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Research article

Fostering students' critical thinking through STEM project-based learning: Designing earthquake-resistant buildings

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Abstract: Critical thinking is a key component of the 4Cs skills required to navigate the challenges of the twenty-first century. However, Indonesian students' critical thinking performance remains below the international average, as indicated by the PISA results. This study explored the influence of STEM-based project learning (PjBL) activities on junior high school students' critical thinking skills, particularly in lessons related to earthquakes. A quantitative methodology was adopted, employing a quasi-experimental nonequivalent control group design that included pretest and posttest measures. The experimental group received instructions through STEM PjBL, whereas the control group was taught via conventional learning. A total of 102 eighth-grade students from a public junior high school in Bandung, Indonesia, took part in this study, with 51 students assigned to the experimental group and 51 to the control group. Data were collected via an essay test comprising eight open-ended questions designed to measure critical thinking skills following the criteria by Ennis. The results revealed a significant difference in critical thinking improvement between the two groups. The N-gain value of the experimental group (0.6) was higher than that of the control group (0.4), suggesting a greater improvement in learning outcomes. These findings suggest that compared with conventional instruction, STEM PjBL provides more supportive learning conditions for developing students' critical thinking skills in earthquake-related science topics.

Keywords: critical thinking skills, earthquakes topic, STEM, STEM project-based learning

1. Introduction

Indonesia's geographical location along the Pacific Ring of Fire makes the country highly prone to destructive earthquakes. Major seismic events, such as the 2004 Sumatra–Andaman earthquake and tsunami [1], the 2016 Pidie Jaya earthquake [2], and the activity of the Lembang Fault near Bandung [3], highlight the relevance of earthquake-related topics in education [4–6].

Earthquakes pose serious threats to human safety, infrastructure, and social well-being, particularly in regions located along active fault lines [7–9]. The absence of earthquake education in schools may contribute to increased fatalities and injuries, as understanding seismic hazards plays a critical role in disaster preparedness and self-protection efforts [10]. Consequently, the use of earthquake contexts in science learning offers meaningful real-world scenarios where students can practice applying scientific knowledge and develop critical thinking skills.

In the context of rapid technological advancement, critical thinking has become one of the most essential competencies for students in the twenty-first century [11–13]. However, international assessments such as the Evidence from the Programme for International Student Assessment (PISA) suggest that the academic performance of Indonesian students in scientific reasoning and critical thinking remains below the global average [14,15]. This condition underscores the need for instructional approaches that meaningfully support the development of higher-order thinking skills through authentic learning contexts.

In Indonesia, the Merdeka curriculum promotes contextual, inquiry-based, and project-oriented learning to address real-world problems [16,17]. The curriculum emphasizes learner autonomy, critical thinking, creativity, and the authentic application of knowledge. These principles align closely with STEM project-based learning (PjBL), which integrates science, technology, engineering, and mathematics through project activities that require students to investigate problems [18], design solutions [19], collaborate with peers [20], and reflect on outcomes on the basis of evidence [21]. Within this framework, learning extends beyond content mastery to the development of transferable cognitive skills.

Prior research has shown that STEM-oriented PjBL effectively improves students' critical thinking skills in a range of science subjects. Positive outcomes have been reported in contexts such as animalia [22], waste management [23], water treatment [24], fluid statics [25], and optics [26]. Nevertheless, most existing studies focus primarily on STEM integration or engineering design outcomes and do not explicitly examine the development of critical thinking within disaster-related contexts.

Research on STEM learning in earthquake-related topics indicates that engineering projects, such as designing earthquake-resistant structures, can enhance students' engineering design thinking and STEM conceptual understanding through iterative and collaborative design processes [27,28]. Other studies have also reported improvements in students' problem-solving skills through STEM PjBL Learning on Earth science and natural disaster topics [29]. However, research that explicitly designs STEM PjBL to foster junior high school students' critical thinking skills through authentic earthquake projects supported by simulation-based technology remains very limited.

The present study aims to address the lack of empirical evidence regarding the effectiveness of STEM PjBL in developing junior high school students' critical thinking skills within the context of earthquake learning. The novelty of this study lies in the integration of an earthquake-resistant building design project with a technology-based earthquake simulation program developed by researchers. Through this approach, students not only design and construct earthquake-resistant structures but also evaluate their designs via simulated seismic events, thereby gaining authentic learning experiences that closely resemble real-world STEM practices.

Accordingly, this study specifically analyzes the effect of STEM PjBL on the critical thinking skills of junior high school students in the context of earthquake topics. By situating critical thinking development within a contextualized and technology-enhanced STEM project, this research is expected to contribute to the STEM education literature and offer practical implications for science learning, particularly in disaster-prone regions.

2. Method

2.1. Research design

The research was conducted through a quasi-experimental approach with a nonequivalent pretest–posttest group design [30]. Both pretests and posttests were administered to measure changes in students' critical thinking skills. Table 1 presents the scheme of the quasi-experimental research design, where the experimental group received STEM project-based learning (PjBL) interventions, whereas the control group participated in conventional learning.

Table 1. Nonequivalent pretest–posttest group design

Group	Pretest (O_1)	Treatment	Posttest (O_2)
Experiment class	O_1	X	O_2
Control class	O_1	-	O_2

Notations:

O_1 is a pretest of the student's critical thinking skills

X is the treatment, STEM PjBL

- is the treatment, conventional learning

O_2 is a posttest of the student's critical thinking skills

2.2. Population and sample

This study was conducted at a junior high school in Bandung, Indonesia, implementing the Merdeka curriculum. The population included all eighth-grade students aged 13–14 years. The sample consisted of 102 students, including 52 males and 50 females, selected via convenience sampling on the basis of the following criteria: 1) attendance greater than 80%, and 2) willingness to participate in all stages of the study. This technique was chosen because of its accessibility, availability, and participants' willingness to engage [30]. The limitation of this sampling method is the potential for bias, as not all students had an equal chance of being selected. Details of the population and sample are presented in Table 2.

Table 2. Population and sample.

Gender	Experiment class		Control class	
	Frequency	Percentage	Frequency	Percentage
Male	26	51%	26	51%
Female	25	49%	25	49%
Total	51	100%	51	100%

2.3. Research instrument

The research instrument measured students' critical thinking skills via an open-ended essay test consisting of eight questions. The questions were designed to promote students' analysis, evaluation, and synthesis of ideas. Instrument validity was assessed through content validity by three experts in science and STEM education. The critical thinking indicator followed the criteria of Ennis as presented in Table 3. The criteria scoring rubrics are detailed in Table 4.

Table 3. Test of critical thinking skills.

Indicator of critical thinking skills	**Sub-indicator of critical thinking skills**	**Question numbers**	**Total**	**%**
Basic clarification	Analyze arguments	1, 2	2	25%
Basic decision	Using existing knowledge	3, 4	2	25%
Inference	Make and judge inductive arguments	5	1	12.5%
Advanced clarification	Define terms and judge definitions	6, 7	2	25%
Nonconstitutive but helpful	Rhetorical strategies	8	1	12.5%
	Total		8	100%

Table 4. Interpretation of indicator critical thinking skills [31].

Scores	Interpretation
95–100	Master thinker
82.5–95	Advanced thinker
67.5–82.5	Practicing thinker
37.5–67.5	Challenged thinker
Below 37.5	Unreflective thinker

2.4. Research procedure

The study was conducted over four sessions, covering all stages of STEM PjBL George Lucas [32]:

1. Asking questions: Students formulated questions related to earthquake-resistant buildings.
2. Designing project: Students developed project designs following STEM principles.
3. Scheduling: Students determined the steps and timeline for project completion.
4. Monitoring progress: The teacher supervised and provided feedback on project development.

5. Assessing outcomes: Projects were evaluated via STEM and critical thinking rubrics.
6. Evaluation: Reflection and class discussion were conducted to consolidate learning.

The STEM activities included experiments, design tasks, and the application of STEM content (science, mathematics, and technology), enabling students to learn concepts while engaging in hands-on practice. The control group participated in conventional learning, which consisted of teacher explanations, discussions, and limited exercises without STEM projects. All the students completed a pretest before the intervention and a posttest after the project to assess critical thinking skills. Table 5 presents the activities for both the experimental class using STEM and the control class.

Table 5. Activities in the experimental and control classes.

Meetings	**STEM PjBL**	**Conventional learning**
	Experiment class	**Control class**
First meeting	Students take a pretest **Stage 1: Starting with a question** Students are asked to analyze the causes of earthquakes based on the teacher's questions **Stage 2: Designing a project** Students design a project within a group	Students take a pretest
Second meeting	Stage 3: **Make a schedule** Teachers and students decide the time allocation for the project Stage 4: **Monitoring and progress of the project** Students start making their project Teachers monitor the process	1) Teachers ask students guiding questions regarding earthquakes and show a video. 2) Students listen to the teacher's explanation. 3) Students are divided into groups and answer the teacher's questions, presenting their answers in front of the class.
Third meeting	Stage 4: **Monitoring and progress of the project** Students continue making their project	1) Students answer the teacher's questions regarding the earthquake in Indonesia after watching a video. 2) Students listen to the teacher's explanation. 3) Students are asked to answer questions regarding the topic in a quiz in front of the class.
Fourth meeting	Stage 5: **Assess the outcome** Students conduct an earthquake simulation project competition Stage 6: **Evaluate the experience** Students evaluate the experience together Students take a posttest	Students take posttest

3. Results and discussion

3.1. The effect of STEM project-based learning on students' critical thinking skills

This study was conducted over four meetings, with each meeting consisting of two 40-min sessions. The first meeting involved the pretest, and the fourth meeting involved the posttest. The learning process followed six stages of STEM PjBL: starting with a question, designing a project, creating a schedule, monitoring project progress, assessing the outcome, and evaluating the experience. Table 6 presents the results of a paired samples t-test for pretest and posttest scores.

Table 6. Results of paired samples t-tests for pretest and posttest scores.

Group	N	Pretest mean (SD)	Posttest mean (SD)	t-test	df	p-value
Experimental (paired t-test)	102	33.09 (10.101)	71.57 (20.090)	-13.866	50	<0.001*
Control (Paired t-test)	102	33.46 (10.064)	59.68 (13.654)	-10.841	50	<0.001*

*p < 0.05 indicates statistical significance. Paired samples t-tests were conducted to compare pretest and posttest scores within each class.

The results of the paired t-test show that students' critical thinking skills increased significantly after the intervention in both the experimental and control groups. In the experimental class, the mean score increased markedly from 33.09 (SD = 10.101) during the pretest to 71.57 (SD = 20.090) during the posttest [$t(50) = -13.866$, $p < 0.001$]. In the control class, the average score also increased, although to a lesser extent than in the experimental class, rising from 33.46 (SD = 10.064) during the pretest to 59.68 (SD = 13.654) during the posttest. These results indicate that both instructional approaches, STEM PjBL and conventional instruction, produced positive gains in students' critical thinking skills in each class.

Table 7. Results of independent samples t-tests for pretest and posttest scores.

Group	N	Pretest mean (SD)	Posttest mean (SD)	t-test	df	p-value
Pretest (independent t-test)	102	33.09 (10.101)	71.57 (20.090)	-0.184	100	0.854
Posttest (independent t-test)	102	33.46 (10.064)	59.68 (13.654)	3.495	100	<0.001*

*p < 0.05 indicates statistical significance. Independent samples t-tests were conducted to compare the experimental and control classes on pretest and posttest scores.

Table 7 presents the results of independent samples t-test for pretest and posttest scores. Independent t-test results revealed no significant difference between the experimental and control classes at pretest [$t(100) = -0.184$, $p = 0.854$], confirming that both groups started with comparable abilities. However, the posttest comparison revealed that the experimental class performed significantly better than the control class [$t(100) = 3.495$, $p < 0.001$], demonstrating that, compared with conventional teaching methods, STEM PjBL was more effective at enhancing students' critical thinking [23].

As shown in Table 8, the N-gain analysis indicated a difference in the improvement of students' critical thinking skills between the experimental and control classes. The experimental class achieved a mean N-gain of 0.60, which falls within the medium category, whereas the control class obtained a mean N-gain of 0.40, which was also classified as medium.

Table 8. N-gain analysis of student's critical thinking skills.

Class	N	Pretest mean	Posttest mean	N-gain	N-gain category
Experimental	51	33.09	71.57	0.60	Medium
Control	51	33.46	59.68	0.40	Medium

N-gain was calculated via raw scores (0–2 per item). Although the values appear small, they represent normalized learning improvement relative to the maximum score and remain comparable across groups. N-gain categories: low (<0.30), medium (0.30–0.70), and high (>0.70).

Although both groups are in the same category, the higher N-gain value in the experimental class suggests that, compared with conventional instruction, STEM PjBL leads to greater improvement in students' critical thinking skills. This result implies that student engagement in STEM-based project activities, which involve planning, testing, and reflection, provides stronger support for the development of critical thinking skills. Figure 1 shows a comparison of the N-gain improvement between the experimental and control classes.

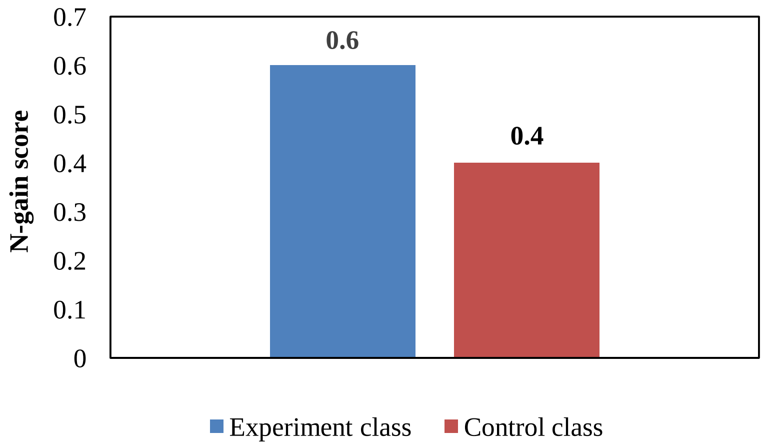


Figure 1. Comparison of students' N-gain in the experimental and control classes.

These findings are consistent with the results of the independent t-test on posttest scores, which revealed a significant difference between the experimental and control groups. Therefore, the N-gain analysis strengthens the evidence that the implementation of STEM PjBL is more effective in enhancing students' critical thinking skills than conventional learning approaches.

These findings are consistent with recent studies indicating that STEM project-based learning is more effective than conventional instruction in improving students' critical thinking skills. Students taught using STEM PjBL achieved significantly higher posttest scores and N-gain values, as confirmed through independent t-test analyses [33,34]. The integration of interdisciplinary STEM concepts with authentic projects encourages active engagement, problem solving, and higher-order thinking, which explains the greater learning gains observed in the experimental group. Therefore, the convergence of the independent t-test and N-gain results provides strong evidence that, compared with conventional learning approaches, STEM PjBL offers superior effectiveness in enhancing students' critical thinking skills [35].

The integration of science, technology, engineering, and mathematics (STEM) was implemented through an earthquake-resistant building design project, as presented in Table 9. This mechanism is particularly evident during the *Starting with a Question* stage of the project. At this initial stage, the students were introduced to two contrasting real-world earthquake events, namely earthquakes in Japan and those in Myanmar. The teacher guided the students' thinking through guiding questions that encouraged them to move beyond surface-level observations and examine the underlying causes of the differences in damage severity. This approach positions students in a problem-based learning context that requires initial analysis before proceeding to the solution design stage.

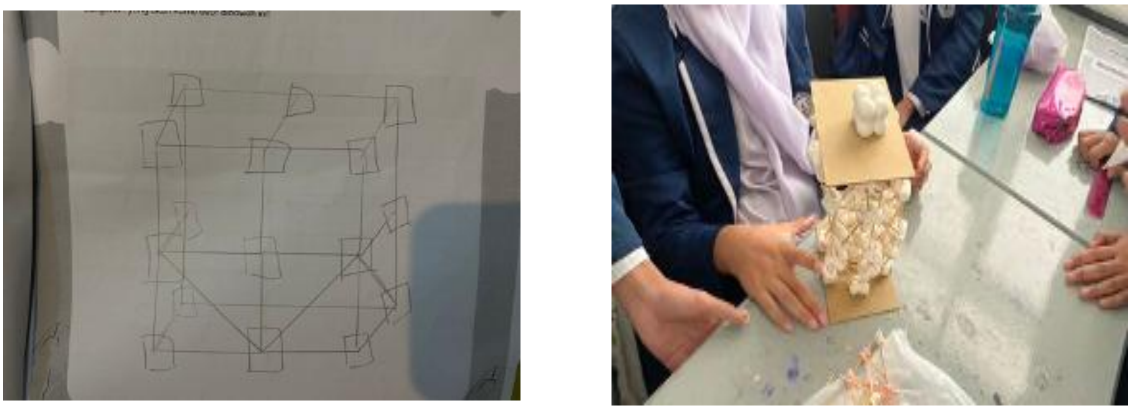
Table 9. Integration of STEM in earthquake-resistant building learning.

STEM approach			
Science (S)	Technology (T)	Engineering (E)	Mathematics (M)
Identify how earthquake vibrations affect buildings. Identify the reason why some structures remain standing while others collapse.	Find information and test the building model using earthquake simulations.	Design the project and construct an earthquake-resistant model based on height, width, and regulations.	Calculate the structural balance to ensure the design achieves stability.

For example, students were asked to explain why the earthquake in Myanmar caused more severe damage than the earthquake in Japan and identify factors that helped reduce damage in Japan on the basis of their observations. These guiding questions require students to analyze contextual information, compare structural and environmental factors, and justify their reasoning before proposing earthquake-resistant building design solutions. Some excerpts of questions provided to the students are presented below.

> *"In your opinion, why did the earthquake in Myanmar cause more severe damage than the earthquake in Japan?"*
>
> *"Are there any factors that helped reduce the damage caused by the earthquake in Japan? If so, mention them and explain your reasoning based on your observations."*
>
> *"Imagine you are a famous engineer who is asked to design and build an earthquake-resistant building. How would you build your building? Design the building you would build."*

During the design and construction stages, students were required to integrate concepts from science, technology, engineering, and mathematics to produce structurally stable building models. Decision-making related to the building height, base width, shape selection, and load distribution requires logical reasoning and the evaluation of multiple alternative solutions. When initial designs failed during load testing or earthquake simulations, students were required to analyze the causes of failure and revise their designs accordingly. This cycle of testing, failure analysis, and redesign encouraged reflective thinking and supported evidence-based decision making. Figure 2 shows examples of student-designed buildings and the project testing process.



(a) (b)

Figure 2. (a) Earthquake-resistant building design project. (b) Project load testing.

In addition, during the monitoring and evaluation stages, the students continuously assessed the effectiveness of the strategies they employed and justified design modifications on the basis of the testing results. This process encouraged the students to move beyond random trial-and-error approaches and engage in systematic reasoning. The final presentation and reflection stages further strengthened students' critical thinking skills, as they were required to articulate the rationale behind their designs, evaluate their learning processes, and connect scientific principles to real-world contexts. Figure 3 illustrates the stages of students revising their projects and the earthquake-resistant building contest.

(a) (b)

Figure 3. (a) Students revising their projects. (b) Earthquake-resistant building contest.

Overall, the findings of this study indicate that the greater improvement in critical thinking skills observed in the experimental group was attributable not only to the use of projects as an instructional method but also to the structured integration of inquiry, interdisciplinary reasoning, and reflective problem solving inherent in STEM PjBL. By engaging students in authentic problems that require sustained analysis and iterative revision, STEM PjBL creates learning conditions that are more supportive of the development of critical thinking skills than conventional instructional approaches [33,34,36].

3.2. The effect of STEM project-based learning on each indicator of critical thinking skills

Using the same approach applied to the assessment of students' critical thinking skills in STEM PjBL, each critical thinking indicator was analyzed separately to obtain a more detailed understanding. This study examined several critical thinking indicators, including basic clarification, basic decision, inference, advanced clarification, and rhetorical strategies. A summary of students' critical thinking achievements for each indicator is presented in Table 10. The analysis results indicate that in the experimental class, most students demonstrated improvements in critical thinking skills within the medium to high categories.

Table 10. Summary of each indicator of critical thinking skills.

	Component	Basic clarification	Basic decision	Inference	Advanced clarification	Rhetorical strategies
Control	$\bar{x}$ Pretest	9.97	9.81	4.59	9.25	1.02
	$\bar{x}$ Posttest	14.66	13.37	8.34	16.17	8.10
	N-gain	0.283	0.133	0.453	0.380	0.596
	Category	Low	Low	Medium	Medium	Medium
Experimental class	$\bar{x}$ Pretest	9.97	9.81	4.59	8.99	0.89
	$\bar{x}$ Posttest	18.18	18.29	10.25	16.69	8.9
	N-gain	0.501	0.531	0.718	0.445	0.702
	Category	Medium	Medium	High	Medium	High

Figure 4 presents the N-gain scores for each critical thinking indicator. The analysis revealed that the control group achieved low to medium N-gains across all the indicators, whereas the experimental group reached medium to high levels. This difference indicates that STEM PjBL is more effective in developing students' critical thinking skills than conventional instruction, as students are actively trained to formulate focused questions, evaluate arguments, and appropriately respond to clarification questions.

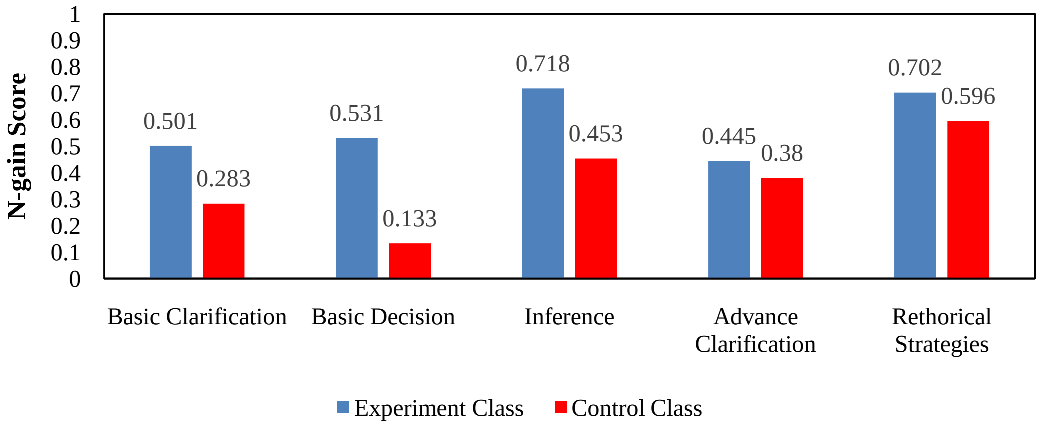


Figure 4. N-gain score in each critical thinking skill indicator.

3.2.1. Basic clarification

Table 10 shows that the control group's N-gain scores for all critical thinking measures are low to medium, while the experimental group had medium to high N-gain scores for all critical thinking indicators. This suggests that STEM PjBL improves critical thinking more than the other method. Students should learn how to ask focused questions, evaluate arguments, and ask and answer clarifying enquiries [37].

Figure 4 shows the N-gain scores for the basic clarification indicator in both the control and experimental classes. The control class achieved an N-gain of 0.283, which is categorized as low, indicating that students' ability to explain concepts remained at a basic level. In contrast, the experimental class reached an N-gain of 0.501, reflecting a medium level of improvement in basic clarification skills. This finding suggests that STEM PjBL effectively enhances students' ability to clarify and evaluate arguments. An example of the basic clarification question used in this study is presented in Figure 5.

Read the following statements carefully!

Roni believes that all earthquakes are caused by human activities, such as mining, oil drilling, and the construction of tall buildings. According to him, if humans stop these activities, earthquakes can be prevented.

Meanwhile, Sinta disagrees. She says that most earthquakes are caused by the natural movement of tectonic plates beneath the Earth's surface and cannot be stopped by humans.

What is your opinion about these two statements? Who do you think is more correct? Explain your reasons.

Read the following statements carefully!

Andi believes that tectonic plate movement only happens during major earthquakes. He thinks that if there is no earthquake, it means the Earth's plates are not moving.

Meanwhile, Lita states that tectonic plates are always moving slowly, and earthquakes occur only when there is a sudden release of energy caused by friction or collisions between plates.

In your opinion, whose statement is more accurate? Explain your reasons.

Figure 5. Basic clarification question.

Some students' answers to these basic clarification questions are shown in Figure 6.

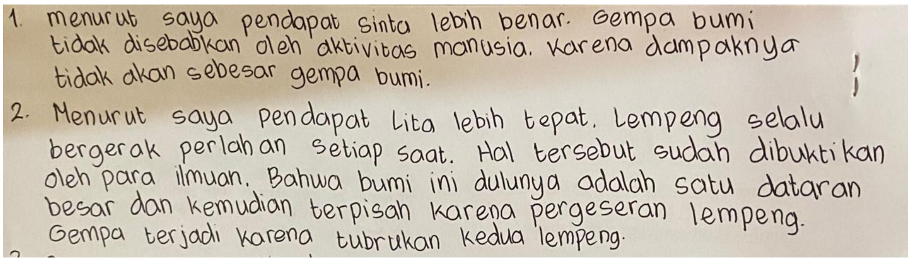

1. menurut saya pendapat sinta lebih benar. Gempa bumi tidak disebabkan oleh aktivitas manusia. karena dampaknya tidak akan sebesar gempa bumi.
2. Menurut saya pendapat Lita lebih tepat. Lempeng selalu bergerak perlahan setiap saat. Hal tersebut sudah dibuktikan oleh para ilmuan. Bahwa bumi ini dulunya adalah satu dataran besar dan kemudian terpisah karena pergeseran lempeng. Gempa terjadi karena tubrukan kedua lempeng.

Figure 6. Basic clarification answer.

As shown in Figure 6, for question number 1, the student answered, "In my opinion, Sinta is right. Earthquakes are not only caused by human activity, and their impact will not be as great as that of an earthquake." For question number 2, the student answered, "In my opinion, Lita's opinion is more accurate. The plates are always moving slowly at all times. Scientists have proven that the Earth was once a large landmass and then separated due to plate movement. Earthquakes occur because of plate collisions." The basic clarification/analysis indicator states that "students are able to judge the arguments that are given to them." The student's answers show that they can answer the questions properly and provide a good justification for their answers.

3.2.2. Basic decision

To make basic decisions, students must engage in several key processes, including evaluating source credibility, making observations, assessing observation reports, and applying prior knowledge [37]. Students use what they already know; they make decisions on the basis of what they have learned in the past and their own experiences. They can find connections, spot trends, and weigh the pros and cons of different circumstances by drawing on what they already know about a variety of subjects.

Figure 4 shows the N-gain scores of basic decision-making for students in both the control and experimental classes. The N-gain in the control class increased students' basic decision, reaching 0.133. The basic decision of students in the control class can be categorized as low-level. The experimental class N-gain reveals that all aspects of students' basic decisions improved, with a value of 0.531. In the experimental class, using STEM PjBL effectively increased students' basic decisions to a medium level. An example of the basic decision question is shown in Figure 7.

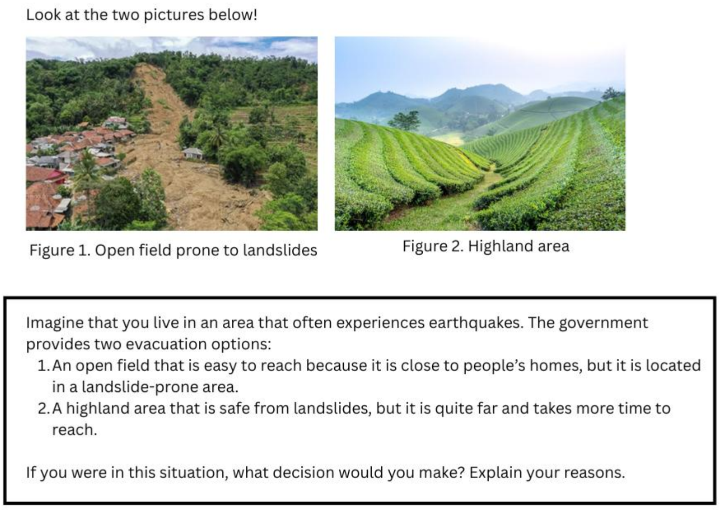


Figure 7. Basic decision question.

An example of a student's answers to these basic decision questions is shown in Figure 8.

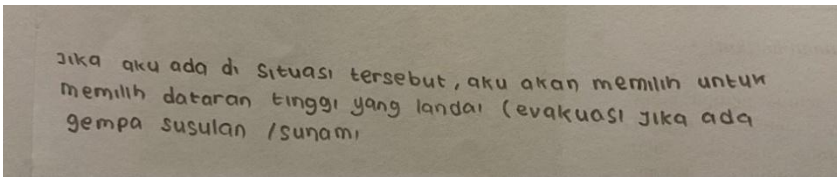


Figure 8. Basic decision answer.

As shown in Figure 8, the student's answer was, "If I were in that situation, I would choose to go to higher ground and evacuate if there were aftershocks or a tsunami." The basic decision/use of existing knowledge indicator states that "Students use what they already know and have been through to help them make decisions. They use their knowledge to make connections, spot patterns, and think about what might happen next." Figure 8 shows that students can answer the questions properly and provide good justification for their answers.

3.2.3. Inference

Inference skills include many important things that students need to learn, such as how to make and evaluate deductions, inductive inferences, and arguments, as well as how to make and evaluate value judgments [37]. Students show that they can make and evaluate inductive inferences and arguments by carefully looking at how strong the evidence is and how likely it is that the conclusions are correct.

Figure 4 shows the N-gain scores of students' inference skills in both the control and experimental classes. The N-gain in the control class increased the number of students' inferences to 0.453. The inferences of students in the control class can be categorized as medium-level. The experimental class's N-gain reveals that all aspects of the students' inferences improved to a value of 0.718. In the experimental class, using STEM PjBL effectively increased students' inferences to a high level. The inference question is shown in Figure 9.

Figure 9. Inference question.

One example of a student's answer to this question, concerning inference indicators, is shown in Figure 10.

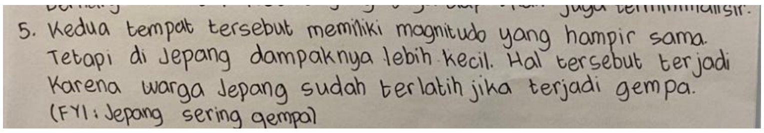


Figure 10. Answer to the inference question.

As shown in Figure 10, the student answered, "Both places had earthquakes of almost equal magnitude, but the impact was smaller in Japan. This is because Japanese citizens are trained in disaster mitigation in the event of an earthquake. FYI: Earthquakes are common in Japan." The inference skills and judging inductive inferences and arguments indicator states that "Students are good at making inductive inferences and arguments by carefully evaluating the facts and the chances that the conclusions are correct." Figure 10 shows that students can answer the questions properly and provide good justification for their answers.

3.2.4. Advanced clarification

Ennis [37] stated that advanced clarification involves several essential aspects that students need to develop, such as defining terms, evaluating definitions, handling equivocation appropriately, and identifying and assessing unstated assumptions. Figure 4 shows the N-gain scores of students' advanced clarification skills in both the control and experimental classes. The N-gain in the control class increased to 0.380. The experimental class's N-gain reveals that all aspects of students' advanced clarification improved to 0.445. In the experimental class, using the STEM PjBL effectively increased students' degree of advanced clarification to a medium level. The advanced clarification question is shown in Figure 11.

Read the following information carefully!

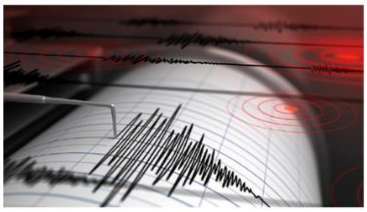


Figure 3. Illustration of an Earthquake

"An earthquake can be defined as the shaking of the lithosphere and the Earth's surface caused by certain factors. These include collisions between tectonic plates and active faults, volcanic activity, and large-scale rock collapses. Most earthquakes occur due to friction between two plates within the Earth's crust. These plates include oceanic plates and continental plates. When the plates rub against or collide with each other, they produce shock waves that we know as earthquakes."

Source: https://www.detik.com/jogja/berita/d-7258811/mengapa-gempa-bumi-bisa-terjadi-ini-penyebab-dan-prosesnya.

After reading the information about the causes of earthquakes, the teacher asks the students to have a group discussion to better understand how and where earthquakes can occur. In the discussion, three students, Fahmi, Laras, and Rudi, share different opinions.

Fahmi states, "Earthquakes happen because of collisions between tectonic plates, so the epicenter is always located at plate boundaries."

However, Laras has a different opinion. She says, "Earthquakes can also occur far from plate boundaries because there can be cracks or faults inside the plates."

Meanwhile, Rudi adds, "Earthquakes happen when a volcano erupts. So, all earthquakes must be near volcanoes."

In your opinion, whose statement is the most accurate? Explain your reason.

Figure 11. Advanced clarification question.

An example of a student's answer to this question on the advanced clarification indicator is shown in Figure 12.

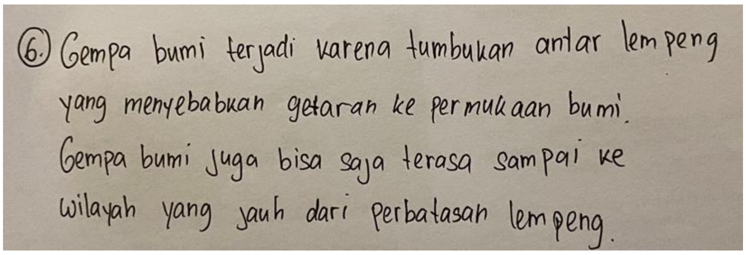


Figure 12. Advanced clarification answer.

As shown in Figure 12, the student answered, "Earthquakes occur due to collisions between tectonic plates, causing vibrations on the Earth's surface. Earthquakes can also be felt in areas far from the plate boundaries." The advanced clarification and judging inductive inferences and arguments indicator states that, "Students show that they can accurately describe the terms used in presentations, discussions, or studies. They know how vital it is to be clear about what words imply and to use the right terms. They can also check the definitions that other people give to see if they are correct and appropriate." Figure 12 shows that students can answer the questions properly and provide good justification for their answers.

3.2.5. Rhetorical strategies

Rhetorical strategies include something that students need to work on that, although not being a part of the course, is useful [37]. Rhetorical strategies are the approaches and procedures used to effectively obtain ideas, arguments, or information across an audience. Figure 4 shows the N-gain scores of students’ rhetorical strategy skills in both the control and experimental classes. The N-gain in the control class increased to 0.596. The rhetorical strategies of students in the control class was categorized as medium level. The experimental class N-gain reveals that all aspects of students' rhetorical strategies improved to 0.702. In the experimental class, using STEM PjBL effectively increased the number of students' rhetorical strategies to a medium level. The rhetorical strategies are shown in Figure 13.

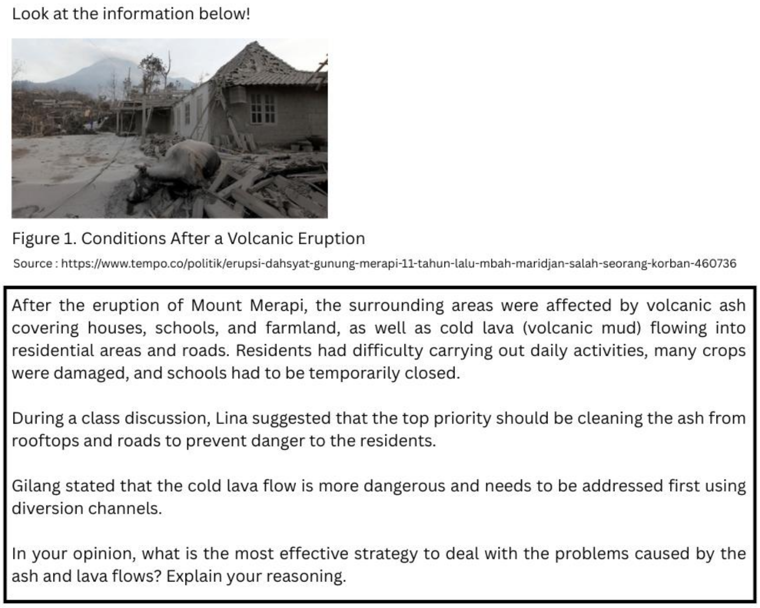

Look at the information below!

Figure 1. Conditions After a Volcanic Eruption

Source : https://www.tempo.co/politik/erupsi-dahsyat-gunung-merapi-11-tahun-lalu-mbah-maridjan-salah-seorang-korban-460736

After the eruption of Mount Merapi, the surrounding areas were affected by volcanic ash covering houses, schools, and farmland, as well as cold lava (volcanic mud) flowing into residential areas and roads. Residents had difficulty carrying out daily activities, many crops were damaged, and schools had to be temporarily closed.

During a class discussion, Lina suggested that the top priority should be cleaning the ash from rooftops and roads to prevent danger to the residents.

Gilang stated that the cold lava flow is more dangerous and needs to be addressed first using diversion channels.

In your opinion, what is the most effective strategy to deal with the problems caused by the ash and lava flows? Explain your reasoning.

Figure 13. Rhetorical strategies question.

An example of a student’s answer to this question on the rhetorical strategies indicator is shown in Figure 14.

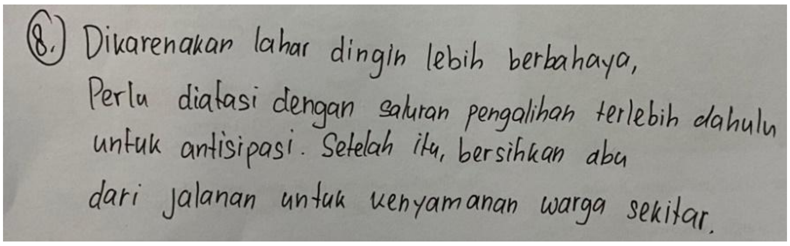
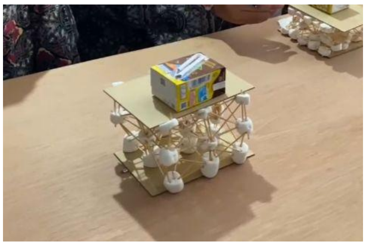

8.) Dikarenakan lahar dingin lebih berbahaya, Perlu diatasi dengan saluran pengalihan terlebih dahulu untuk antisipasi. Setelah itu, bersihkan abu dari jalanan untuk kenyamanan warga sekitar.

Figure 14. Rhetorical strategies’ answer.

As shown in Figure 14, the student’s answered, “Since cold lava is more dangerous, it needs to be dealt with first by diverting it to prevent further damage. After that, clean the ash from the roads for the comfort of the local residents.” The rhetorical/nonconstitutive but helpful strategies indicator stated that "Rhetorical strategies are the ways and means of communicating ideas, arguments, or information to an audience in a clear and effective way." Figure 14 shows that students can answer the questions properly and give a good justification for their answer.

This research revealed that STEM PjBL is suitable for increasing students' critical thinking in all aspects. In the experimental class, students had the chance to enhance their product, creating a situation in which students had to think to determine the best method to improve their product. In this case, students' ability to think critically is important for developing a good way to fix their product. This explains why students in the experimental class had better critical thinking skills. A summary of the project revisions performed by the students can be found in Table 11.

Table 11. Comparison between the initial project and the revised project.

	Earthquake-resistant building	
	Initial project	Final project
Product		
Load testing	110 g	110 g
Height	±7 cm	±15 cm
Width	-	±15 cm
Length	-	±15 cm
Earthquake test	±2SR	±4SR

The study indicated that the way teachers teach and students learn affects how well students can think critically, especially in STEM subjects. This can help students think critically and comprehend the topic better [23]. Studies have shown that the way lessons are taught can alter critical thinking [38,39]. Students learn more and think more critically in STEM courses when they are given the chance to improve [23]. Working together [40,41], learning through experience [42,43], and addressing real-world problems [44,45] all motivate students to ask questions, think critically, and come up with new ideas. These strategies make learning more interesting and useful. This study reveals that the STEM PjBL helps students learn about earthquakes, tectonic plates, volcanoes, and the layers of the Earth and then use what they learn to solve real-world problems. Studies suggest that the STEM PjBL method performs best when it lasts longer, as giving students additional time enables them to be more involved and work on their own [23,46]. STEM PjBL helps students learn and remember things by allowing them to look up information and determine how to solve difficulties.

3.3. STEM project-based learning on earthquake subtopics

Using the same approaches used to test students' critical thinking skills in STEM PjBL, we can also determine subtopics related to earthquake teaching, namely the earth layer, volcanoes, and tectonic plates. There are three questions on earthquakes, one about the layers of the Earth, two about tectonic plates, and two about volcanoes. Table 12 and Figure 15 present detailed information about earthquake subtopics.

Table 12. Summary of students' scores for each subtopic in earthquake teaching.

Class	Component	Subtopic material			
		Earth layer	Tectonic plates	Earthquake	Volcanoes
Control	$\bar{x}$ Pretest	3.70	10.98	13.62	6.34
	$\bar{x}$ Posttest	8.43	14.17	22.82	15.31
	N-gain	0.53	0.17	0.28	0.43
	Category	Medium	Low	Low	Medium
Experiment	$\bar{x}$ Pretest	3.44	10.98	13.62	6.22
	$\bar{x}$ Posttest	7.87	18.80	27.82	17.81
	N-gain	0.44	0.47	0.57	0.61
	Category	Medium	Medium	Medium	Medium

The students' scores for each subtopic show that in the experimental class, students presented a medium improvement in each subtopic. Figure 15 shows the N-gain score of the students for each subtopic.

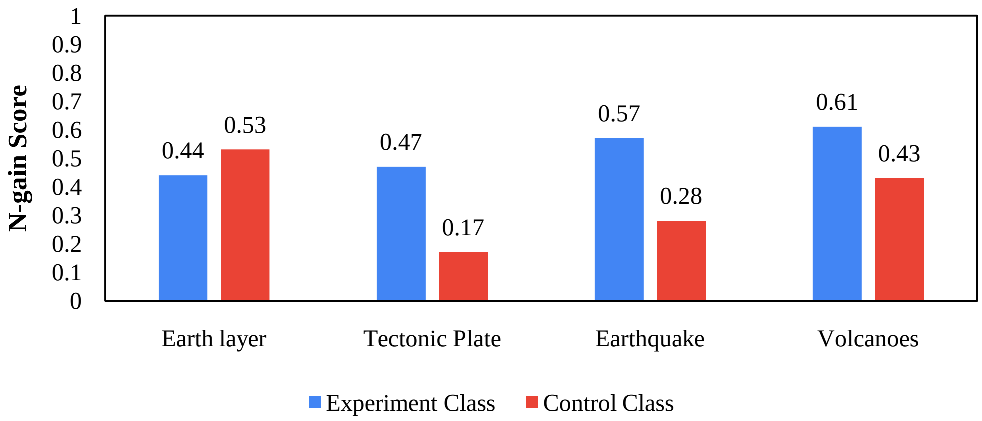


Figure 15. N-gain score for each subtopic in earthquake teaching.

According to Table 12 and Figure 15, the N-gain scores for the control group in the earthquake lesson subtopic are between low and medium. However, the N-gain scores for all subtopics in the experimental group are all at a medium level. This also shows that using STEM PjBL as a learning model helped the students understand the concepts better than the control class.

The findings of this study reinforce previous research showing that STEM PjBL is effective in enhancing students' critical thinking skills and conceptual understanding [23,46]. This is reflected in the increase in students' average scores from the pretest to the posttest in the experimental class, indicating the development of higher-order cognitive skills through active engagement in the learning process. In STEM PjBL, students are confronted with authentic problems that require in-depth analysis, evidence-based decision making, and the integration of science, technology, engineering, and mathematics concepts, thereby fostering sustained critical thinking processes [36].

The difference in instructional treatment between the experimental and control groups was a key factor contributing to the observed differences in critical thinking outcomes, which is consistent with the findings of [34], who reported that project- and inquiry-based learning approaches have a more significant impact on the development of critical thinking skills than conventional instruction.

4. Conclusions

This study demonstrates that STEM PjBL supports the development of students' critical thinking skills through structured inquiry, interdisciplinary reasoning, and reflective problem-solving. This approach creates learning conditions that require students to analyze contextual problems, justify decisions, and revise solutions based on evidence. Meaningful gains in critical thinking emerge when students are consistently engaged in authentic tasks that demand comparison, evaluation, and iterative improvement. The integration of science, technology, engineering, and mathematics within real-world problem contexts enables students to connect conceptual understanding with practical application, thereby fostering deeper reasoning processes.

These findings have important implications for science instruction at the secondary level. Teachers are encouraged to design inquiry-based learning activities that emphasize collaborative problem-solving and provide opportunities for revision and reflection, rather than focusing solely on final products. Such instructional practices can create learning environments that are more conducive to the development of students' critical thinking skills.

In the context of earthquake engineering and other local and global disasters, strengthening critical thinking skills has become increasingly urgent. Disaster-related challenges involve complex and interconnected systems, including interactions among natural factors, technology, and social aspects, which require the ability to analyze information comprehensively, evaluate alternative solutions, and make evidence-based decisions. The learning characteristics fostered through STEM PjBL, such as interdisciplinary reasoning, context-based problem-solving, and iterative refinement of solutions, align with the cognitive demands needed for disaster mitigation and risk reduction. By engaging students in authentic problems, STEM PjBL has the potential to equip learners with analytical and reflective ways of thinking that are essential for understanding and responding to disaster-related challenges, including those associated with earthquake engineering.

Author contributions

Isti Setiasih: Conceptualization; methodology, and writing; Nanang Winarno: Conceptualization, methodology, supervision, and review; Eka Cahya Prima: Supervision, validation, and review; Fairus Qamila: Investigation, data curation, and writing – review and editing, revision; Rohim Aminullah Firdaus: Validation and resources, revision; Nur Jahan Ahmad: Validation and resources, proofreading.

Use of Generative AI tools declaration

AI was employed only to assist with language expression and organizational structure. All ideas, data analysis, and scholarly interpretations were generated by the authors. The AI-supported text has been carefully reviewed and revised to ensure accuracy, clarity, and compliance with academic conventions, and the authors take full responsibility for the content of this manuscript.

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Conflict of interest

The authors declare that they do not have any conflicts of interest.

Ethics declaration

The authors state that ethical approval from a review committee was not required for this study.

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