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Multi-Criteria Assessment of Seismic Vulnerability of Public School Buildings

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Abstract
In the context of disaster risk management, this study addresses the seismic vulnerability of six public school buildings in the seismically active Dakchinkali Municipality of Nepal. These structures play a critical role as educational facilities and emergency shelters, necessitating their resilience. The study aims to comprehensively assess vulnerability by integrating physical, social, and systemic indicators. The objectives involve employing multi-criteria decision-making methods, such as AHP and WSM, to identify vulnerable school buildings. The study's methodology combines the AHP method to evaluate the relative influence of vulnerability factors from the experts and calculate final vulnerability scores utilizing WSM. Initial findings of the AHP analysis highlight consistent expert judgment and produce weights for four main domains and their indicators and sub-indicators. The most influential factor with respect to the main domains was identified as the structure domain, followed by the geotechnical domain, whereas the social and systemic domains were given similar low weight. The results showed that when all domains are considered, social and systemic domains, despite having low weightage did have an impact on the overall score. This comprehensive assessment provides valuable insights into the specific vulnerabilities of these school buildings, crucial for informed policy-making and targeted interventions in disaster risk reduction strategies.

Keywords
Seismic Vulnerability, Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), Weighted Sum Model(WSM).

1. Introduction

In disaster risk management, the seismic vulnerability of the built environment of critical facilities like school buildings is of utmost importance. These structures not only serve as places of education but also act as shelters during emergencies, so the significance of the school building is not only related to the direct consequences of collapse on the vulnerable population but also to post-disaster recovery. Vulnerability is essential to understanding disaster risk and developing effective mitigation strategies. The vulnerability component is vital because it is one of the components that human society may act upon efficiently and effectively to reduce disaster risk.

The Sendai Framework for Disaster Risk Reduction 2015-2030 emphasizes the need to significantly reduce disaster damage to critical infrastructure, including educational facilities, and to develop their resilience by 2030, emphasizing the importance of developing seismic hazard mitigation strategies that aim to reduce the vulnerability of school buildings [1]. In the context of Nepal, various studies in different parts of Nepal before the earthquake of 2015 showed that most of the school buildings were vulnerable to earthquakes [2, 3]. Similarly, the study undertaken by the National Society of Earthquake Technology (NSET) found a compelling need to create and implement a comprehensive, coordinated, and ground-truth plan for dramatically enhancing the seismic safety of schools across the country [4].

There are two ways that previous research on the seismic vulnerability of school buildings in Nepal has gone.

a) assessing the damages determined by the individual earthquakes [5, 6, 7] or

b) predicting the potential damages that may be produced by a future seismic event [8, 9].

Some assessments focused on specific types of school construction materials [10] while others concentrated on different prototypes [6, 11]. The critical component of these assessment papers was the generation of fragility curves, which can be further utilized for risk or loss assessment. While the use of Multi-criteria based approaches are being used for seismic vulnerability assessment [12, 13, 14] in other parts of the world, the application in the case of school buildings is relatively low [15, 16].

This study aims to assess the seismic vulnerability of public school buildings in Nepal by utilizing various factors that contribute to the overall vulnerability of the school building with the help of identified MCDM models. The framework combines two classical MCDM methods i.e AHP and WSM in order to evaluate the seismic vulnerability of 6 public schools from Dakchinkali Municipality which includes 12 individual school buildings blocks considering domains/ indicators/ sub-indicators related to their structural, geotechnical, social, and systemic vulnerability. This study's findings will not only add to the academic body of knowledge but also will have practical implications for policymakers, engineers, and stakeholders involved in disaster risk reduction and management and educational infrastructure development, especially in Dakchinkali Municipality.

2. Methodology

2.1 Selection of vulnerability factors

For a decision to be made for a complex problem affected by multiple factors, the decision-makers should consider specific criteria [13]. Considering the multi-dimensional vulnerability, various factors must be addressed while assessing seismic vulnerability. It is essential to carefully select appropriate indicators that capture the diverse aspects of vulnerability and be careful in the redundancy of factors, data availability, and relevance. Based on the literature review and additional references related to vulnerability indicators, four domains of the vulnerability assessment were identified that complement each other. The four domains are structural, geotechnical, social, and systemic. Under four domains, 13 indicators were selected and 5 sub-indicators were selected. These four domains are widely utilized in the seismic vulnerability assessment considering multiple criteria [15, 16, 13, 14]. The selected parameters are structured in the hierarchy for the AHP analysis(Fig.1). The description related to the factors is given in Table 3.

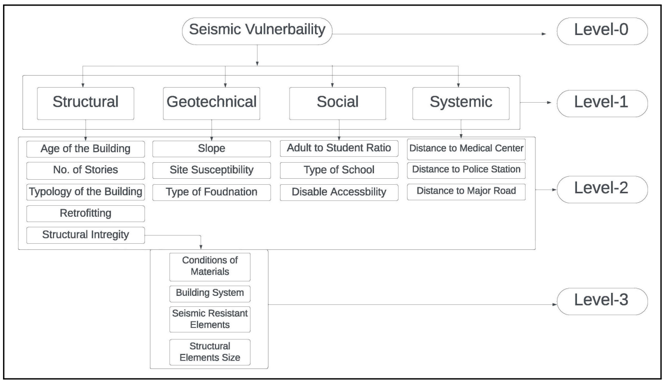

Figure 1: AHP hierarchy of the vulnerability factors in different level

2.2 Analytical Hiearchy Process

AHP stands for Analytic Hierarchy Process, a decision-making approach established in the 1970s by Thomas L. Saaty. It is frequently used to systematically examine complicated problems and make informed decisions in various domains, including engineering, business, and social sciences. AHP has been commonly used in seismic vulnerability analysis [15, 13, 16, 14]. The AHP helps to structure the decision-maker's thoughts and can support organizing the problem in a simple manner to follow and analyze. In this study, AHP has been utilized to obtain weightage for the factors using pair-wise comparisons.

To utilize AHP, firstly, a hierarchical structure to represent the problem has to be established, and then the weight is obtained through pair-wise comparisons of factors at each level of decision-making. AHP typically involves four steps: -

1. Problem Modeling, define the problem i.e seismic vulnerability in this study
2. Structuring domains, indicators, and sub-indicators into a hierarchy.
3. Create matrices for pair-wise comparisons, compute the eigenvector, calculate the Consistency Index (CI), and determine the Consistency Ratio (CR)
4. Determine the relative importance of each element, verify the consistency, and arrive at the final overall rating at each level.

When two elements are compared on the same level in pairs, the results are expressed by a number from 1 to 9(Table 1) according to the predefined scale of absolute numbers and their reciprocals. The results of the pair-wise comparisons of the elements are organized into the matrix of n x n elements will be normalized and used to compute the eigenvector. This eigenvector represents the relative importance of the factors [17]

The most crucial aspect of the AHP method is the consistency between the judgments and weights. The Consistency Index(C.I) factor is utilized to substantiate the consistency between weights and judgment [14]. The consistency index is defined as follows: -

$$CI = (\lambda_{\text{max}} - n)/(n-1) \tag{1}$$

Where n denotes the order of a matrix and λ_{max} represents the principal eigenvalue of a pair-wise comparison matrix. At last, the consistency ratio(CR) is calculated as follows: -

$$CR = CI/RI \tag{2}$$

RI represents the average value of CI value for random matrices using the scale from Table 2.

The judgmental inputs are unreliable and poorly received if the matrix has a high CR value. However, a CR value of 0.10 or less is acceptable.

Table 1: Fundamental scale of AHP [17]

Intensity of Importance	Definition	Explanation
1	Equal importance	Element a and b contribute equally to the objective
3	Moderate importance of one over another	Slightly favor element a over b
5	Essential importance	Strongly favor element a over b
7	Demonstrated importance	Element a is favored very strongly over b
9	Absolute importance	The evidence favoring element over a over b is of the highest possible order of importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed. For example, 4 can be used for the intermediate value between 3 and 5
1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	These values represent the opposite of the reciprocal whole numbers. For example, if "9" means that x is much more important than y, "1/9" means that x is much less important than y.	

Table 2: Random Index [17]

Number of Criteria	RI
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24

Number of Criteria	RI
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51

Table 3: Seismic Vulnerability Factors

Indicators/Sub-indicators	**Short Description**	**Data Collection Method**
Age	Buildings with a longer history of use tends to have endured more wear and tear, making them more susceptible to earthquake damage.	Interview
Typology of Building	Structures constructed from masonry materials are generally thought to have lower seismic resistance compared to those built with reinforced concrete.	Field Obseravtion
No. of Storeys	Taller buildings tend to undergo more material damage and determine higher human tolls than low-height profile ones	Field Observation
Retrofitting	It indicates whether or not the building undergone retrofitting works	Field Observation, Interview
Structural Intregity	It values the overall the structural integrity of the structure based on quick compliance and noncompliance checks based on visual inspections and measurements.	
Conditions of Materials	A building that is not maintained properly will have bad conditions of materials. Poorly maintained buildings tend to undergo more damage during seismic excitations.	Field Observation
Building System	A building with good configuration, a proper gap with adjacent buildings, and a rigid diaphragm tends to perform better in seismic events.	Field Observation
Seismic Resistant Elements	The presence of bands at the lintel, sill, roof level, and corner stitches mitigate the damage due to tension and shear cracks, especially in theunreinforced masonry.	Field Observation
Structural Element Size	The size of the structural elements depends upon the structural design. Properly designed structures will have sufficient structural element size to resist the seismic load.	Field Observation
Slope Percentage	Structures on the sloping ground are found as more vulnerable than the structures on the plain ground, and the degree of vulnerability increases with the increment of slope angle	Field Observation
Site Susceptibility	The areas with a previous history of landslides, mudslides, soil settlement, sinkholes, construction on fill, or buried on or at sites that are more vulnerable. The buildings located in the vicinity of potential earthquake-induced slope failures or rock falls are more vulnerable.	Field Observation, Interview
Type of Foundation	The foundation plays a crucial role in spreading seismic stresses during an earthquake and preserving the stability of the building. The interaction of soil, foundation, and structure may significantly affect the fragility of the structure.	Field Observation, Interview
Adult to Student Ratio	A higher ratio of adults to students suggests reduced vulnerability since there are more educators and support staff available to supervise and attend to the students.	Interview
Type of School	The age distribution of the students plays a significant role in their ability to respond appropriately during emergency situations.	Interview
Disable Accessibility	Disabled students require special care during emergency situations because they are less able to help themselves and others.	Interview, Field Observation
Distance to Medical Centers	The greater the distance, the greater the total vulnerability of the school.	GIS network Analysis
Distance to Police Station	The greater the distance, the greater the total vulnerability of the school.	GIS network Analysis
Distance to Major Road	The greater the distance, the greater the total vulnerabilityof the school.	GIS network Analysis

For group decision-making, the decision matrix has to be constructed incorporating judgment from the group. It has been proved that the geometric mean is a unique way to combine individual judgment with group judgment [18]. Aggregation judgment matrices of the group experts are calculated by:

$$A_{ij} = \left[\prod_{k=1}^{n} a_{ij}\right]^{1/n} \quad (3)$$

Where,
A_{ij} = Consolidated Matrix Element
n = Number of Experts,
a_{ij} = Individual Matrix Elements,

2.3 Data Collection

This study collects two types of data for the multi-criteria evaluation. At first, to calculate the weightage of the domains, indicators, and sub-indicators Analytical Hierarchy Process(AHP) survey is employed to the experts from which the weightage of each domain, indicator, and sub-indicator is determined with the help of pair-wise comparisons. The questionnaire from the AHP survey was sent to 20 experts from different backgrounds such as structural engineers, earthquake engineers, geotechnical engineers, and disaster managers. From 20 experts, 16 people responded to the survey whose judgments were utilized in the AHP analysis. Secondly, the data about the indicators and sub-indicators are collected through methods such as site inspections, surveys, as-built drawings, and interviews with school administrators. This data collection aims to obtain comprehensive and reliable information about the characteristics and conditions of the school buildings being studied. Similarly, data related to the systemic vulnerability component is collected through network analysis in QGIS. The data collection method for different factors is given in Table 3.

2.4 Data Analysis

For data analysis, all the indicators and sub-indicators are expressed in terms of low, medium, and high vulnerability based on the recommendation of experts and literature review [13, 19]. The different categories' quantitative value is expressed in terms of 0-1 as providing different weights to every indicator and sub-indicator is a complex and time-consuming task. Here, the weight of the highly vulnerable category is 0.5, the medium vulnerable category is 0.333, and the low vulnerable category is 0.167 [20]. The categorization of indicators has been different in various papers, which is usually based on the data availability and context of the research. The Weighted Sum Model (WSM) is a strategy for evaluation and decision-making used to rank and evaluate options according to weighted criteria. It's a basic strategy that is frequently applied in multi-criteria decision-making. By allocating weights to several criteria and producing a weighted total for each alternative, the WSM enables decision-makers to assess various alternatives quantitatively. The final score of the alternative, i.e. each school building at a different level is calculated by:-

$$W = \sum_{k=1}^{n} W_i \times x_i \quad (4)$$

Where,
W = Vulnerability Score of the Schools
w_i = weight of each domain/indicator/sub-indicator derived from AHP
x_i = domain/indicator/sub-indicator score categorized into high, medium and low
n = number of domains/indicator/sub-indicator

3. Case Study

Six public schools from Dakchinkali municipality are selected to apply the developed framework of seismic vulnerability assessment including multiple criteria. The six school building consist of 12 school building blocks which is made of different construction materials constructed in different time frames. The selected public schools encompass a diverse range of schools, considering factors such as urban, peri-urban, and rural settings, as well as variations in school size, type of school, and other relevant characteristics. The six schools sample includes a variety of schools including basic school, secondary school, and higher secondary school. The details of the school building are given in Table 4.

Table 4: General Information of Schools

School Name	Building_ID	Age	Typology
Arundaya Secondary School	ASS_1	14	Brick-Cement URM
Arundaya Secondary School	ASS_2	34	Brick-Cement URM
Arundaya Secondary School	ASS_3	38	Brick-Cement URM
Dallu Adarbhut Bhidyalya	DAV_1	35	Stone-Mud URM
Dallu Adarbhut Bhidyalya	DAV_2	4	RC Engineered
Shree Ganesh Adarbhut Bhidyalya	SGAB_1	36	Brick-Cement URM
Shree Ganesh Adarbhut Bhidyalya	SGAB_2	5	RC Engineered
Shree Setidevi Secondary School	SSSS_1	19	Brick-Cement URM
Shree Setidevi Secondary School	SSSS_2	32	Stone- Cement URM
Shree Setidevi Secondary School	SSSS_3	4	RC Engineered
Champadevi Secondary School	CDSS_1	36	Stone-Mud URM
Shree Chalnakhel Adarbhut Bhidalaya	SCAB_1	32	Stone- Cement URM

The school buildings listed in Table 4 were surveyed and the factors related to seismic vulnerability as given in Table 3 were collected with the help of interviews and field observation. GIS techniques known as network analysis were employed to find out the data related to the systemic domain of the assessment framework which mainly includes the physical distance of different elements from the school buildings. The data collection methods for all the factors are mentioned in Table 3.

4. Results

4.1 AHP

The consolidated matrix from every 16 individual judgments at each level of the hierarchy of Figure 1 results in the weightage of each domain, indicator, and sub-indicator being consolidated using Equation 3. For all the comparison and weightage calculation levels, the consistency ratio is less than 0.1, indicating that the group judgment is consistent. The results of the AHP process for consistency check are presented in Table 5 and weightage of the factors is presented in Figure 2.

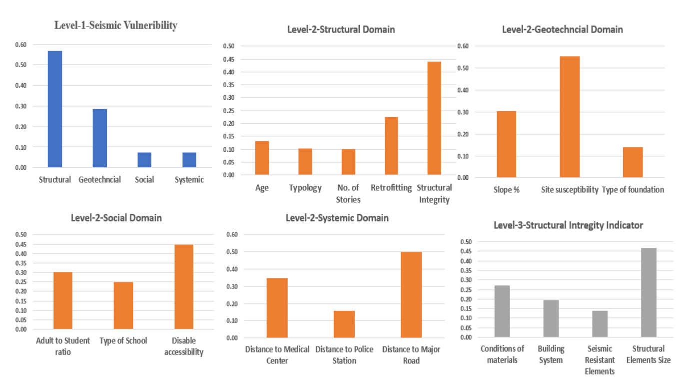

Figure 2: AHP weightage of the vulnerability factors in different levels

Table 5: Table showing consistency of pairwise comparison.

S.No.	**Level**	**n**	λ_{max}	**C.I.**	**R.I.**	**C.R.**
a.	Level-1	4	4.083	0.027	0.9	0.030
b.	Level-2 Structural	5	5.04	0.011	1.12	0.0103
c.	Level-3 Structural Integrity	4	4.044	0.014	0.9	0.0166
d.	Level-2 Geotechnical	3	3.004	0.0023	0.58	0.0039
e.	Level-2 Social	3	3	0.000	0.58	0.000
f.	Level-2 Systemic	3	3.018	0.009	0.58	0.0159

Here,

- Level refers to the hierarchy level as presented in Figure 1.
- n refers to the consolidated matrix size.
- λ_{max} refers to the principal eigenvalue.
- C.I refers to the Consistency index calculated as per Equation 1.
- R.I refers to the Random Index taken from Table 2.
- C.R refers to the Consistency Ratio calculated as per Equation 2.

In the first level of the hierarchy, the structural domain(0.56) was the most influential one, followed by the geotechnical domain(0.28) whereas social and systemic were given similar low importance(.07). It is observed that structural integrity (0.44) has the highest influence among the indicators, followed by retrofitting (.23) in the structural domain. The typology and number of stories had similar low effects (0.10). In contrast, the age of the buildings had a bit high impact (0.13). The most influential indicator in geotechnical assessment was considered to be site susceptibility(0.55), followed by slope percentage(0.3), whereas the type of foundation had the least influence(0.14). For the social domain, three indicators were selected, i.e. adult student ratio, type of school, and disabled accessibility, whose influence on the social vulnerability assessment is shown in Figure 2. Disabled accessibility had the highest effect (.44), followed by the adult-to-student ratio (.30), and the type of school had the lowest relative influence (0.25). According to Figure 2, the most influential indicator in the vulnerability assessment of physical distance is the distance to major roads (.49), followed by the distance to the medical center (0.34), and the distance to the police station had a minor influence(.15).

4.2 Seismic Vulnerability Assessment

Results for each domain of vulnerability are presented in the tables below. The rank is provided to the school building based on the score it received using Equation 4.

Table 6: Structural Vulnerability Score

Building_ID	**Structural Score**	**Rank**
ASS_1	0.239853	9
ASS_2	0.245184	8
ASS_3	0.29915	3
DAV_1	0.282932	5
DAV_2	0.226765	10
SGAB_1	0.300462	1
SGAB_2	0.226765	10
SSSS_1	0.299574	2
SSSS_2	0.282397	6
SSSS_3	0.226765	10
CDSS_1	0.265311	7
SCAB_1	0.29915	3

Table 6 shows the structural vulnerability score of the 12 schools' building blocks. Some of the schools received the same ranking as the vulnerability scores were the same. From the table, we can see that SGAB_1 received the highest score and can be regarded as the most structurally vulnerable school building block among the 12 school building blocks. Similarly, DAV_2, SGAB_2 and SSS_3 received similar lower scores and both of them can be regarded as the least structurally vulnerable schools.

Table 7: Geotechnical Vulnerability Score

Building_ID	**Geotechncial Score**	**Rank**
ASS_1	0.264725946	6
ASS_2	0.264725946	6
ASS_3	0.264725946	6
DAV_1	0.305960268	3
DAV_2	0.25888325	9
SGAB_1	0.214077018	10
SGAB_2	0.167	11
SSSS_1	0.305960268	3
SSSS_2	0.305960268	3
SSSS_3	0.167	11
CDSS_1	0.315679987	1
SCAB_1	0.315679987	1

From Table 7, we can see that SCAB_1 and CDSS_1 received the highest score, therefore these schools are most geotechnically vulnerable. Similarly, SGAB_2 and SSS_3 received the lowest score which means it is the least geotechnically vulnerable.

Table 8: Social Vulnerability Score

Building_ID	Social Score	Rank
ASS_1	0.480565	2
ASS_2	0.522352	1
ASS_3	0.439027	4
DAV_1	0.407154	6
DAV_2	0.257791	12
SGAB_1	0.407154	6
SGAB_2	0.273429	11
SSSS_1	0.315217	10
SSSS_2	0.405658	8
SSSS_3	0.372989	9
CDSS_1	0.422793	5
SCAB_1	0.480565	2

Table 8 shows the social vulnerability score of the 12 school building blocks. The highest score is received by ASS_2 block of Arundaya Secondary School. Therefore, this school building can be considered as most vulnerable in terms of social factors. In contrast, the DAV_2 block of Dallu Adarbhut Vidyalaya received the lowest score, therefore it can be regarded as the least vulnerable in terms of the social domain.

Table 9: Systemic Vulnerability Score

Building_ID	Systemic Score	Rank
ASS_1	0.276665	7
ASS_2	0.276665	7
ASS_3	0.276665	7
DAV_1	0.41697	1
DAV_2	0.41697	1
SGAB_1	0.219239	10
SGAB_2	0.219239	10
SSSS_1	0.359198	4
SSSS_2	0.359198	4
SSSS_3	0.359198	4
CDSS_1	0.384802	3
SCAB_1	0.193041	12

Table 9 shows the systemic vulnerability score of the school building of the 12 sample schools. The score is similar for the building blocks that are located adjacent to each other as the systemic domain is concerned with physical distance vulnerabilities. The table shows Dallu Adarbhut Bhidhyalaya (DAV_1 and DAV_2) received the highest score rendering it the most vulnerable one and Shree Chalnakhel Adarbhut Bhidhyalaya(SCAB_1) received the lowest score making is the least vulnerable in terms of systemic vulnerability.

Table 10 shows the combined score of each school building block combining the results from different domains. From the table, the highest score was received by SCAB_1 which can be the most vulnerable school building block with respect to the 12 school building block. Similarly, the SGAB_2 was assigned the lowest score rendering it the least vulnerable school building.

Table 10: Combined Seismic Vulnerability Score

Building_ID	Final Score	Rank
ASS_1	0.267640139	9
ASS_2	0.273786434	8
ASS_3	0.29816539	6
DAV_1	0.308725457	2
DAV_2	0.252352084	10
SGAB_1	0.277884407	7
SGAB_2	0.212737738	12
SSSS_1	0.306992588	3
SSSS_2	0.304010269	4
SSSS_3	0.230595681	11
CDSS_1	0.30026394	5
SCAB_1	0.309501232	1

5. Discussion

All of the indicators and sub-indicators have an important role in the seismic vulnerability of buildings, but they do not contribute equally to the overall vulnerability. Hence, the overall vulnerability cannot be determined by focusing solely on one indicator or domain. Therefore, to achieve a holistic understanding of the seismic vulnerability of the school buildings, all the elements have been considered simultaneously utilizing the MCDM methods. Then the domains are combined to produce an overall seismic vulnerability index for each school building. To have a better understanding of the findings, two situations have been explained below: -

- In the first level of the hierarchy, the structural domain was the most influential one in which the structural integrity indicator was of high importance. In contrast, The social and systemic domains were considered the least important (0.07) during the AHP analysis. When considering the influence of the indicators on the overall seismic vulnerability, structural integrity had the highest influence (0.25), and structural element size also had the most important influence (.10) despite being in the third level of the hierarchy. Another high influencing indicator was site susceptibility (0.15). The high influence of the structural domain on the overall seismic vulnerability highlights the importance of addressing issues related to the structural integrity and structural design of school buildings. Similarly, the influence of site susceptibility on overall vulnerability emphasizes the importance of site selection during the construction of school buildings.

- The scores of individual domains are given in Table 6-9 and the final score is given in Table 10. From the AHP weightage results(Fig. 2), it is clear that the structural and geotechnical domains have the highest weight in determining the seismic vulnerability. However, when all the domains are considered the social and systemic domains despite having low weightage did have an impact on rank as we can see from the final score table. For example, SGAB_1 despite receiving the first rank on the structural domain was reduced to 7th rank when all the domains were considered. This highlights the importance of considering relevant factors affecting seismic vulnerability while assessing the seismic vulnerability of school buildings.

6. Conclusion

The construction of earthquake-resistant school buildings which can be used as temporary shelter during emergencies plays a significant role in ensuring the safety and well-being of students and staff as well as in post-disaster recovery. However, accurately assessing the seismic vulnerability of school buildings poses a challenge, as it requires considering multiple factors simultaneously. Therefore, the purpose of this study was to represent a simple and cost-effective approach for the holistic measurement of seismic vulnerability of Nepali School Buildings with the help of classical MCDM techniques. Though limited by the number of school buildings selected for the study the framework can be further utilized in other areas with similar conditions. The results show that social and systemic domains despite having relatively low importance compared to structural and geotechnical domains did have an impact on the combined seismic vulnerability score when all the domains were considered. This highlights the importance of considering multiple factors in the assessment of seismic vulnerability of school buildings. The results of this study will be helpful to policymakers, engineers, and stakeholders involved in disaster risk reduction and management and educational infrastructure development of Dakchinkali municipality. Though four domains utilizing 13 indicators and 5 sub-indicators were used in this study, some other factors like local soil type, and economic or environmental factors are not included in the study due to unavailability and limited scope of the study which could be targeted in further research.

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