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Statistical Approach in the Determination of Causality Factors of Seismic Capacity of Reinforced Concrete Residential Buildings

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Abstract

Earthquakes are known destructive phenomena causing damages on buildings; yet their occurrence cannot be anticipated. Nevertheless, one could ensure that a building is resilient to earthquakes in terms of its seismic capacity. The traditional way of simulation to attain the building performance in various earthquake scenarios is inefficient and time-consuming especially when many structures need to be assessed. Hence, there is a need for an innovative process using a predictive model that could aid engineers in assessing structures faster and more efficiently. A critical step in developing this process is to identify the potential factors that affect the seismic capacity. Hence, preliminary data were collected through desktop review and interview followed by validity and reliability tests. As a result, one out of thirteen factors was rejected after the content validity test. Then, the pilot survey was conducted, yielding Cronbach's alpha of α=0.920. Lastly, the actual survey was conducted which was immediately followed by Exploratory Factor analysis. With this, the analysis yielded initial and final Kaiser-Meyer-Olkin (KMO=0.664) and Bartlett's test ($p>0.05$), indicating that the factors were suitable resulting in four major factors: Structural Detail, Material Strength, Architectural Detail, and Distance from the Nearest Faultline. Therefore, this study demonstrated the effective generation of relevant factors to develop structural measures to reduce safety risks and enhance earthquake preparedness in residential areas.

Index Terms—seismic capacity, earthquake damage, exploratory factor analysis, causality factor

Introduction

Earthquakes are characterized by their rapid movements beneath the earth's surface, causing potential geologic changes to their area of proximity. In fact, earthquakes have largely affected communities and societies by a large margin of 1500 earthquakes with magnitudes 5 and more per year [1]. Most cases of earthquakes mainly come from countries coming from the Pacific Ring of Fire region. This is supported by Duffin [2] who stated that countries belonging to this region are the leading sources for earthquake policies and science due to the high degree of tectonic activities.

Al-Marwaee [3] posed that the uncertain ground motion produces extensive range of frequencies that affect building stability, leading to structural failures and faulty construction. Furthermore, Hassan et al. [4] emphasized that failures and faulty construction are two common experiences in the construction industry, both of which could potentially arise due to the cost, resources, and time of the project. This argument entails the different unforeseen factors, which could potentially affect seismic capacity of an infrastructure. This is supported by Sudha and Venkateswarlu [5] who proved that such inefficient action to these factors would lead to sub-standardizing which greatly worsens the status of a structure. As a result, the weakening of the material's strength takes effect, causing huge impact to the structural integrity of the infrastructure [5].

In every seismic event, a building must be stable to prevent any structural failures from occurring [6]. The importance of building stability is indispensable, as a building holds the life of the people. Thus, this study focused on the factors causing disruptions in building stability.

Further, the extent of seismic impact on buildings is limitless. This impact greatly affects the seismic capacity of the building, which refers to the capacity at which a building starts to experience a certain type of damage, the seismic capacity of a structure is affected. Because of this, the study sought to determine the causality factors of seismic capacity of reinforced concrete residential buildings in the Philippines. Specifically, the study addressed the following:

1. Identify and analyze all potential seismic capacity causality factors using desktop review and interview.
2. Develop and validate a questionnaire that would be used in acquiring data necessary to finalizing the possible factors and inquiries.

Generate the final seismic capacity causality factors using the validated questionnaire and applying factor analysis in finding out the significant differences among the answers made by the interviewees.

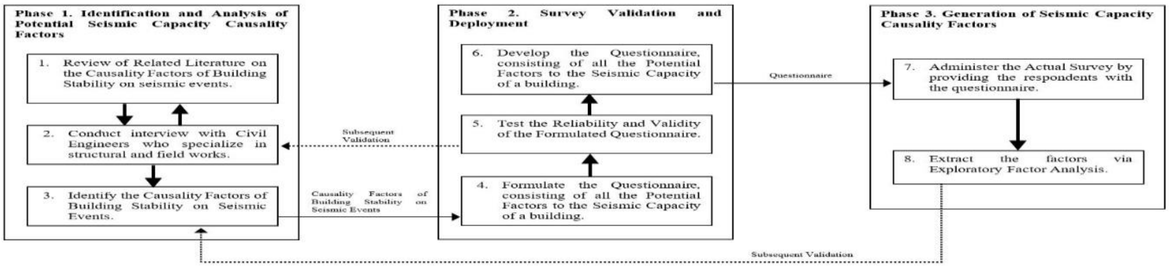

Fig. 1. *Conceptual framework containing the sequential phases of generating seismic capacity* causality factors

I. Materials And Methods

This study involved three phases, including their corresponding steps, that must be followed in order to accomplish the main objective of this study, which was to determine the causality factors of seismic capacity of reinforced concrete residential buildings. The procedure of this study is illustrated in Fig. 1.

A. Data Samples

The respondents of this study were Civil Engineers whose specialization was in structural engineering. In particular, the study consulted Civil Engineers practicing structural engineering in the Philippines. For the interview, as described in Step 2, at least ten Civil Engineers were interviewed. This sample size is supported by Shetty [7] in which a minimum number of ten respondents is enough for an interview, assuming that the integrity of the population of a group is recruiting. In conducting the validity test, as described in Step 5, twelve Civil Engineers were considered. This number was the same for the reliability test. Regarding the validity and reliability tests, the sample size of twelve is supported by Julious [8] in which pilot studies are recommended to have at least ten participants. For the respondents in Step 7, at least fifty respondents were considered.

B. Data Instruments

In the first phase, the gathering of information regarding the potential seismic capacity causality factors was made using literature reviews such as online articles, research studies, e-books, journals, etc. For the interview, the tools used in the were Google Meet, Google Email, and ZOOM.

In the second phase, the questionnaire constructed based on the desktop review and interview was arranged using Google Forms. The questionnaire was distributed via email to all respondents of the study. To determine the internal consistency from the reliability test, the Cronbach's alpha was used via SPSS.

In the third phase, the final questionnaire was answered by the respondents of the study. Like the second phase, this questionnaire was also made using Google Forms and was distributed via email to all respondents. To analyze the responses of the respondents from the survey to extract the factors out of the potential factors, the EFA was conducted via SPSS.

C. Data Gathering Procedure

The processes necessary in identifying potential factors were inspired from the first three of the six phases described by Cabuñas and Silva [9]. The first phase included a desktop review from existing studies and journals and interviews with the chosen respondents. Then, identification of potential causality factors of building stability on seismic events was established.

After identifying the potential factors, the second phase was conducted. This enabled the researchers to check the validity and reliability of the identified factors with respect to seismic capacity. This was obtained by making a questionnaire which contained all the factors gathered in the previous phase. A pilot survey was also conducted prior to test the validity and reliability of the questionnaire constructed. Once verified, the questionnaire was finalized for the actual survey. The third phase took place as the questionnaire was given to the respondents. These responses were then subjected to EFA using Principal Component Analysis (PCA), which helped in diminishing other factors initially listed as potential factors. This resulted to a lesser number of factors, where factors were grouped into components. These components or groups were named based on the nature of the factors being grouped.

D. Data Analysis

In this study, statistical treatments were made. Specifically in Step 5, there were three fundamental criteria to consider: content validity, construct validity, and criterion validity [10]. However, in this study, only the content and construct validity tests were done, as no model or equation where the factors could be applied was made that would accomplish the criterion validity. First, the content validity tested how the questionnaire adhered to the interest of the study. This meant that assessing the questionnaire's validity based on its importance to the study was done. In contrast, the questionnaire for the content validity was different, as this test was formulated using a dichotomous type. This meant that each factor that the respondent checked had to be responded with a yes or no answer, with a "yes" answer referring to the approval of the respondent with the factor as valid and a "no" answer referring to the disapproval of the respondent with the factor as valid. Factors that had an approval of at least 50% were retained. Otherwise, they were removed from the potential factors. Second, the construct validity pertained to the final factors resulting from the actual survey, which was achieved in the phase 3. Aside from the validity test, a pilot survey was used to assess the questionnaire's reliability. The questionnaire was evaluated for consistency in this test by performing a pilot survey. Cronbach's alpha was employed as the defining criteria for the questionnaire's internal consistency. Reliability values for the Cronbach's alpha are described in Table I. For the extraction of factors as described in Step 8, EFA was conducted in order to determine whether or not there were factors that were needed to be removed from the initial list. Furthermore, the extraction method used in the EFA was PCA. According to Jolliffe and Cadima [12], PCA is a method that cuts the dimensionality of the data set into smaller quantities. The reduction of the dataset resulting from this method only minimizes the loss of information

Table I *Cronbach's Alpha Reliability Level [11]*

Cronbach's Alpha Score	Level of Reliability
0.0 – 0.20	Less Reliable
>0.20 – 0.40	Rather Reliable
>0.40 – 0.60	Quite Reliable
>0.60 – 0.80	Reliable
>0.80 – 1.00	Very Reliable

In conducting the EFA, four results were observed and analyzed. These were: (1) KMO and Bartlett's Test, (2) Communalities, (3) Total Variance Explained, and (4) Pattern Matrix. For the KMO and Bartlett's Test, two values were evaluated. These were the KMO Measure of Sampling Adequacy and the p value or significant level of the Bartlett's Test of Sphericity. According to Miljko[13], a KMO greater than 0.60 results to a sufficiency of the factor. In addition, a p value less than 0.05 indicates a significantly different correlation matrix from the identity matrix. In other words, the correlations of each variable or factors in the analysis are equal to zero. The communalities, on the other hand, mentioned that communalities refer to the measure on how the variance of each factor is being accepted by the factor model [14]. Furthermore, the range of accepted minimum values for communalities is from 0.25 and 0.4; although, communalities of 0.7 and above are considered ideal. For this study, a communality of 0.4 was set as the minimum value. For the total variance explained, the cumulative percentage of at least 60% for the initial eigenvalues must be achieved. The eigenvalue to be set as basis for the extraction was greater than 1. This was supported by Rahn [15] where an eigenvalue of 1 is commonly a default value for the number of formulated factors. For the rotation method, the promax method was used with a kappa value set to the default value of 4. Promax Rotation is an oblique type of rotation which allows factors to be correlated. In turn, this rotation method allows for a faster calculation [16]. The default value of 4 is recommended due to its ability to provide higher correlations and simple structure of the loadings [17]. This, in turn, makes this kappa value to be optimum. From the pattern matrix, loadings with values below 0.4 were removed, while loadings above 0.4 are considered significant [18].

II. Results And Discussion

The results and discussion of this study are presented in this section. These revealed the outcomes of the different phases involved.

A. Phase 1

The identification of the potential seismic capacity causality factors came from the inferences of numerous literature reviews and interview. Based on the gathered information, there were thirteen factors identified. These were the following:

- Span of Building (Both Ways)
- Number of Storeys
- Wall Quantity
- Column Dimension
- Beam Dimension
- Footing Dimension
- Slab Thickness
- Size of Non-Structural Elements
- Rebar Cross-Sectional Area
- Design Strength of Concrete
- Design Strength of Rebar
- Soil Bearing Capacity
- Distance from the Nearest Faultline

To simplify the manifestation of the results for this test, assigning the factors with codes was necessary. Table II shows the corresponding codes to the potential factors.

These factors were derived using sources indicated in the scope and limitation of this study, which meant that these factors were deemed as timely in the current situation of the Philippine structural engineering.

B. Phase 2

When the potential factors of seismic capacity were identified, the need to assess the factors in terms of their validity and reliability had to be done. These assessments were done by putting these factors in a questionnaire where the respondents could answer. As stated, the first test made was the content validity test. From this, the questionnaire was distributed to the thirteen respondents of the study. The results shown in the latter, they were tallied and converted to percentage. These results were summarized in Table III. A graphical presentation of the summarized results of the content validity test is shown in Figure 2. Based on the results shown, it can be inferred that the only potential factor that was deemed by the respondents to be irrelevant was the PF13. Hence, this factor was removed in the analysis. In conjunction, the reliability test only considered factors from PF1 to PF12.

Table Ii *corresponding Codes To The Potential Factors*

Potential Factor	Code
Span of the Building (Both Ways)	PF1
Number of Storeys	PF2
Wall Quantity	PF3
Column Dimension	PF4
Beam Dimension	PF5
Footing Dimension	PF6
Slab Thickness	PF7
Rebar Cross-Sectional Area	PF8
Design Strength of Concrete	PF9
Design Strength of Rebar	PF10
Soil Bearing Capacity	PF11
Distance from the Nearest Faultline	PF12
Size of Non-Structural Elements	PF13

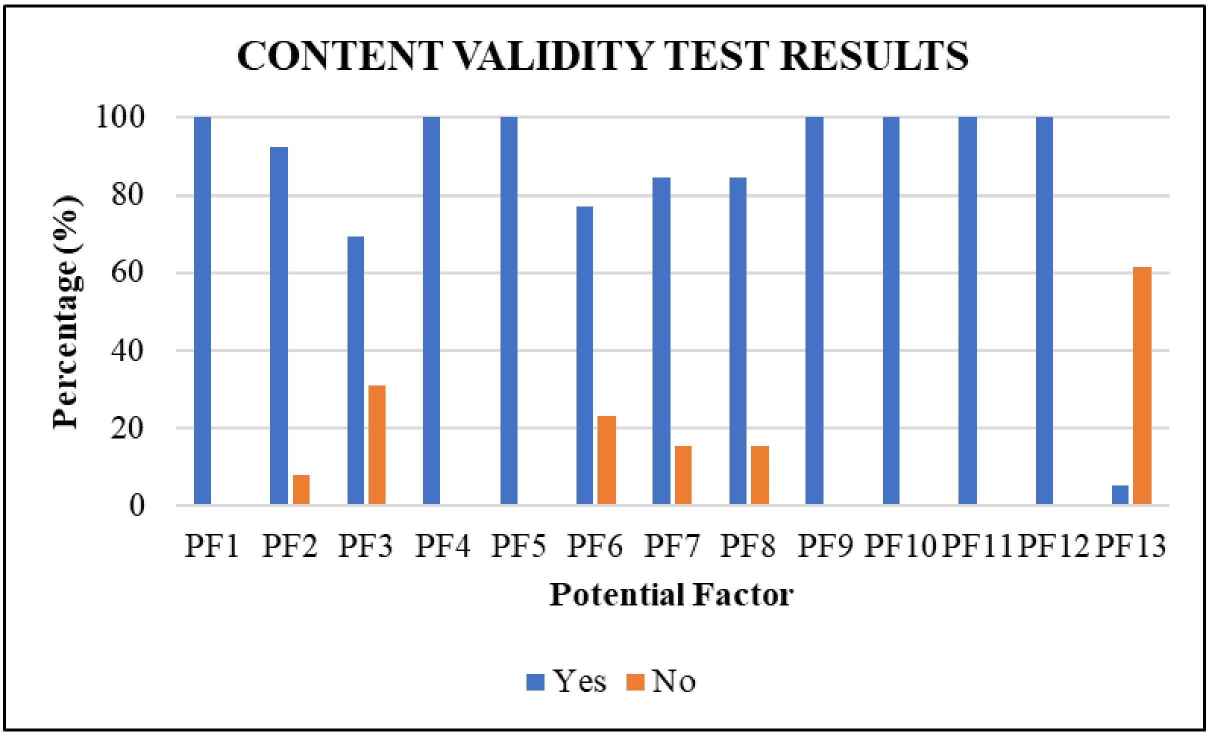

Fig. 2. *Graphical Representation of the Results of Content Validity Test*

Table III *Summarized Results Of The Content Validity Test*

Potential Factors	Yes		No	
	Tally	% Form	Tally	% Form
PF1	13	100.00%	0	0.00%
PF2	12	92.31%	1	7.69%
PF3	9	69.23%	4	30.77%
PF4	13	100.00%	0	0.00%
PF5	13	100.00%	0	0.00%
PF6	10	76.92%	3	23.08%
PF7	11	84.62%	2	15.38%
PF8	11	84.62%	2	15.38%
PF9	13	100.00%	0	0.00%
PF10	13	100.00%	0	0.00%
PF11	13	100.00%	0	0.00%
PF12	13	100.00%	0	0.00%
PF13	5	38.46%	8	61.54%

When the reliability test was conducted via pilot survey, the study gained thirty-two responses. By getting the reliability result of the pilot survey, the Cronbach's alpha (α) was needed. Based on the result made in the SPSS, it was found that the value was at α=0.920. Based on Table 1, the α=0.920 was found to be very reliable. This meant that the questionnaire, together with the factors, were found to be consistent and reliable.

This phase focused on the development and validation of the questionnaire that was used in the actual survey. It served as the preliminary assessment for the factors to be considered in the model. Two tests were involved in this phase, namely validity and reliability tests. First, one out of the three validity tests, content validity test, was conducted and yielded a result that removed the *size of non-structural elements* factor from the list of potential factors. This was considerable because this factor did not have any direct impact to the seismic performance of the building. From the name itself, elements belonging to this factor were not part of the structural configuration of the building. This might be the reason why majority of the respondents decided to disagree with this factor. The construct validity test was determined and discussed in phase 3.

On the other hand, the reliability test was conducted to check the overall consistency of the factors. The result was a strong consistency amongst the factors. The turnout of this test proved that the factors were reliable in measuring or determining the same construct, which in this case was the seismic capacity of the buildings. Furthermore, the Cronbach's alpha implied that the factors considered in the measuring of seismic capacity went through an extensive deliberation. Thus, the potential factors to be considered for the actual survey were appropriate.

Based on the presentation and deliberation, all of the factors were easily found in the building plan. This proved to be an advantage because of the accessibility. The problem, however, was that the gathering of the factors could have overlooked other factors that could have been considered, which may not be necessarily found in the building plan. Technically, the more factors that are considered, the better the determining power of the model could be. Some cases in which some buildings may be similar in few factors but could differ in other. Thus, this allowed the model to further distinguish the seismic capacity of the buildings despite the similarities in some factors. Overall, the potential factors considered in this study were considerably appropriate, as the study mainly focused on the performance of the buildings' configuration.

C. Phase 3

A total of fifty respondents participated in the actual survey. After subjecting the factors to the EFA, four results were gleaned, which were then observed and analyzed. Table IV shows the initial KMO and Bartlett's Test Result. When the EFA was conducted, the initial findings were that the KMO Measure of Sampling Adequacy was greater than 0.6, and the *p* value was less than 0.05. This meant that the factors sufficed the needed requirement for the KMO and Bartlett's Test.

Next, the initial communalities were observed. Table V shows the initial communalities of the factors. Based on the table, the factors were above the minimum value of 0.4. This meant that the factors had a good correlation with respect to the other factors. After evaluating the communalities, the total variance was made. Table VI shows the initial total variance explained. Based on this table, the component that had the least eigenvalue greater than 1 was the component 4. This meant that the number of components to be considered was 4. Also, the cumulative percentage generated was 73.143%, which was higher than the minimum of 60%. After determining the number of components, the loadings of the factors with respect to their components had to be evaluated.

Table Iv *initial Kmo And Bartlett's Test Result*

KMO Measure of Sampling Adequacy	Bartlett's Test of Sphericity (*p* value)
0.664	0.000

Table V *Initial Communalities*

Factor	Initial	Extraction
Building Span	1.000	0.779
Number of Storeys	1.000	0.772
Wall Quantity	1.000	0.532
Column Dimension	1.000	0.829
Beam Dimension	1.000	0.827
Footing Dimension	1.000	0.730
Slab Thickness	1.000	0.401
Rebar Cross-Sectional Area	1.000	0.718
Design Strength of Concrete	1.000	0.866
Design Strength of Rebar	1.000	0.901
Soil Bearing Capacity	1.000	0.787
Distance from the Nearest Faultline	1.000	0.634

Table Vi *Initial Total Variance Explained*

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	4.317	35.978	35.978	4.317	35.978	35.978	3.629
2	1.875	15.627	51.606	1.875	15.627	51.606	3.192
3	1.324	11.036	62.642	1.324	11.036	62.642	2.385
4	1.260	10.501	73.143	1.260	10.501	73.143	1.472
5	0.836	6.965	80.108				
6	0.737	6.138	86.246				
7	0.545	4.544	90.790				
8	0.382	3.181	93.971				
9	0.304	2.535	96.506				
10	0.192	1.603	98.109				
11	0.147	1.228	99.337				
12	0.080	0.663	100.000				

Table VII shows the initial pattern matrix. Based on this table, each factor was loaded to a certain component. In addition, no factor was excluded since all of them had a loading above 0.4. However, there was a cross loading in which the *footing dimension* factor loaded on components 1 and 4. When a cross-load occurs, removing items until the desired result is achieved must be done [19].

Further, despite the *footing dimension* factor being the factor that cross-loaded on two components, it was observed that the *slab thickness* factor had the lowest communality value and lowest loading in its corresponding component in the pattern matrix. Thus, the *slab thickness* factor was removed from the factors. When this particular factor was removed, the analysis was run again. Table VIII shows the final KMO and Bartlett's Test. From this table, the KMO and *p* value still qualified to their parameters. The final communalities were then generated after.

Table Vii *Initial Pattern Matrix*

Factor	Component			
	1	2	3	4
Column Dimension	0.937			
Beam Dimension	0.920			
Soil Bearing Capacity	0.741			
Footing Dimension	0.551			-0.424
Slab Thickness	0.466			
Design Strength of Concrete		0.937		
Design Strength of Rebar		0.929		
Rebar Cross-Sectional Area		0.694		
Number of Storeys			0.905	
Building Span			0.849	
Wall Quantity			0.653	
Distance from the Nearest Faultline				0.818

Table IX shows the final communalities. All factors had communalities that were greater than 0.4. Hence, the factors still had a good correlation with respect to each other. Similar to Table VI, the final total variance explained yielded values that resulted to 4 components. This meant that there was no change in the number of components.

Table X shows the final total variance explained. Also, the cumulative percentage generated was 76.833%, which was higher than the minimum of 60%. After determining the number of components, the loadings of the factors with respect to their components had to be evaluated. Table XI shows the final pattern matrix. From this, each factor was loaded to a certain component. This time, no factor was subjected to remove as no cross-loadings were found.

Table Viii *Final Kmo And Bartlett's Test Result*

KMO Measure of Sampling Adequacy	Bartlett's Test of Sphericity (*p* value)
0.664	0.000

Table Ix final Communalities

Factor	Initial	Extraction
Building Span	1.000	0.785
Number of Storeys	1.000	0.793
Wall Quantity	1.000	0.509
Column Dimension	1.000	0.835
Beam Dimension	1.000	0.831
Footing Dimension	1.000	0.730
Slab Thickness	1.000	0.718
Rebar Cross-Sectional Area	1.000	0.868
Design Strength of Concrete	1.000	0.906
Design Strength of Rebar	1.000	0.825
Soil Bearing Capacity	1.000	0.650
Distance from the Nearest Faultline	1.000	0.785

Table X *Final Total Variance Explained*

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	4.016	36.505	36.505	4.016	36.505	36.505	3.297
2	1.862	16.925	53.430	1.862	16.925	53.430	3.106
3	1.319	11.992	65.422	1.319	11.992	65.422	2.235
4	1.255	11.411	76.833	1.255	11.411	76.833	1.358
5	0.737	6.699	83.532				
6	0.674	6.125	89.657				
7	0.386	3.511	93.168				
8	0.304	2.767	95.934				
9	0.215	1.956	97.891				
10	0.149	1.352	99.242				
11	0.083	0.758	100.000				

Table Xi *Final Pattern Matrix*

Factor	Component			
	1	2	3	4
Column Dimension	0.900			
Beam Dimension	0.876			
Soil Bearing Capacity	0.811			
Footing Dimension	0.586			
Design Strength of Concrete		0.941		
Design Strength of Rebar		0.934		
Rebar Cross-Sectional Area		0.704		
Number of Storeys			0.909	
Building Span			0.851	
Wall Quantity			0.643	
Distance from the Nearest Faultline				0.820

Table Xii *description Of The Final Factors*

Final Factor	Unit	Source
Column Dimension	m^2	Taken from the largest column detail
Beam Dimension	m^2	Taken from the second-floor framing plan
Soil Bearing Capacity	kPa	Taken from the notes and specifications of the plan
Footing Dimension	m^2	Taken from the largest footing detail
Design Strength of Concrete	MPa	Taken from the notes and specifications of the plan
Design Strength of Rebar	MPa	Taken from the notes and specifications of the plan referring to the largest column
Rebar Cross-Sectional Area	m^2	Taken from the largest column detail
Number of Storeys	units	Taken from the plan
Building Span	m	Average of the longest length and width of the first floor
Wall Quantity	units	Quantity of walls present in the plan
Distance from the Nearest Faultline	km	HazardHunterPH using location coordinates

Table Xiii *code Designation Of The Grouped Factors*

Grouped Factor	Code
Structural Detail	X_1
Material Strength	X_2
Architectural Detail	X_3
Distance from the Nearest Faultline	X_4

After having the results coming from Table XI, determining what the unit of measurement for each factor, as well as what element in the building the factor was going to be derived from, was necessary Table XII shows the description of the final factors. On the other hand, the need to characterize the components was necessary.

The four components were formulated. These were named as Structural Detail, Material Strength, Architectural Detail, and Distance from the Nearest Faultline. The labelling of these components was based on the nature of the factors. To standardize the naming of the grouped factors, Table XIII presents their code designation. Based on the results that transpired from this phase, the second validity test which is construct validity, was also achieved because the final factors became the determining elements that would measure the seismic capacity. Through observation, all components made sense in terms of the categorization of the factors since these factors adhere to their respective functions.

Conclusion

The study demonstrated an innovative process of generating causality factors of seismic capacity of reinforced concrete residential buildings. The study underwent an array of processes in order to achieve its objectives. First, the study was able to identify and analyzed all possible factors needed. This allowed the study to characterize the factors causing disruptions in building stability. Second, the study was able to develop and validate a questionnaire containing the potential factors, which were used in the model. Third, the potential factors were subjected to EFA, which led to the reduction of the number of factors previously gathered. This process also led to the characterization of the factors based on their similar nature resulting in four major grouped factors namely, Structural Detail, Material Strength, Architectural Detail, and Distance from the Nearest Faultline. These factors can serve as the qualitative and quantitative groundwork required to establish a predictive model to efficiently assess building seismic capacity.

Recommendation

This study can be considered as the first step towards the development of a predictive model which could estimate seismic capacity of residential buildings. Future studies should aim at taking a closer look at the intersections within and among the produced factors and possibly include other factors that can be studied in depth.

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