

## Determining the Seismic Vulnerability Index of RC Buildings Based on NL- Parametric Analysis.

\*Moustafa Muffed Kassem<sup>1)</sup> Fadzli Mohamed Nazri<sup>1)</sup> and Ehsan Noroozinejad Farsangi<sup>2)</sup>

<sup>1)</sup>School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia.

<sup>2)</sup> Department of Earthquake Engineering, School of Civil Engineering and Surveying, Graduate University of Advanced Technology (KGUT), Kerman, Iran.

<sup>1)</sup> [PhD\\_moustafa@student.usm.my](mailto:moustafa@student.usm.my)

### ABSTRACT

Many of the buildings and facilities were significantly damaged during 2015 Ranau earthquake in Malaysia. With this purpose, a school building which has been damaged during Ranau earthquake was selected as a target RC-building. To assess the seismic vulnerability of the RC structures, an improved seismic vulnerability index (SVI) methodology is formulated based on 8 modeled parameters that are designed according to earthquake resisting design concept (ERD). The parametric analysis is performed using nonlinear time history analysis (NL-THA) based on an array of ground motion records. The results indicated that there is a good correlation between the analytical modeling approach with the observed fragility features during in-situ field investigations (Post-damages).

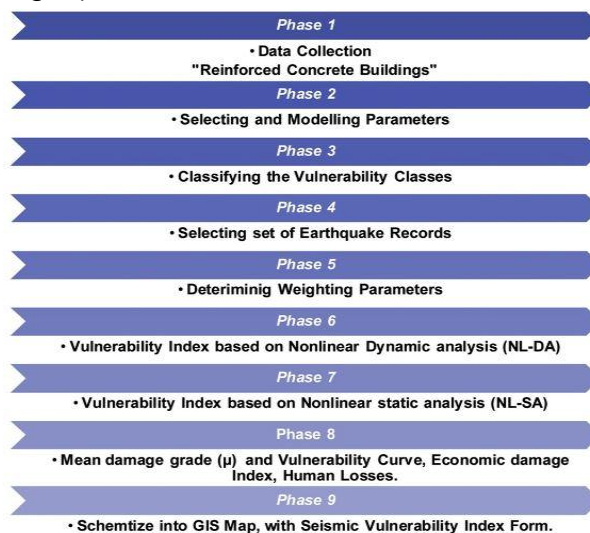


Fig. 1 Improved Seismic Vulnerability Index approach

<sup>1)</sup> PhD Student

<sup>1)</sup> Associate Professor

<sup>2)</sup> Professor

## **1. INTRODUCTION**

The seismic vulnerability assessment studies were undertaken in terms of risk assessment, which is a part of loss prediction that can be classified into two major groups; empirical and analytical approaches. One of these approaches is the vulnerability index method, which is used to express the damage level of a large population of structures or even for a single building. This type of vulnerability assessment is categorized as empirical or qualitative approach since it depends on a detailed analysis of damage data information consequent from post-earthquake, and expert opinions. To this purpose, several researchers have been applied the vulnerability index method, European macro seismic approach, and the Rapid Visual screening (RVS) as a qualitative methods in many urban cities [Athens-Greece (Eleftheriadou et al. 2014); Nepal (Chaulagain, 2015); Portugal (Ferreira et al. 2017); Morocco (Cherif et al. 2017); Algeria (Athmani et al. 2018), Almeria-Spain (Rivas-Medina et al. 2013); and Cologne-Germany (Tyagunov et al. 2013)] that determine the seismic risk based on a large data input in terms of damage observations, that it may impossible to collect in many countries having a limited data due to lack of seismic events such as Malaysia.

Therefore, the uncertainty obtained from the limited data in the empirical methods gives credit to the analytical approach which have the capability to validate the fragility features observed in the field by considering the parametric analysis affecting the building behaviour.

In this paper, a new methodology for vulnerability assessment of Reinforced Concrete structures is proposed based on the method developed by Benedetti and Petrini (1984) of GNDT with some modifications. This methodology deal with a new improved approach for developing a seismic vulnerability index (SVI) based on the structural parameters influencing the vulnerability of RC-buildings, where the quantitative parameters are defined and modeled to develop the vulnerability index based on number of parametric analyses that are required to be carried out, in order to consider the possible vulnerability scenarios with a focus on earthquake resistant design (ERD). For this purpose, a school building that was damaged during Ranau earthquake which was classified as the strongest earthquake hitting Malaysia since 1976, is selected as the target reinforced concrete building to validate the proposed methodology with the observed fragility features affected the building during in-situ field investigations.

## **2. IMPROVED SVI METHODOLOGY**

The proposed methodology focused on modeling eight parameters that have more influence on the seismic vulnerability of RC structures. The eight parameters taken into account are as follow:

- |                                     |                                |
|-------------------------------------|--------------------------------|
| 1- P1: Beam-Column Joint Connection | 5- P5: Ductility Level         |
| 2- P2: Boundary Conditions          | 6- P6: Horizontal Irregularity |
| 3- P3: Horizontal Diaphragm System  | 7- P7: Vertical Irregularity   |
| 4- P4: Type of Soil                 | 8- P8: Concrete Strength       |

The process followed the previous approaches (GNDDT1993 and RISK\_UE,EMS) with some modifications on the chosen parameters, by modeling and defining the weighting coefficients of each parameter based on ERD concept and by allocating each into three vulnerability classes of ERDs; Low-, Moderate-, and High-ERD. The vulnerability classes are defined as follows:

1. Low-ERD Class (L): The structure is not designed according to the seismic regulations and the structure have low seismic performance (No or Low Ductility Expected).
2. Moderate-ERD Class (M): The structure is in moderate performance to resist seismic loading (Intermediate Ductility Expected).
3. High-ERD Class (H): The structure is specially designed according to seismic code (High Ductility Expected).

Nevertheless, the hypothesis behind modelling the eight parameters is to adopt a numerical modelling strategy to define and calibrate structural parameters in order to develop the seismic vulnerability index (SVI). This modeling strategy is illustrated in the Table 1.

Table 1 Modelling parameters based on ERD vulnerability classes

Modelling Parameters	Earthquake Resisting Design -Vulnerability Classes		
	Low-ERD	Moderate-ERD	High-ERD
P1: Beam-Column Joint Connection	Flexible Joint ( $\beta=0.0$ )	Partially-Rigid Joint ( $\beta=0.5$ )	Fully Rigid Joint ( $\beta=1.0$ )
P2: Boundary Conditions	All supports are Hinged, Restrained ( $U_x, U_y, R_z$ )	1 <sup>st</sup> case	2 <sup>nd</sup> case
		Supports Externally Fixed and Internally Hinged	Supports Externally Hinged and Internally Fixed
P3: Horizontal Diaphragm System	Flexible diaphragm	Semi-Rigid diaphragm,	Rigid diaphragm
P4: Type of Soil	Spring supports (Soil Type D) based on EC8	Spring supports (Soil Type C) based on EC8	Spring supports (Soil Type B) based on EC8
P5: Ductility Level	Behaviour factor $q < 1.5$ , (DCL)	Behaviour factor $1.50 < q < 4.0$ , (DCM)	Behaviour factor $q > 4$ , (DCH)
P6 & P7: Horizontal and Vertical Mass Irregularity	$m_r m_{location}$ $2m_{Top}, 4m_{Top},$ and $6m_{Top}$	$m_r m_{location}$ $2m_{Bottom}, 4m_{Bottom},$ and $6m_{Bottom}$	Mass ratio =1.0
P8: Concrete Strength	C16 (16MPa)	C25 (25MPa)	C35 (35MPa)

\*  $\beta$ : rigid offset length,  $U_x$ : Translation in X-direction,  $U_y$ : Translation in Y-direction,  $U_z$ : Translation in Z-direction,  $R_x$ : Rotating around x-axis,  $R_y$ : Rotating around y-axis,  $R_z$ : Rotating about z-axis.

\* DCL: Ductility Class Low, DCM: Ductility Class Medium, DCH: Ductility Class High.

\*  $m_r$ : mass ratio,  $m_{location}$ : mass location.

On the other hand, a parametric analysis is performed via applying nonlinear time history analysis (NL-THA) to determine the weighting coefficient of each parameter via simulating a series of seismic records to extract the IDA curves, and quantifying the top maximum displacement as an engineering demand parameter (EDP) that allow to estimate the damage state during the earthquake events as illustrated in Fig. 2.

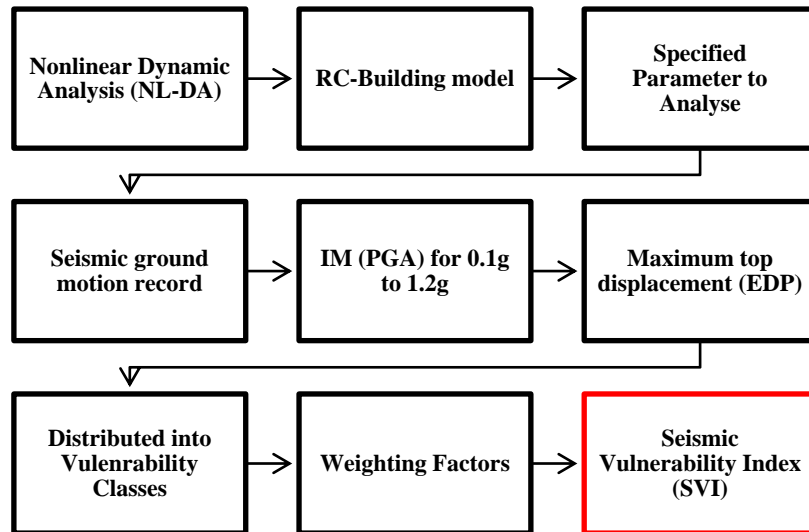


Fig. 2 Seismic vulnerability index estimating process diagram

## 2.1. STRONG GROUND MOTION SELECTION

The selection of suitable ground motion records is a fundamental step to obtain the reliable IDA curves to develop the seismic vulnerability index (SVI). The international requirements in building codes such as EC8, UBC97, IBC2006, and FEMA356 recommend that at least three ground motion records should be selected. In this work, 7 ground motion records were used. The ground motions were selected from Consortium of Organizations for Strong-Motion Observation Systems Database (COSMOS). The chosen records were characterized to be within Magnitude ( $M_w$ ) ranges of 5.0 to 8.0, having soil type D, and categorized as far field records (Epi-central Distance > 20km), since most of the earthquake felt in Malaysia were having these characteristics. Table 2 describe the time history of the selected seismic records.

Table 2 Selected far-field seismic records for nonlinear time history analysis (COSMOS)

## 2.2. WEIGHTING FACTORS

To estimate the seismic vulnerability index (SVI) for a single building or a set of buildings, the weighting factors are determined based on the following procedure:

Step 1: Calculate the displacement capacity ratio for each vulnerability class ( $K_i$ ), where  $D_{max}$  represents the maximum displacement.

$$K_i = \frac{D_{max}}{\sum_{i=1}^{i=3} D_{max}} \quad (1)$$

Step 2: Calculate the average factor with respect to number of seismic records ( $K_L$ ), where  $N$  represent the number of seismic records.

$$K_L = \frac{\sum_{i=1}^{i=N} K_i}{\text{Number of Seismic records, } N} \quad (2)$$

Step 3: Normalizing the final weighting factor ( $K_n$ ) by dividing the ( $K_L$ ) values for each parameter over the sum of  $K_L$  factors obtained in the vulnerability class (Low-ERD).

$$K_n = \frac{\sum_{i=1}^{i=n} K_i}{\sum K_{L \text{ class Low - ERD}}} \quad (3)$$

Finally, from the normalized factor obtained in step 3, the seismic vulnerability index of each vulnerability classes (Low-ERD, Moderate-ERD and High-ERD) is calculated using Eq. (4), where ( $n$ ) represents the number of modeled parameters ( $n=1,2,3,4,5,6,7$  and 8) in this study. The mean seismic vulnerability index  $SVI$  (*mean*) with  $\pm\sigma$  and  $\pm 2\sigma$  is as well calculated to consider the effect of uncertainties in final results.

$$SVI = \sum_{n=i}^{n=j} K_n \quad (4)$$

## 2.3. VULNERABILITY CLASSIFICATIONS OF RC BUILDINGS

Number	Event	Station	Year	PGA (g)	Distance (km)	Magnitude (Mw)
1	Izmit- Kocaeli	Nuclear Research Center	1999	0.181	101.10	7.40
2	Landers	San Bernardino, CA	1992	0.332	79.60	7.28
3	Superstition Hills	Calipatria, CA	1987	0.252	27.00	6.54
4	Chi-Chi	Taichung, Taiwan	1999	0.527	38.90	7.6
5	Loma-Prieta	Emeryville, CA	1989	0.490	67.70	7.00
6	Northridge	Santa Monica, CA	1994	0.684	28.20	6.69
7	Ranau, Sabah	KKM_HNE	2015	0.125	60 to 70	6.10

Based on the seismic vulnerability index value, five categories of damage are defined as; Negligible, Minor, Moderate, Partial Collapse, and Total Collapse. For values from vulnerability index comprised between [0.10-0.20] the building is classified as Green 1 and represents negligible to light damages, between [0.20-0.40] the building is classified as Green 2 and represents light to moderate damages, between [0.40-0.55] the building is classified as Orange 3 which denoted to have moderate to heavy damages, and finally the values ranging between [0.55-0.70], and [0.70-1.0] are classified to have partially to total collapse and denoted by Orange 4 and Red5, respectively (Belheouane and Bensaibi, 2013).

### 3. SMK-SCHOOL BUILDING APPLICATION

In the present work, a 4-storey reinforced concrete building is selected as the reference model for this study to verify the precision of the proposed methodology. The structural system is classified as a “simple beam-column” system known as a Gravity Load Design (GLD), structurally speaking no provision for seismic design. The height of each storey is 3.5m with a variable bay width and a slab thickness of 15cm as shown in Fig. 3. For the present example, the selected column size measured as 300mm x 300mm and 250mm x 250mm, whereas the drop beam size measured as 300mm x 600mm, 550mm x 250mm, and 600mm x 250mm.

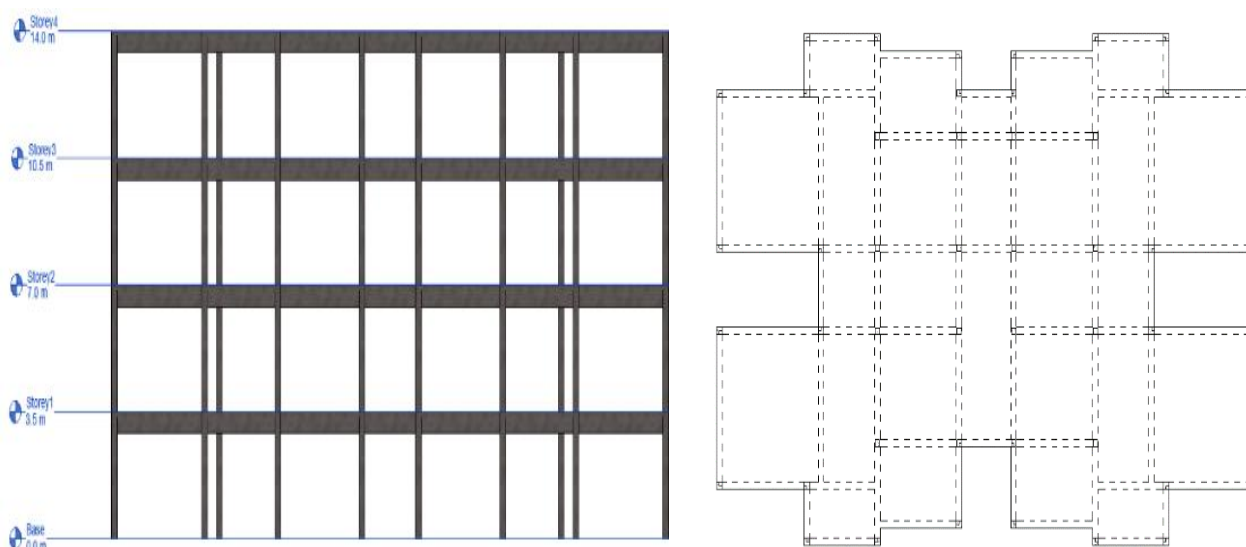


Fig. 3 Elevation and Plan view of the selected building

#### 3.1. BUILDING DAMAGE FIELD OBSERVATION

During the in-situ field investigations and based on the measurements on site, it can be noticed that the Ranau earthquake caused damages on structural and non-structural elements particularly on reinforced concrete buildings. The structural damages of the selected building were concentrated in the 1<sup>st</sup> story columns, and beam-column connections, whereas the nonstructural damages distributed in the

masonry infill walls, fire resistance brick wall and the finishing. Fig. 4 shows the damage which observed at the investigated school building due to Ranau earthquake.



Fig. 4 Observed building damages observed during Ranau earthquake

#### 4. VALIDATION OF THE IMPROVED SVI APPROACH

To validate the proposed methodology, the following damage measurements such as vulnerability index, maximum displacement, plastic hinges formation, and vulnerability curves must be determined to assess the physical damages that can be correlated with the observed fragility features.

##### 4.1. SEISMIC VULNERABILITY INDEX CALCULATION

After applying the 7 strong ground motion records on the analytical model and performing the nonlinear time history analysis, the calculated mean seismic vulnerability index of this building is determined as ( $SVI=0.702$ ), which is equal to ( $Iv=69$ ) based on the correlation with GNDT approach. Therefore, the construction of this building is determined to be in the Red vulnerability class at a certain seismic intensity, and the school building is categorized to be in the vulnerability class A as an ordinary building designed without seismic resistance according to European macro seismic approach. Table 3 illustrates the seismic vulnerability index ranges of SMK-Ranau School Building considering uncertainties.

Table 3 Seismic Vulnerability Index ranges of SMK-Ranau School Building

Seismic Vulnerability Index Range				
$SVI - 2\sigma$	$SVI - \sigma$	$SVI(\text{mean})$	$SVI + \sigma$	$SVI + 2\sigma$
0.165	0.433	0.702	0.971	1.240

#### 4.2. PARAMETERS INFLUENCING THE BUILDING VULNERABILITY

In Fig. 5, the influence of the modelled parameters on the structural response is depicted. It can be seen, that among all the parameters evaluated; P1, P3, and P5 have the greatest influence on the vulnerability of building, when seismic design is not considered. On the other hand, P2 that is known as boundary condition parameter, shows the most influence on the physical vulnerability of the building due to high %drift indication. In contrast, for the concrete strength parameter that is symbolized by P8, the results show a little variation in building vulnerability comparing to other parameters.

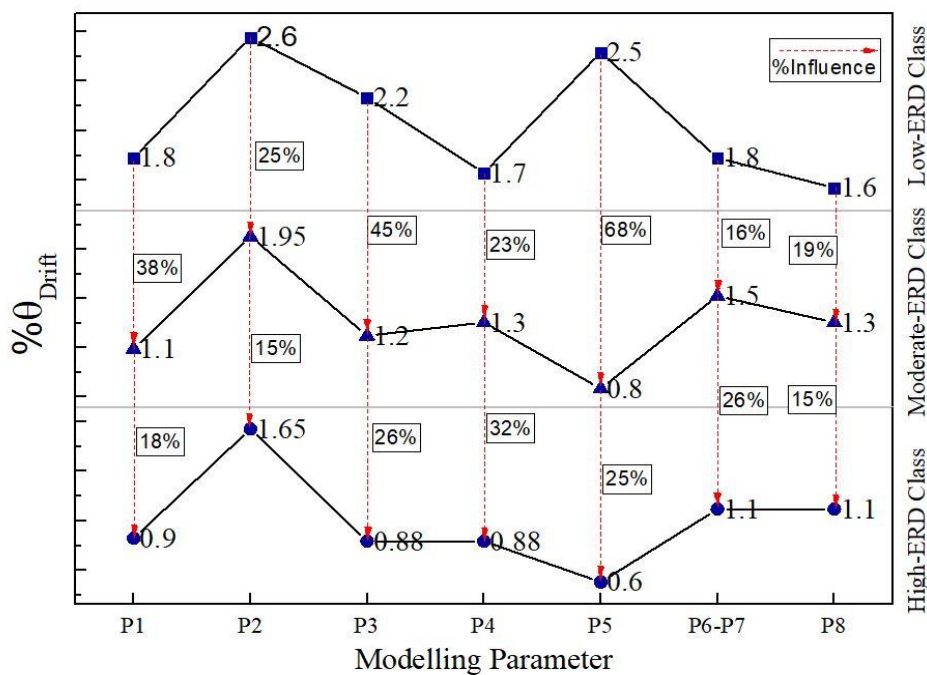


Fig. 5 Influence of the 8 Parameters on the building response behavior

#### 4.3. MEAN DAMAGE STATE -Vulnerability Curves

Based on the previously obtained seismic vulnerability index (SVI), for the selected reinforced concrete building, it is essential to estimate the mean damage

grade related to the building according to the European macro seismic EMS-98 approach. A mean vulnerability function is expressed to correlate seismic hazard with mean damage grade ( $0 < \mu_D < 5$ ) of the RC building in a relation with the seismic vulnerability index (SVI) as shown in Eq. (5). Fig. 6 shows the vulnerability curves related to the mean seismic vulnerability index, with the upper and lower bounds attained by adding and subtracting, single and double standard deviation values with respect to seismic intensities (EMS-98). Fig. 7 presents the fragility curves obtained for the mean vulnerability index through probabilistic approaches of D2 and D3 damage states.

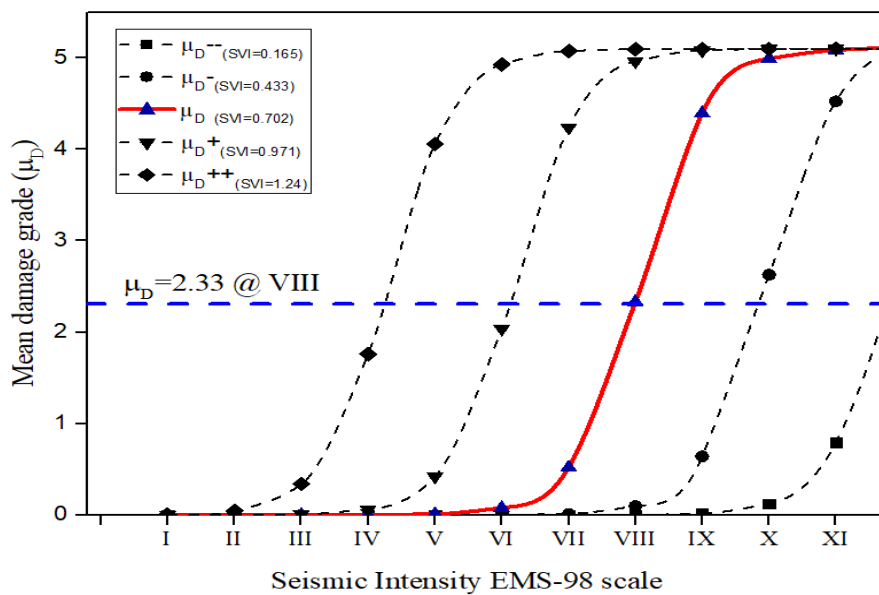


Fig. 6 Vulnerability curves for lower bounds, mean, and upper bound of seismic vulnerability indices based on Mean damage grade.

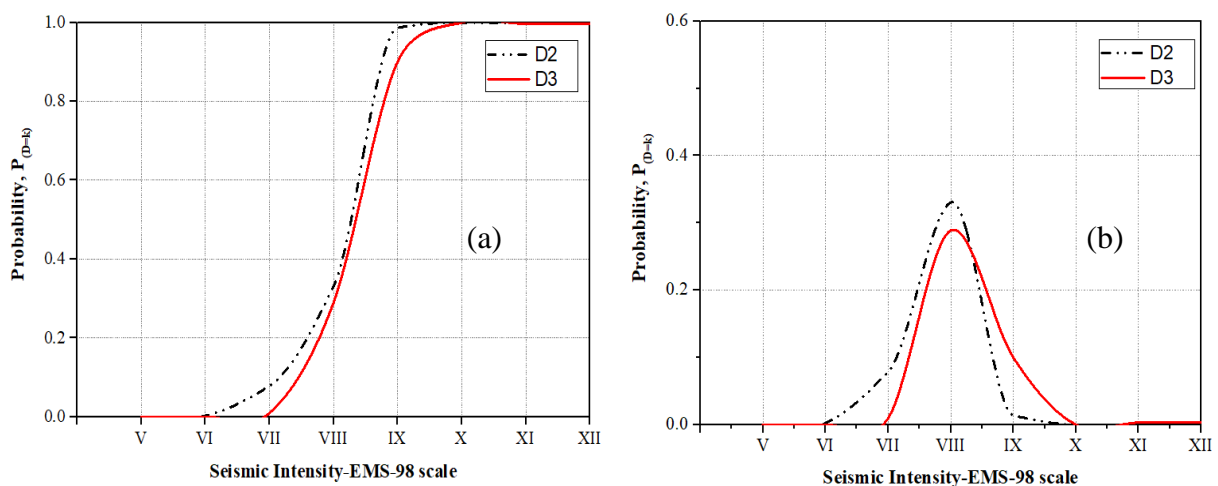


Fig. 7 SMK-School building damages represented by (a) fragility curves (b) probability of mean seismic vulnerability index for grades D2 and D3.

Table 4 Possibility of damage related to Ranau seismic intensity, VIII

Damage distribution possibility for different Seismic Intensity in %		
Mean damage grade	Description	Seismic Intensity $I_{EMS}$ VIII
D2	Slight SD, Moderate N-SD	33.1
D3	Moderate SD, Heavy N-SD	28.8

Based on the vulnerability results presented in Fig. 6, Fig. 7, and Table 4 the seismic event with intensity VIII of 0.702 average vulnerability index, results in structural mean damage grades of 33.1% and 28.8% between D2 and D3, respectively, meaning that the vulnerability of the non-structural elements in the building suffered from moderate to heavy damages. Thus, the result is very compatible with the field observations after Ranau earthquake in Sabah-Malaysia. Moreover, it was observed from the analysis outcome that the formation of plastic hinges was significantly concentrated in the bottom and 1<sup>st</sup> floors RC-column which have experienced high interstorey drift ratios due to weak column-strong beam design approach, as shown in Fig. 8(a) and (b).

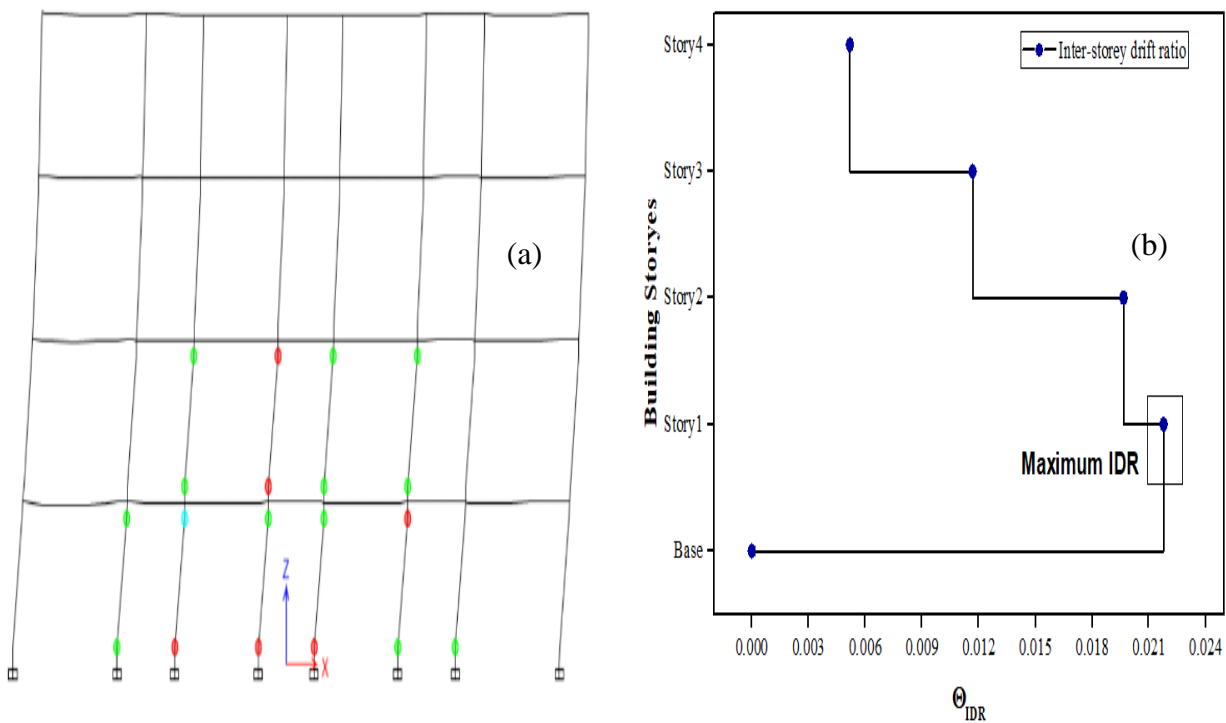
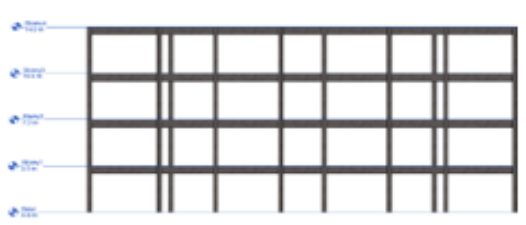
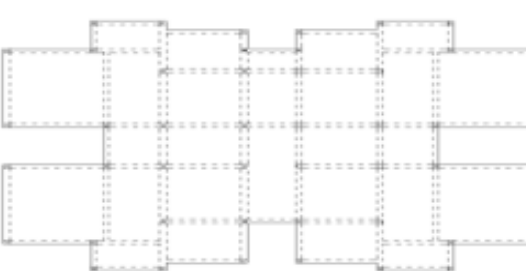



Fig. 8 SMK-School building damages represented by (a) fragility curves (b) probability of mean seismic vulnerability index for grades D2 and D3.

#### 4.4. SEISMIC VULNERABILITY IND

Seismic Vulnerability Index of SMK-School Building in Sabah-Ranau Data Collection Form		Surveyor Name(s): Date:			
<p style="text-align: center;"><b>Elevation View</b></p> 	<p>Address: <b>Sabah-Ranau</b></p> <p>Building Name: <b>Sekolah Menengah Kebangsaan (SMK)</b></p> <p>Number of Storeys: <b>Four Storeys</b></p> <p>Story Height(m): <b>3.5metre</b></p> <p>Total Floor Area(sq-m): <b>1899 sq-metre</b></p> <p>GPS Coordinate (If available): <b>(5°58'28.1"N 116°40'24.9"E)</b></p> <p>Construction Drawing Available: Yes <input checked="" type="checkbox"/> / No <input type="checkbox"/></p>				
<p style="text-align: center;"><b>Plan View</b></p> 					
<b>Occupancy Type</b>		<b>Soil Type (NEHRP 2000)</b>			
<input type="checkbox"/> Assembly <input type="checkbox"/> Government <input type="checkbox"/> Office <input type="checkbox"/> Commercial <input type="checkbox"/> Historic <input type="checkbox"/> Residential <input type="checkbox"/> Industrial <input checked="" type="checkbox"/> School		<input type="checkbox"/> A (Rock) <input type="checkbox"/> B (Rock) <input type="checkbox"/> C (Soft Rock) <input checked="" type="checkbox"/> D (Stiff Soil) <input type="checkbox"/> E (Soft Soil)			
Seismic Vulnerability Index Score (VI)					
Number	Parameters	Vulnerability Classes Weighing Parameters (Kn)			SVI, Mean
		Low (L)	Moderate (M)	High (H)	
1	Beam-Column Connection Joint	0.127	0.076	0.060	$SVI_{mean} = \sum Kn$ $= 0.702$
2	Boundary Condition Support	0.127	0.077	0.059	
3	Diaphragm Floor System	0.128	0.0076	0.059	
4	Type of Soil	0.115	0.087	0.061	
5	Building Ductility	0.164	0.059	0.041	
6-7	Mass Irregularity (V and H)	0.112	0.086	0.065	
8	Concrete Strength	0.114	0.083	0.067	
<b>Total Seismic Vulnerability Index (L, M, and H) ERDs</b>		1	0.630	0.477	
<b>Result Interpretation:</b>					
<i>Modelling and Design classes according to vulnerability:</i>					
Low Class (L): The parameter is not designed within seismic regulations and away from consistency, where the performance is in low resisting to seismic loading.					
Moderate Class (M): The parameter is in moderate performance to resist seismic loading, intermediate position.					
High Class (H): The parameter is specially designed according to seismic code, and in high performance to resist seismic loading					
<b>RC-building Vulnerability Classifications:</b>					
Green 1: $0.1 < VI < 0.2$ , $VI_{Mean} = 0.15$					
Green 2: $0.2 < VI < 0.4$ , $VI_{Mean} = 0.3$					
Orange 3: $0.4 < VI < 0.55$ , $VI_{Mean} = 0.475$					
Orange 4: $0.55 < VI < 0.7$ , $VI_{Mean} = 0.625$					
Red 5: $0.7 < VI < 1$ , $VI_{Mean} = 0.85$					
		Damage Categories	Class	Description	
		Negligible	Green 1	Negligible to light damage	
		Minor	Green 2	Light for the structural elements, and moderate for the not structured elements	
		Moderate	Orange 3	Moderate for the structural elements, and heavy for the not structured elements	
		Serious	Orange 4	Heavy for the structural elements, and heavy for the not structured elements	
		Collapse	Red 5	Collapse Total or close	
					Further Evaluation Recommended
					Yes <input checked="" type="checkbox"/> No <input type="checkbox"/>

## 5. CONCLUSION

The vulnerability assessment of a reinforced concrete school building was conducted using an improved seismic vulnerability index via nonlinear parametric analysis. The proposed methodology and its application are validated by obtaining a good correlation between the analytical results and the observed fragility features in the field investigations. According to the obtained probabilistic vulnerability curves for different seismic scenarios, the reference building is classified to be in D2 and D3 damage grades, which is thoroughly correlated to the observed damage in the field in-situ investigations during Ranau earthquake of seismic intensity (VIII).

## ACKNOWLEDGMENTS

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