma.go.jp/jma/kishou/books/gizyutu/133/gizyutu_133.html

- 気象庁[Japan Meteorological Agency]. (n.d.). 気象庁: [Japan Meteorological Agency]. Retrieved April 10, 2024, from https://www.jma.go.jp/jma/indexe.html

- 田淵[Tabuchi], 田. (1975). 石垣 [Ishigaki]. 法政大学出版局[Hosei University Press].

- 藤森[Terunobu], 藤. (1993). 日本の近代建築上[Modern Japanese Architecture]: 幕末・明治篇[Late Edo and Meiji Periods] (3rd ed.) [Printed]. 岩波書店[Iwanami Shoten].

- 西ヶ谷[Nishigaya], 西. (2008). 城郭の見方・調べ方ハンドブック: [A guide to viewing and researching castles.] [Printed]. 東京堂[Tokyo-Do].

Thank you for taking the time to read
this master’s thesis.

Sincerely,

Mathieu Gourbeyre