Application of ground penetrating radar for evaluating foundation structure condition after earthquake

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Abstract: At the time of seismic activity, the failure of the foundation structure will lead to building damage. When the West Pasaman 2022 earthquake occurred, PT. XYZ is constructing a feed mill tower. Since strong earthquake shocks were felt at the project location, foundation structure evaluation is needed to ensure the safety of the building. Ground Penetrating Radar (GPR) is a tool that is widely used to detect subsurface conditions. This study used GPR as a non-destructive testing technique to evaluate the condition of the foundation structure. The building evaluated is a high-rise steel building, using spun pile foundation. GPR test was carried out in specified lanes, with measurement tracks set at 10 lanes. Any cracks or fractures on the foundation will be indicated by the interruption of waves at the point of the crack or fracture. The GPR test results from readings of electromagnetic wave propagation showed that waves can reach the end of each foundation tested, ranging from 17.10 m to 17.82 m deep. It means that there are no cracks or fractures found on the slab, pile cap, or foundation. Analysis results showed that all slabs and pile caps thicknesses and the detected foundation piles depths are in accordance with the foundation design, which means that the foundations are still in good condition.

Keywords: Sustainable cities and communities; Mitigation and disaster risk reduction; Steel Tower; Indo-Australian plate

1. Introduction

Indonesia's territory includes regions with a very high level of earthquake risk because these regions are located at the confluence of four active tectonic systems, namely the Eurasian Plate, the Indo-Australian Plate, the Philippine Plate, and the Pacific Plate [1], [2]. The zone where the Indo-Australian plate subducts beneath the Eurasian plate is called the Sunda Arc. This arc is more than 4000 km long, begins at Sumatra Island and ends at Flores Island, runs parallel to the west coast of Sumatra, the south coast of Java and the Lesser Sunda Islands.

West Sumatra province is an earthquake-prone area due to its location on the west coast of Sumatra, which is tectonically close to a subduction zone of the Indo-Australian plate under the Eurasian plate, as shown in Figure 1 [3], [4], [5]. The movement of these plates will generate earthquakes that are often large in magnitude. In addition, the active Great Sumatra Fault will always threaten the region whenever there is a shift in the fault zone [6]. Volcanic activity from active volcanoes in this province, such as Marapi, Tandikat, and Talang, can also generate quite strong earthquakes. The subduction zone, the Great Sumatra Fault, and these active volcanoes are interrelated and influence each other [7], [8]. Therefore, West Sumatra is vulnerable not only to earthquakes, but also to other disasters, such as volcanic eruptions, tsunamis, floods, and even landslides (due to earthquake vibrations) [9], [10].

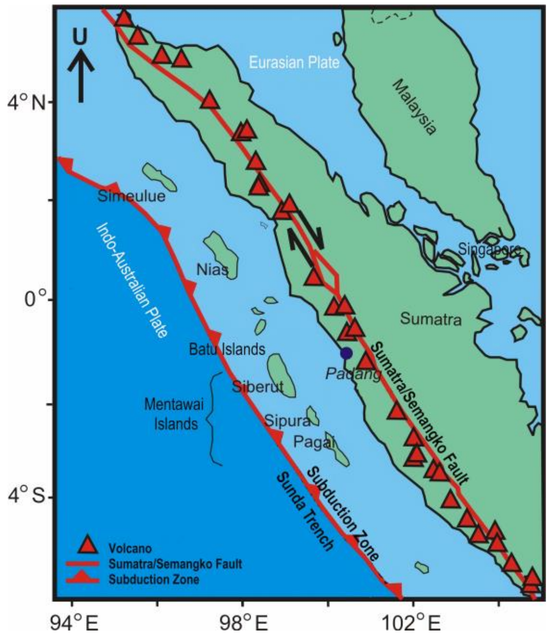

Figure1. Map of the Sumatra subduction zone

The earthquake map of Indonesia based on SNI for Building Earthquake Resistance Planning 1726:2002 can be seen in Figure 2 [11], [12]. In this map, Indonesia is determined to be divided into 6 earthquake regions, where Earthquake Region 1 is the region with the lowest seismicity, and Earthquake Region 6 has the highest seismicity [13], [14], [15]. The division of this earthquake region is based on the peak acceleration of bedrock due to the influence of design earthquakes with a return period of 500 years [15], [16]. Referring to the map, West Sumatra province falls into regions 5 and 6 category, which means it has high seismicity.

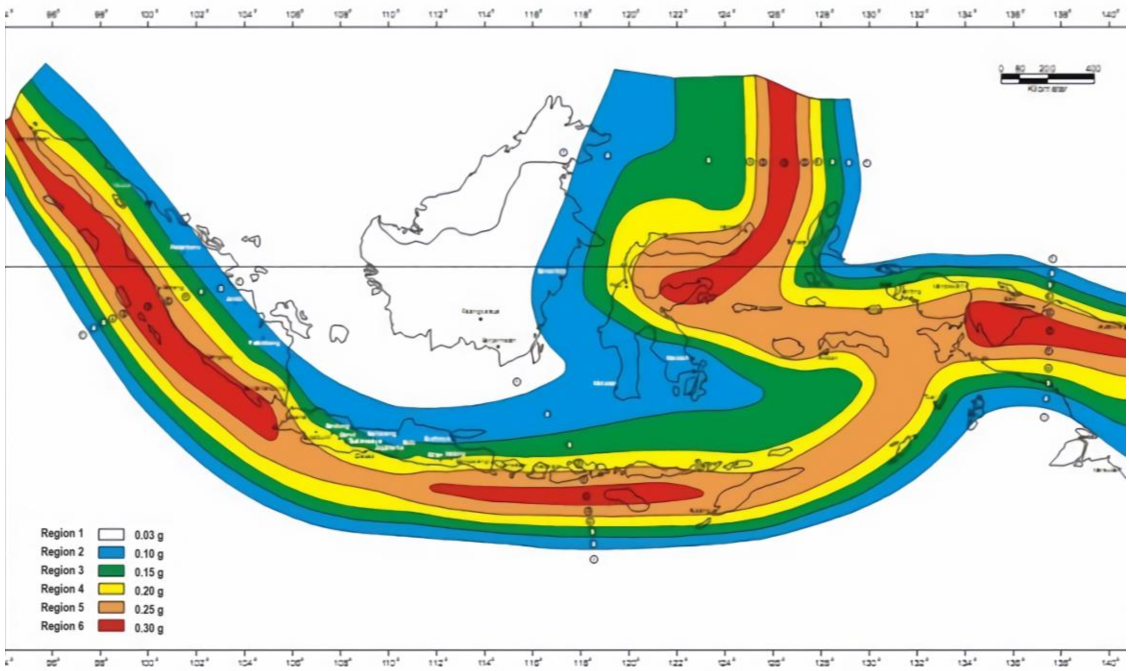

Figure 2. Earthquake map of Indonesia

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The latest strong earthquake in this province occurred on February 25, 2022, at 08:39 Indonesian Western Time, with a magnitude of 6.1 on the Richter scale. The epicenter of the earthquake is located in West Pasaman Regency, as shown in Figure 3. This earthquake is a shallow crustal earthquake triggered by active fault activity, i.e. Semangko Fault, in the uncharted Talamau segment precisely [17]. The analysis of the source mechanism shows that this earthquake had a horizontal movement mechanism [18].

Figure 3. West Pasaman earthquake epicenter point

The number of confirmed fatalities is 27, at least 457 people were injured, and more than 16,000 people were displaced. Physical damage includes 2,025 houses, 75 educational facilities, 42 government offices, 40 places of worship, and 18 health facilities [19]. Most of those fatalities and injuries are caused by building collapse, and one of the most common causes of building collapse is the failure of the foundation structure of the building [20].

Building foundation is the structure of the lower part of the building (substructure) directly related to the ground or the parts located below ground level, carrying the load of all other building parts. The foundation must be carefully calculated to ensure the stability of the building against the dead loads (self-weight of the structure and all its permanent components), live loads (occupants, furniture, and other contents), and external forces such as wind loads, seismic loads, and others [21], [22], [23]. In bearing all these loads, there will usually be vertical movement of the base of the footing, called the settlement, with a certain allowable settlement limit. At the time of seismic activity, the failure of the foundation structure will lead to building damage. The impact of a settlement beyond the allowable limit, or fracture on the foundation, ranges from visible cracks on the walls and floors, wavy roofs, damage to walls, tilting, to the complete collapse of the building [24], [25].

There are two types of foundations in general: shallow and deep. Shallow foundations are used for simple buildings, for example, a single-story house. This foundation can also be used for larger buildings built on hard ground. Types of shallow foundations in Indonesia include river stone isolated footing, river stone strip footing, concrete isolated footing, and concrete strip footing foundations [26], [27]. The deep foundation is used in buildings built on soft soil, buildings with a relatively wide span (>6m distance between columns), and multi-story buildings. Pile foundations (concrete, iron, steel pipes), bored pile foundations, and pit foundations are examples of deep foundation types.

When the West Pasaman earthquake occurred, PT. XYZ is constructing a feed mill tower in the Padang Industrial Park, Kasang, Pariaman area. The feed mill tower is a high-rise steel building with ten-floor levels and a height of 50 m. Since strong earthquake shocks were felt at the location of the construction project, it is necessary to carry out an investigation or test on the foundation structure to ensure the safety of the building.

Testing foundation systems is often necessary for various reasons, including to ensure their quality and compliance. Various non-destructive testing methods are available to evaluate deep foundations, including the Ultrasonic Pulse Velocity (UPV) test and Pile Integrity Test (PIT). The UPV test uses ultrasonic waves that propagate through the concrete to determine the integrity value of the concrete [28]. It can be used to determine the concrete quality and homogeneity, detecting cracks, and internal flaws. UPV test can provide quick and reliable results. However, this test is dependent on material properties, its accuracy can be affected by surface conditions, and the evaluation of the results requires a high level of knowledge, training, and experience [29].

PIT is developed to check the integrity of a pile foundation. This test is suitable for concrete piles; usually is used to detect the existence of discontinuity, such as cracks or voids along the pile, and the quality of connection joint between two segments of the pile. PIT can also be used to estimate pile depth [30] [31]. The test is carried out by applying a low-strain impact wave to the pile head, and the response of the wave is monitored. However, this test is influenced by soil conditions, may require a smooth and accessible foundation head, is not effective in piles with highly variable cross sections, and can only assess the integrity of the foundation up to a certain depth [31] [32].

Following the earthquake, several tests were carried out on the feed mill tower building foundation, from visual inspection to UPV test and PIT. Visual inspection found hairline cracks on the surface of the ground floor, but no structural damage. The results of the UPV test on the crack depth showed that the maximum crack depth is 32 mm and the minimum crack depth is 15 mm. The depth of the cracks does not exceed the concrete ducking. However, the PIT results showed that all samples experienced a reduction in impedance around a depth of ± 3.0 m below the sensor with BTA values of 75%, 78%, and 72% and fell into the damaged category [31]. The presumption is that the reduction in impedance at a depth of 3 meters is most likely part of the connection joint between two segments. Nevertheless, another test is needed to support or deny this presumption.

Another non-destructive testing method that can be used to estimate pile depth and check the joints of the foundation is Ground Penetrating Radar (GPR) [33], [34]. GPR is widely used to detect subsurface conditions, and can also be used to check the condition of underground structures [35], [36]. GPR is an electromagnetic analog of sonic and ultrasonic pulse-echo methods. It is based on electromagnetic energy propagation through materials with different dielectric constants [37]. The more significant the difference between the dielectric constants at an interface between two materials, the greater the amount of electromagnetic energy reflected. The smaller the difference, the smaller the amount reflected; conversely, more energy continues to propagate to the second material. In this case, the difference in dielectric constant in the propagation of electromagnetic energy is analogous to the difference in impedance in the propagation of sonic and ultrasonic energy. The form of mapping the condition of the substructure using the GPR tool is shown in Figure 4.

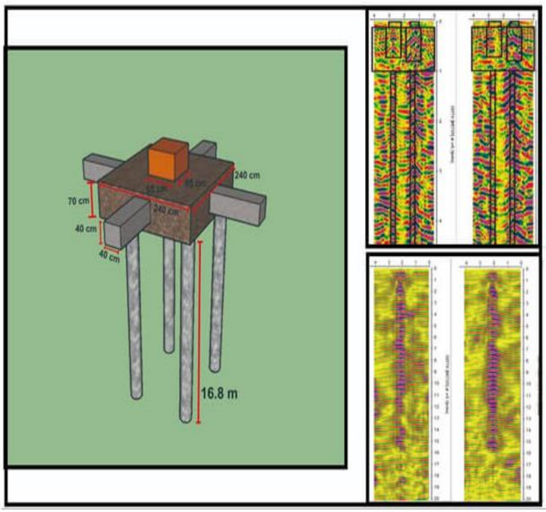

Figure 4. Form of foundation mapping with GPR

Zhou and Zhu [35] in their study proposed a new approach to utilizing the GPR. They used GPR to solve engineering disputes between the building's contractor and consultant regarding the quality of foundation piles and the existence of internal reinforcing bars of the piles [35]. It is usually difficult to detect and reveal deeply embedded reinforcing bars in radar image. Zhou and Zhu used low center frequency antenna and processed the raw data by using digital filtering techniques to solve this problem. To validate the estimated depth of the reinforcing bars, the pile foundation was excavated. In another study, Parwatiningtyas [34] utilized GPR to investigate the condition of building foundations of Panasonic Companies, Tapos Depok, West Java. This research was needed due to the land subsidence in this area, moving downwards more than 5 meters to the east. Her study was conducted on 6 buildings, including 3 factories and 1 office building. All buildings use a deep foundation type. Data collected from the GPR were processed by using the Reflex-W software to gain information regarding the condition of the subsurface, the foundation structure, and depth.

Those two previous studies were carried out independently, and not related to the results of other tests. Conclusions regarding the condition of the foundation structure are drawn based only on the results of the GPR test. This is the difference between this research and those two previous studies. In this research, the GPR test is conducted after the PIT results cannot provide certainty regarding the condition of the foundation structure. The objective of this study is to evaluate the condition of the foundation structure after the earthquake through the application of GPR, aimed to obtain better and certain results than PIT results.

2. Material and methods

GPR tools can be used in various media such as rock, soil, ice, fresh water, pavements, and structures. As a non-destructive testing technique, it has been proved that GPR can be applied to determine conditions inside a concrete structure [35]. When conditions are right, GPR can be utilized to detect changes in material properties beneath the surface, as well as voids and cracks. This georadar method utilizes high-frequency radio waves, usually in the range of 10 MHz to 2.6 GHz. The transmitter and antenna from the GPR device transmit electromagnetic waves to the ground. When the wave meets a buried object, it will be reflected back to the surface, to a receiver antenna [37]. The method for carrying out testing using GPR is as follows [34], [35]:

1. A survey is carried out to determine the building trajectory and the location of the path to be measured (Georadar trajectories are made to cut subsurface structures to determine the depth of subsurface structures).

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2. GPR equipment is prepared and taken to the test location.
3. Measurements or collecting data at the location is carried out.
4. Georadar recorded data from measurements in the field is processed using Reflex-W software on a computer which aims to strengthen the diffraction signal so that it is easier to interpret.
5. After processing the data, the next step is to read the position and depth of the structure and compare it with the planning design and standards.

The GPR equipment used in this study is the IDS RIS-ONE GPR with antenna TR 40 MHz manufactured by the IDS GeoRadar, as shown in Figure 5.

Figure 5. IDS RIS-ONE GPR equipment

The way the GPR tool works is shown in Figure 6. The radar trajectory is carried out on a predetermined path with an indication that there is a subsurface structure. The radar track is made to cut the subsurface structure and determine the subsurface structure's depth.

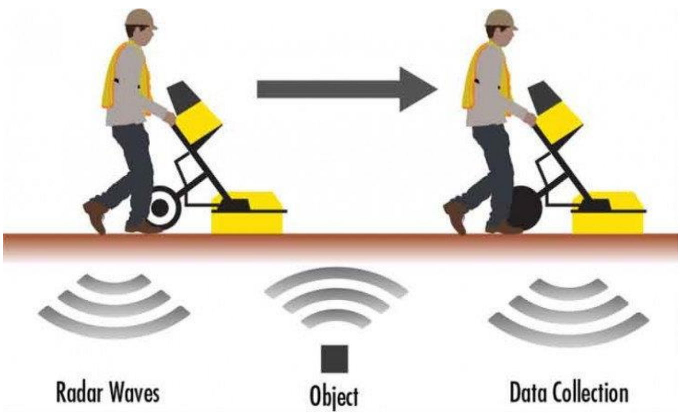

Figure 6. How mapping works with GPR

The object of this research is a feed mill tower building with steel frame construction as the upper structure. This building uses a deep foundation type for the substructure, i.e. spun pile foundation. The diameter of spun piles is 600 mm, designed with a depth range between 16-19 m. The thickness of the pile cap is 1 m, while the thickness of the slab is 20 cm. The layout of the foundation as the research object to be analyzed and tested by using GPR is shown in Figure 7, and the upper structure modeling can be seen in Figure 8.

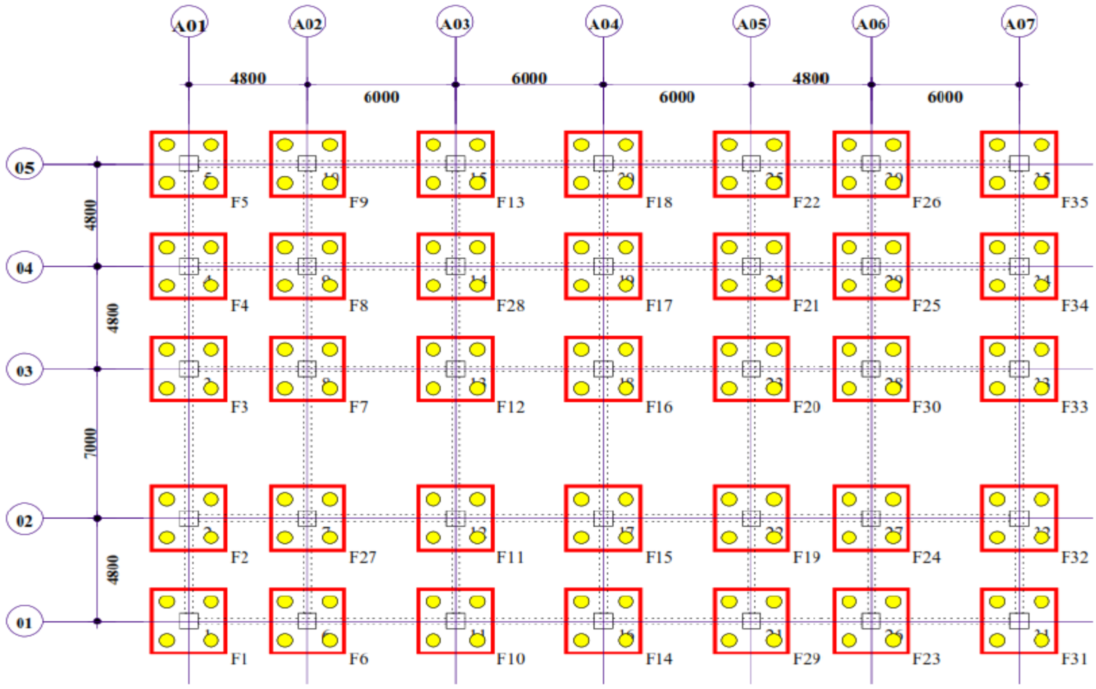

Figure 7. Foundation layout plan

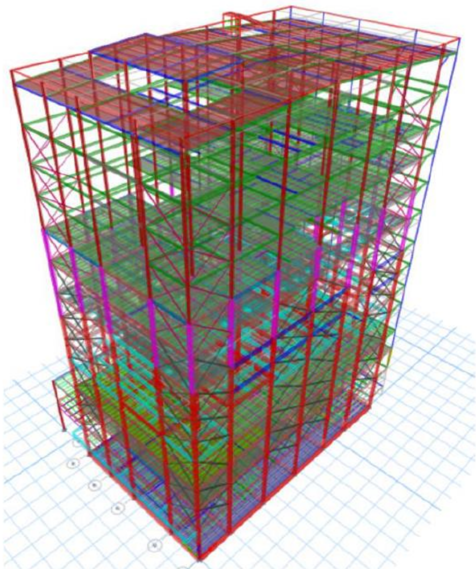

Figure 8. Feed mill tower modeling by using ETABS

After field data acquisition, raw radar data is processed and analyzed. Georadar data processing using the Reflex-w software aims to amplify the diffraction signal recorded on the georadar data so that it can be more easily interpreted. In addition, data processing is carried out to remove noise recorded in the radar data during measurements. This aims to avoid misinterpretation of the radar program. After processing the data, the next step is to interpret the radar data to obtain the position and depth of the foundation structure. The analysis was carried out based on the study objectives to evaluate the condition of the foundation structure after an earthquake, and then compare it with the PIT results to gain more reliable conclusions. If the detected foundation depth is still within the range of design depth range, and there are no cracks or fractures in the slab, pile cap, or spun pile detected, it means the foundation is still in good condition [34], [35]. Investigation stages are depicted in Figure 9.

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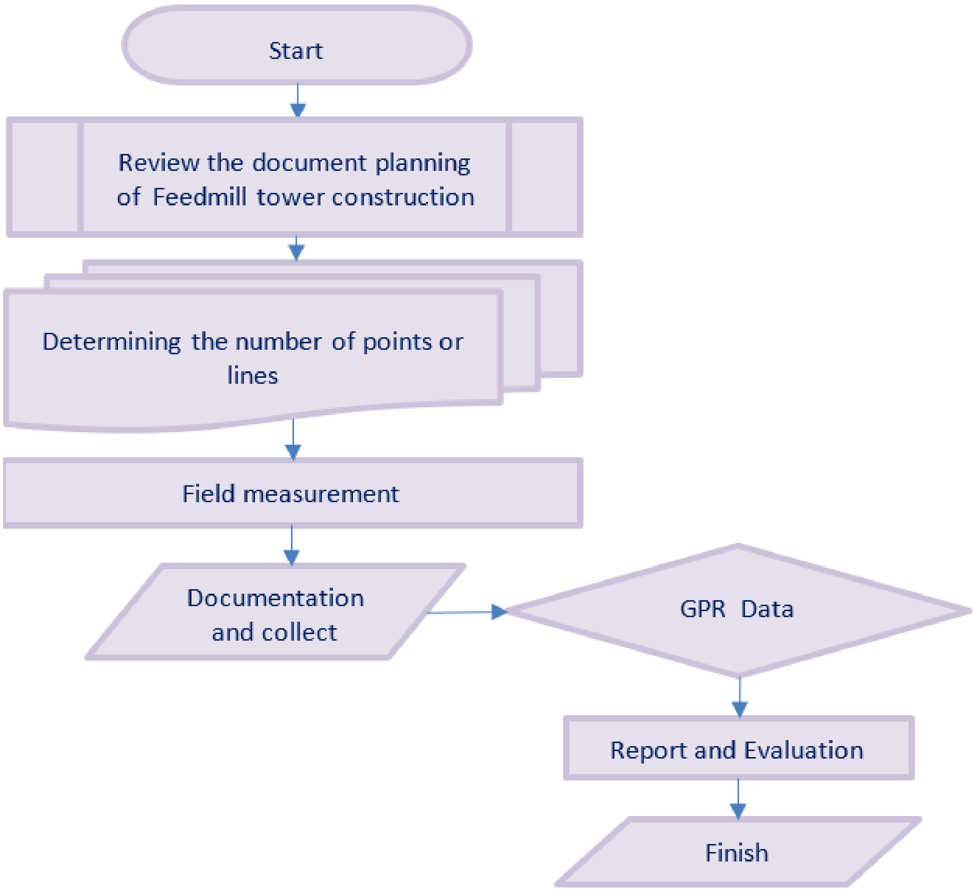

Figure 9. GPR testing and analysis stages

3. Results and discussion

GPR testing was carried out in specified lanes, determined to represent the entire foundation. The number of measurement tracks is set at 10 lanes. Each lane is named in accordance with the building's structural grid. The path and direction of GPR data collection is shown in Figure 10.

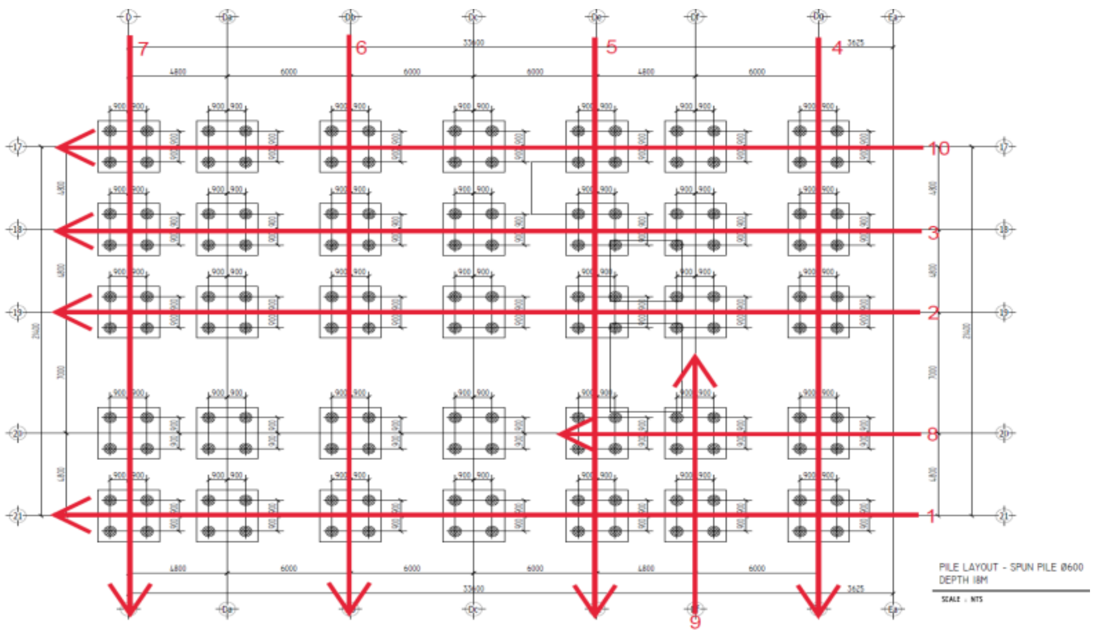

Figure 10. The path and direction of GPR testing

The GPR test results on Track 1 to Track 10 show the thickness of existing slabs, the thickness of pile caps, and the depth of the existing foundation piles. Data from GPR measurements can be seen in Figures 11 to Figure 20.

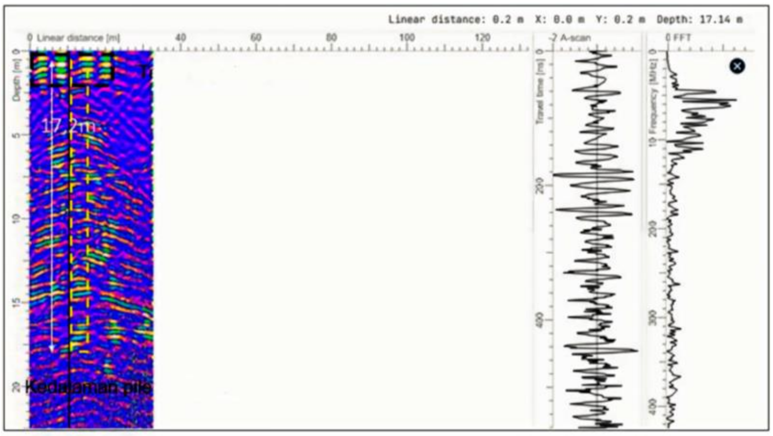

Figure 11. Track 1 – Lane 21

On Track 1, the detected depth of the foundation is 17.14 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

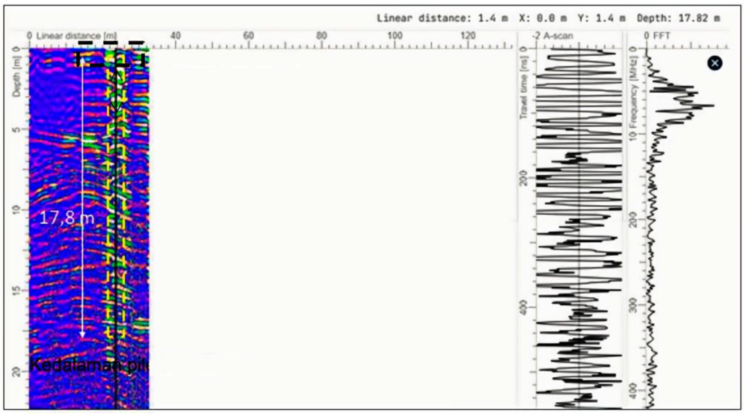

Figure 12. Track 2 – Lane 19

On Track 2, the detected depth of the foundation is 17.82 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

Figure 13.Track 3 – Lane 18

On Track 3, the detected depth of the foundation is 17.58 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

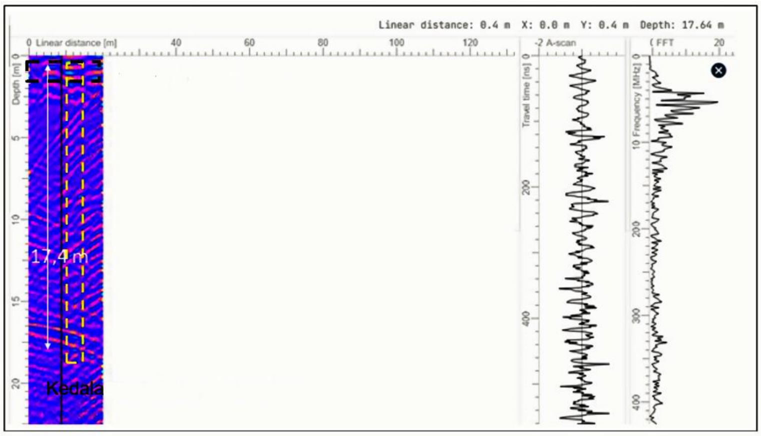

Figure 14. Track 4 – Lane Dg

On Track 4 the detected depth of the foundation is 17.64 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

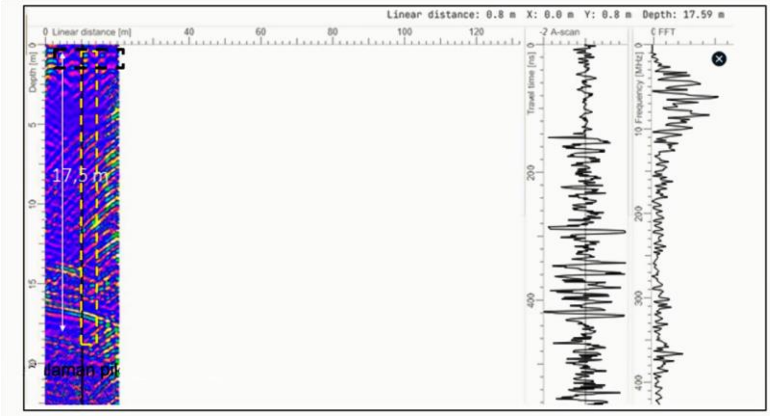

Figure 15. Track 5 – Lane De

On Track 5, the detected depth of the foundation is 17.59 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

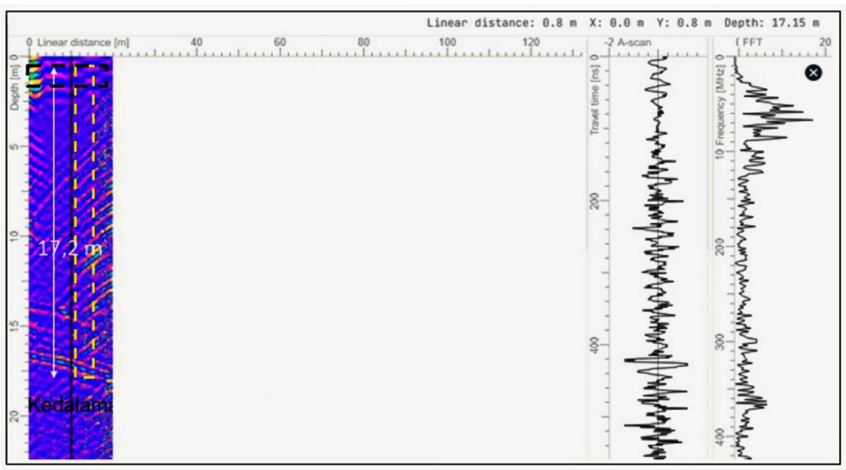

Figure 16. Track 6 – Lane Db

On Track 6, the detected depth of the foundation is 17.15 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

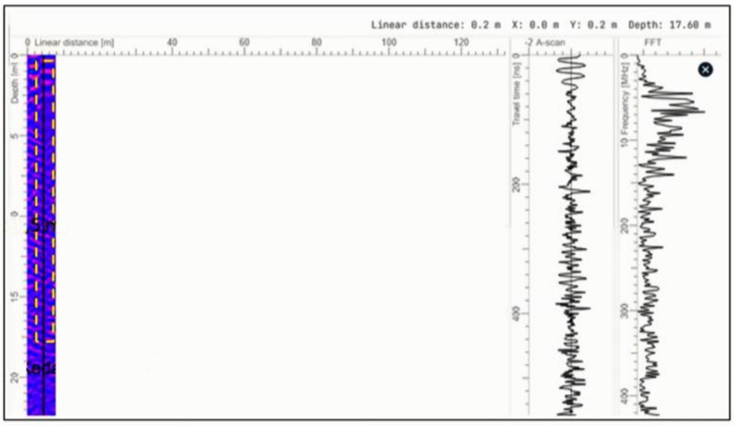

Figure 17. Track 7 – Lane D

On Track 7, the detected depth of the foundation is 17.68 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

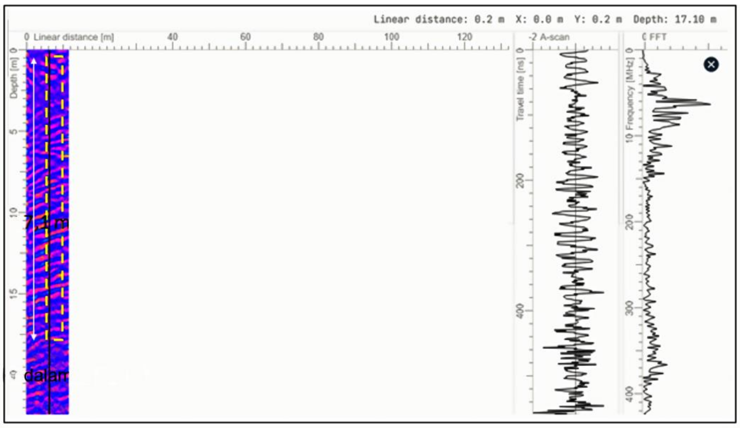

Figure 18. Track 8 – Lane 20

On Track 8, the detected depth of the foundation is 17.10 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

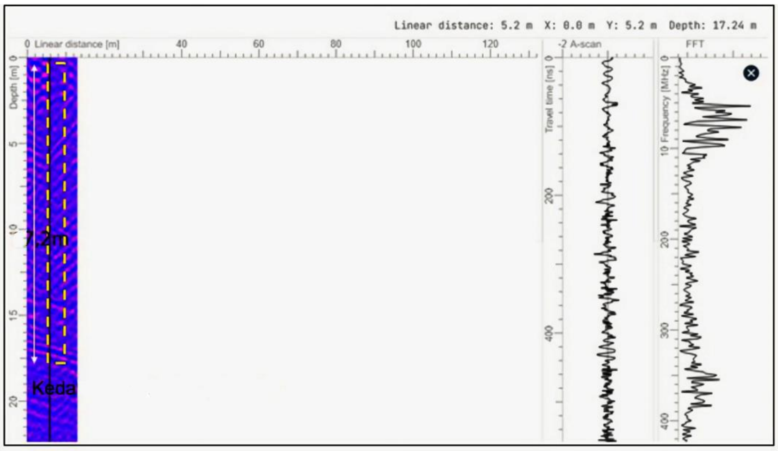

Figure 19. Track 9 – Lane Df

On Track 9, the detected depth of the foundation is 17.24 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

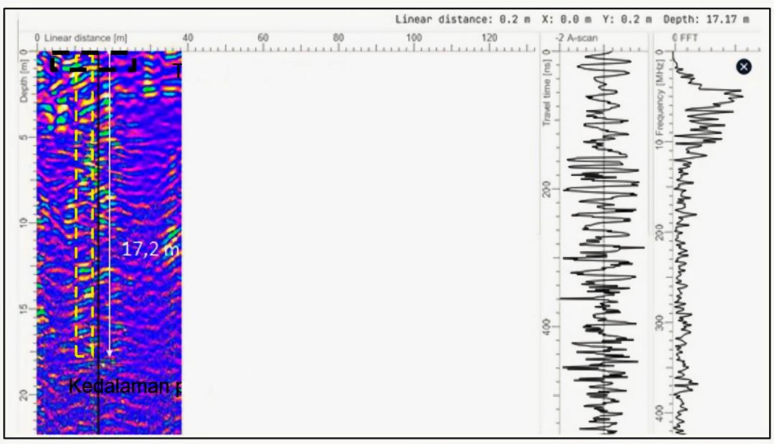

Figure 20. Track 10 – Lane 17

On Track 10, the detected depth of the foundation is 17.17 m, the thickness of the slab is 20 cm, and the thickness of the pile cap is 1 m.

Table 1: GPR test measurement results

Track No.	Slab thickness	Pile cap thickness	Detected spun pile depth
1	20 cm	1 m	17.14 m
2	20 cm	1 m	17.82 m
3	20 cm	1 m	17.58 m
4	20 cm	1 m	17.64 m
5	20 cm	1 m	17.59 m
6	20 cm	1 m	17.15 m
7	20 cm	1 m	17.68 m
8	20 cm	1 m	17.10 m
9	20 cm	1 m	17.24 m
10	20 cm	1 m	17.17 m

Test results using GPR on each track show the conformity of the existing slabs and pile caps thickness to the foundation design, and the detected depth of the foundation piles ranges from 17.10 m to 17.82 m. The results of the GPR test from readings of electromagnetic wave propagation of the depth and condition of the foundations stated that all foundations were by the designed depth. These results and the visual inspection results support the presumption drawn from the PIT that the reduction in impedance at a depth of 3 meters is most likely part of the connection joint between two segments of the spun pile foundation in the shaft.

The results of this study also strengthen findings from Parwatiningtyas's study [34] that GPR can be used as an effective tool for non-destructive techniques in evaluating the condition of foundations. Her research aimed to evaluate whether ground movement affects the arrangement of the foundation and beams. Based on the GPR test results, she concluded that the beam structures were still neatly arranged, and the overall condition of the buildings was in good condition. The building's structure remains consistently solid and robust, supported by deep foundations. The foundation depth detected by GPR reached 10 – 26 m.

This research also supports the research findings of Zhou and Zhu [35] that the use of GPR is effective in providing in-depth information about the quality of the foundation and reinforcing bars embedded in the pile foundation. In their case, GPR test results help the contractor and consultant of the building to solve engineering disputes based on the key information gained from the research. Data from the investigation explains that the length of reinforcement in the embedded foundation piles was found to meet the standards and was in very good condition.

4. Conclusion

Based on the results of the GPR test, it can be concluded that the foundation structure of the feed mill tower building after the West Pasaman earthquake is still in good condition. The foundation structure was not damaged by the magnitude 6.1 earthquake. This conclusion was drawn based on the fact that radar waves of GPR could propagate well to the end of each foundation pile tested, which means that there are no cracks or fractures on the slabs, pile caps, or spun piles. GPR test data analysis showed that all slabs and pile caps thicknesses and the detected foundation pile depths are in accordance with the foundation design. As with the majority of studies, this study is subject to limitations. GPR test is carried out only on slabs, pile caps, and spun file foundations. This could be addressed in future research by adding parameters such as reinforcing bars or beams.

Author contribution

Risma Apdeni and Zel Citra: Writing – original draft, project document review, formal analysis, and investigation. Prima Yane Putri, Fitra Rifwan and Yosie Malinda: Prepare tools, resources, data curation, visualization, and projection. Nevy Sandra, Paksi Dwiyanto Wibowo and Reza Ferial Ashadi: Validation, terminology, writing – review & editing, formal analysis, and supervision. Zel Citra, Paksi Dwiyanto Wibowo and Annisa Prita Melinda: Conceptualization, methodology, and validation.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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