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Simplified Vulnerabiltiy Analysis (SVA) Preliminary Design of the Frame Structure in the Architectural DesignProcess

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Abstract

Background: There is a need for a good cooperation between the architects and structural experts in creating of earthquake architecture. Through some ways in the design process, the architects can identify and evaluate the vulnerability of the building from earthquakes. Unfortunately, there is no available evaluation method, so the alternative is adopting SVA (Simplified Vulnerability Analysis) method, a limited engineering analysis based on the information from the architecture and structure drawings of the existing buildings. The Japan Building Disaster Prevention Association (JBDPA) and Matsutaro Seki developed the SVA, and then Seki adopted the SVA of JBDPA and adjusted it to the international earthquake regulation. In principle, the JBDPA and Seki SVA is a safe structure if the seismic structure index ≥ the seismic demand index. The modification of the JBDPA and Seki SVA in this research is that the seismic structure index consists of the column dimension index, column rigidity index; strong column/weak beam index, redundancy index, and structure ductility index. Meanwhile, the seismic demand index is the multiplication between seismic response index and the priority factors of building functions. **Methods**: It is a quantitative research with experimental research method. The modified SVA formulation was compared with the pushover analysis from other researchers. The results were then \ovulated and compared. **Findings**: Generally the modification on SVA formulation from JBDPA and Seki show a relatively good result in evaluating the vulnerability of preliminary design of the frame structure in the architectural design process. **Applications**: The SVA procedure can be used to underlie the potential status of the selected buildings and subsequently there is a list of the buildings which needs more detailed vulnerability assessment conducted by the structural experts.

Keywords: Architectural Design, Earthquake, Irregular, Simplified Vulnerability Analysis, SVA

1. Introduction

Indonesia is an earthquake-prone area, so the buildings should have earthquake resistant constructions. In order to create an earthquake architecture[1] which is aesthetically appealing and structurally resistant to earthquake, it needs a good cooperation between architects and structural experts. The first step in creating the earthquake architecture, in the design process, is that the architects can identify and evaluate the vulnerability of the building towards the earthquakes[2]. Unfortunately, there is still no evaluation method available, so the alternative is adopting the SVA (Simplified Vulnerability Analysis) method[3] which is a limited engineering analysis based on the information from architectural drawings and structures of the existing buildings. Some of the developers of SVA are The Japan Building Disaster Prevention Association (JBDPA)[4] and Matsutaro Seki[5]. Seki adopted the SVA of JBDPA and adapted it to international earthquake regulation. The purpose of the developing SVA is the structural verification of retrofitting hence the need for modification in the architectural design process when using it to

*Author for correspondence

identify and evaluate the vulnerability of buildings. The proposed purpose of SVA in this research is to build the procedures or methods which can be used by architects in evaluating the vulnerability of buildings to earthquakes during the architectural design process, and which are in accordance with the conditions in Indonesia. In the architectural design process, the focuses are on the structure dimensions and on the geometric shapes. The research is limited to the dimension and type of structure commonly used in Indonesia (moment-resisting frame with 1 or 2-way floor system), the middle rise maximum height (± 10 floors), and the regular-category building's geometric shape.

In principle, the SVA of JBDPA and Seki is a safe structure if the seismic structure index (I_S) ≥ the seismic demand index (I_{SO}). The lateral force resistant system is at least influenced by redundancy, column dimensions, column rigidity, strong column / weak beam and structural ductility[6]. The seismic structure index consists of the lateral force of the column defined as the ratio of the minimum column area and the design column area (I_{Ac-i}), redundancy is defined as the period of structural vibration (I_T), column rigidity is defined as the ratio of the height and width of the column (I_{C-i}), strong column/weak beam is defined as the ratio of the number of columns fulfilling the criteria of the strong column/weak beam and the total number of the columns (I_{SCWB-i}), and structural ductility adopts the Matsutaro Seki's procedures by including the ratio of response modification factor (R) and the over strength factor (Ω_0) - (R/Ω_0). The modification of SVA of JBDPA and Seki in this research is based on the explanation that the seismic structure index (I_S) is the multiplication of column dimension index (I_{Ac-i}), column rigidity index (I_{C-i}), strong column/weak beam index (I_{SCWB-i}), redundancy index (I_T), structure ductility index (R/Ω_0) , irregularity index (S_D) and time index (T). The limited geometric shapes are regular and considered as new buildings, so it is assumed that S_D=1 and T=1. On the other hand, the seismic demand index (I_{SO}) is the multiplication between seismic response index (I_{CS}) and the priority factors of building functions (I_e).The problem in the proposed procedures is to what extent the accuracy in evaluating and assessing the vulnerability of buildings in the design process. In order to find out the validity of building vulnerability assessment procedure in this design process, the procedures will be compared with the more detailed vulnerability assessment procedure from other researchers called the pushover analysis.

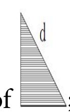
1.1. Seismic Structure Index (I_S)

In general, JBDPA and Seki define the formulation of the seismic structure index as follow:

$$I_S = E_0 . S_D . T \tag{1}$$

In which, I_S = Seismic structure index; E_0 = Basic seismic structure index; S_D = Irregularity Index (regular building S_D=1); T = time index (new building T=1).The modification of the basic seismic structure index (E_0) is based on the concept that the resistance of the column in resisting the lateral load of the earthquake is defined into column dimension, influenced by column rigidity, forms strong column/weak beam, good structure ductility and the unity of the whole structural elements (redundancy). The formulation is as follow:

$$E_0 = \frac{n+1}{n+i}(I_{Ac-i} . I_{C-i} . I_{SCWB-i} . I_T).\frac{R}{\Omega_0} \tag{2}$$

In which, n = the number of building levels the; i = The evaluated level(s). Where the first level is given number 1 and the followings are given n; $\frac{n+1}{n+i}$ = the modification factor of level shear capacity. It follows the distribution of ; I_{Ac-i} = column dimension index of the evaluated level; I_{C-i} = column type index of the evaluated level; I_{SCWB-i} = strong column/weak beam index of the evaluated level; I_T = structural vibration period index, $T_c \le T_{max} \rightarrow I_T = 1$ and $T_c > T_{max} \rightarrow I_T = 0$; T_c = structural vibration period based on the software calculation (seconds); T_{max} = The maximally allowed structural vibration period (seconds) based on the article 7.8.2 of SNI 1726:2012 or on the formulation 25 of SNI 1726:2002; R/Ω_0= structure ductility, R = The modification factor of moment-resisting frame (Table 9 of SNI 1726:2012[7] or Table 3 of SNI 1726:2002)[8], Ω_0 = The overstrength factor of moment-resisting frame based on the Table 9 of SNI 1726:2012 or the Table 3 of SNI 1726:2002.

The concept of column lateral force (I_{Ac-i}) assumed as the ratio of design column area (ΣA_C) and minimum column area ($\Sigma A_{C\,min}$) is described follow:

$$I_{Ac-i} = \frac{\Sigma A_C}{\Sigma A_{C\min}} \tag{3}$$

In which, ΣA_C= total design column area (m^2); $\Sigma A_{C\,min}$= total minimum column area (m^2) 0.15% of the cumulative area of column load[9], in which the minimum column area is 0.09 m^2 or 0.3x0.3 m.

The concept of column rigidity (I_{C-i}) assumed as the ratio of the average of column types (N_Cx0.7-1.0) and total columns ($\sum N_C$) is described below:

$$I_{C-i} = \frac{(N_{C-a}x0.7) + (N_{C-b}x0.8) + (N_{C-c}x1.0)}{\Sigma N_C} \quad (4)$$

In which, N_{C-a} = total of column types –a (Table 1); N_{C-b}= total of column types–b (Table 1); N_{C-c}= total of column types-c (Table 1); 0.7, 0.8, 1.0= index of column types of a, b & c (Table 1); ΣN_C= Total columns. The concept of strong column/weak beam (I_{SCWB-i}) assumed as the ratio of the number of columns fulfilling the criteria of the strong column/weak beam (N_{SCWB}) and total columns (ΣN_C) is described below:

$$I_{SCWB-i} = \frac{N_{SCWB}}{\Sigma N_C} \quad (5)$$

In which, ΣN_C= total columns, N_{SCWB}= number of columns fulfilling the criteria of the Wp column ≥ 1.2xWp beam, Wp=plastic modulus, Wp=0.25xbxh^2, b&h= dimension of width and height of beam or column[10].

1.2. Seismic Demand Index (I_{SO})

The concept of column lateral capacity (I_{Ac-i}), the ratio of the design column area and minimum column area, is also applied to the lateral seismic load (I_{SO}) concept, which is the ratio of the design and minimum lateral seismic loads. The design lateral seismic loads is based on the spectral responses of S_S and S_1, for those using SNI 1726:2012 or coefficients of Ca and Cv for those using SNI 1726:2002 in each building site; while the minimum lateral seismic loads is based on seismic zone division FEMA 155[11] which is a low seismic zone with S_S =0.25 g and S_1=0.1 g or zone 2A according to UBC 1997[12]. The concept of seismic demand index or lateral seismic load index (I_{SO}) is the multiplication of seismic response coefficient index (I_{CS}) and the priority factors of building function (I_e). Meanwhile, the seismic response index (I_{CS}) is the ratio of design seismic coefficient (C_S) and the minimum seismic coefficient (C_{Smin}).

$$I_{SO} = \frac{n+i}{2n-i+1}.(I_{CS}.\ Ie) \quad (6)$$

$$I_{CS} = \frac{C_S}{C_{S\min}} \quad (7)$$

In which, I_{SO} = seismic demand index; n = number of building levels; i = evaluated level(s), where the first level is given number 1 and the followings are given n; $\frac{n+i}{2n-i+1}$ = modification factor of seismic demand of the levels, following the distribution of  ; C_S = Seismic response coefficient of the design based on the formulations 21-25 of SNI 1726:2012 or on the formulation 26 of SNI 1726:2002; C_{Smin} = minimum seismic response coefficient S_S=0.25g and S_1=0.1g based on FEMA 155 or zone 2A of UBC 1997; I_{CS} = seismic response coefficient index; I_e = the priority factors of building function based on the Table 1, 2 of SNI 1726:2012 or based on the Table 1 of SNI 1726:2002.

1.3. Seismic Structure Index (I_S) vs Seismic Demand Index (I_{SO})

The concept of ratio of seismic structure index (I_S) and seismic demand index (I_{SO}). Structure is safe if:

$$I_S \geq I_{SO} \quad (8)$$

Table 1. Index of combined shear stress average and ductility index of structure elements (Source: processed from[4,5])

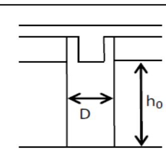
Types of Lateral Elements	**Requirements**		**Index (I)**
Columns	**Clear Height /Column Depth; h_0/D**	**Definition h_0/D**	
a). Slender columns	$6 \leq h_0/D$		0.7
b). Normal columns	$2 < h_0/D < 6$		0.8
c). Short columns	$h_0/D \leq 2$		1.0

Table 2. Recommendation for the evaluation of potential seismic vulnerability *based on the seismic performance (source : modification of procedure*[5]*)*

Seismic vulnerability evaluation	Potential level of damage	Seismic performance-FEMA 273 (FEMA 1997)	
$I_S > I_{SO}$	Light Damage	<0.5%	IO (*Immediate Occupancy*)
$0.5I_{SO} \leq I_S \leq I_{SO}$	Moderate Damage	<1.5%	LS (*Life Safety*)
$I_S < 0.5I_{SO}$	Heavy Damage	<2.5%	CP (*Collapse Prevention*)

In which, I_S = seismic structure index; I_{SO} = seismic demand index. For other ratios, evaluating the vulnerability of building structures can be done by comparing the seismic structure index towards the seismic demand index, and each level can be identified for its possible level of damage (Table 2).

2. Research Method

This research is an experimental research. In order to verify the proposed procedure, it will be compared with the result of pushover analysis conducted by other researchers, so the result will be more objective. Although the proposed SVA procedure is to analyse the vulnerability of building with a middle rise maximum height (± 10 floors) but the validity limit of the observed model was determined up to 14 floors. The data of earthquake zones and structures were collected from the research [14–19] in Table 3, 4. The calculation steps are as follows:

1. Calculate the modification factor of level shear capacity of each floor, based on the data from Table 3, 4 calculate the column dimension index - I_{Ac-i} (formulation 3), calculate the column type index - I_{C-i} (formulation 4) and calculate the strong column/weak beam index-I_{SCWB-i} (formulation 5). Obtain a T_C and compare it to T_{max} specify the index of the structural vibration period (I_T) and obtain R and Ω_0 values from Table 9 of SNI 1726:2012 or Table 3 of SNI 1726:2002 calculate the structure ductility R/Ω_0. Multiply all values (formulation 1) so that the basic seismic index of structure (E_0) can be obtained. Multiply the basic seismic index of structure (E_0) with the irregularity index (S_D) for regular building S_D=1 so that the seismic capacity index of structure (I_S) can be obtained.
2. Calculate the modification factor of level seismic demand of each floor, based on the data from Table 4, calculate the C_S and C_{Smin} values, and then input them to formulation 7 to obtain I_{CS} value. Obtain I_e value from Table 1 and 2 of SNI 1726:2012 or Table 1 of SNI 1726:2002 for the office function of I_e=1. Input the values of modification factor of seismic demand, I_{CS} and I_e to formulation 6 to obtain the seismic demand index (I_{SO}) value.
3. Compare the I_S and I_{SO} values based on the provisions in Table 2 so that the level performance is possible to find. Then, compare the level performance of SVA results with the level performance of pushover analysis SAP2000/ETABS from the research [14–19].

Table 3. Data of building structure of the model (source : [14–19])

Model	Number of floors/levels (height-m)	Beam Dimension (cm)	Column Dimension (cm)	Building Dimension (m)	Module (m)
a	6 (3.5 m)	25X50	65X65 (1st-3rd floor), 55X55 (4th-6th floor)	18X18	6X6
b	14 (4 m)	40X80 (1st-4th floor), 40X70 (5th-9th floor), 30X60 (10th-14th floor)	80X80 (1st-5th floor), 70X70 (6th-10th floor)	30X30	5X5
c	10 (4 & 3.6 m)	40X60 (main beam), 30X60 (subsidiary beam)	80X80 1st-4th floor), 70X70 (5th-14th floor)	24X24	8X8
d	5 (4 m)	35X60	60X60	42X32	6X8
e	4 (4 & 3.5 m)	30X45 (1st-3rd floor), 30X40 (4th floor)	45X45	18X18	4.5X4.5
f	12 (4 m)	40x60	60X60	42X42	6X6

Tabel 4. Earthquake zone data of the model (source : [14–19])

Model	Code	Earthquake Zone	Site Class	Structure system	Ie
a	SNI 1726-2002	Zone 6 Ca=0.35,Cv=0.54	Moderate Soil	Special moment-resisting frame	1
b	SNI 1726-2002	Zone 6 Ca=0.38,Cv=0.95	Soft Soil	Special moment-resisting frame	1
c	SNI 1726-2002	Zone 6 Ca=0.33,Cv=0.42	Hard Soil	Special moment-resisting frame	1
d	SNI 1726-2012	Banyumas Ss=0.7g,S1=0.25g	Hard Soil	Moderate moment-resisting frame	1
e	SNI 1726-2002	Ternate - Zone 4 Ca=0.28, Cv=0.42	Moderate Soil	Special moment-resisting frame	1
f	SNI 1726-2012	Bobong City Ss=1.355 g, S1=0.537 g	Moderate Soil	Special moment-resisting frame	1

The processes above are tabulated to describe the calculation and comparison.

3. Results and Discussion

3.1. Model a [14]

Table 5, I_S value is the multiplication between E_0 and S_D. E_0 is the basic seismic structure index of the special moment-resisting frame which is the result of multiplication of the modification factor of level shear capacity $\left(\frac{n+1}{n+i}\right)$, column dimension index (I_{Ac-i}) > 1, column type index (I_{C-i}) = 0.8 normal column (2<h0/D<6), strong column/weak beam index (I_{SCWB-i}) = 1, structural vibration period index (I_T) = 1, structural system ductility index (R/Ω_0) = 8/3 and S_D is the irregularity of building geometry because model a has a regular geometric shape so the value = 1.

Table 6, I_{SO} is the seismic demand index which is the multiplication of the modification factor of level seismic demand $\left(\frac{n+i}{2n-i+1}\right)$, seismic response index (C_S/

Table 6. Seismic demand index (I_{SO}) of location model a

Model	floor	$\frac{n+1}{2n-i+1}$		I_{cs}	I_e	I_{SO}
(a)	1st	7/12	0.58	2.18	1.0	1.27
	2nd	7/11	0.64	2.18	1.0	1.38
	3rd	7/10	0.70	2.18	1.0	1.52
	4th	7/9	0.78	2.18	1.0	1.69
	5th	7/8	0.88	2.18	1.0	1.90
	Rf	7/7	1.00	2.18	1.0	2.18

Table 5. Seismic structure index (I_S) model a

Model	floor	$\frac{n+1}{n+i}$		$I_{Ac-i}.I_{C-i}$	I_{SCWB-i}	I_T	R	Ω_o	E_o	S_D	I_S
(a)	1st	7/7	1.00	2.36	1.00	1.00	8	3	6.30	1.00	6.30
	2nd	7/8	0.88	2.02	1.00	1.00	8	3	4.70	1.00	4.70
	3rd	7/9	0.78	1.67	1.00	1.00	8	3	3.46	1.00	3.46
	4th	7/10	0.70	1.38	1.00	1.00	8	3	2.58	1.00	2.58
	5th	7/11	0.64	1.21	1.00	1.00	8	3	2.05	1.00	2.05
	Rf	7/12	0.58	1.15	1.00	1.00	8	3	1.79	1.00	1.79

C_{Smin})=2.18 and the priority factors of building function (I_e)=1 (office). Table 7 shows that from the 1st floor to the roof floor, the comparison is $I_S > I_{SO}$, which means that the column and beam dimensions are well designed hence ensuring the adequate rigidity, strength and ductility when a strong earthquake occurs. Therefore, it will only suffer light damage or IO (Immediate Occupancy).

Table 7 and Figure 1 are the research conducted on model a with pushover analysis resulted in the target displacement = 0.132 m with drift ratio = 0.61%. Based on FEMA 273, model a, located at the Earthquake Zone 6 with Moderate Soil, is in inelastic condition, and thus it is able to resist the earthquake load up to the level of Immediate Occupancy (IO). At the IO level, there is possibility for the structural damage that can be repaired. The prediction on the proposed SVA procedure is relatively similar to the result of the research conducted.

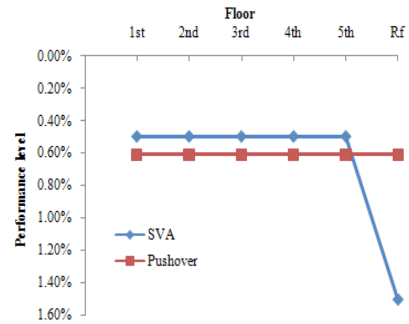


Figure 1. Comparison between between SVA and pushover analysis model a.

3.2. Model b [15]

Table 8, I_S value is the multiplication between E_0 and S_D. E_0 is the basic seismic structure index of the special

Table 7. Comparison between seismic structure index (I_S)and seismic demand index (I_{SO}) *as well as comparison between SVA and pushover analysis model a*

Model	floor	I_S	I_{SO}	SVA	Pushover analysis-SAP2000	
					drift ratio	Performance level
(a)	1st	6.30	1.27	IO	0.61%	IO
	2nd	4.70	1.38	IO		
	3rd	3.46	1.52	IO		
	4th	2.58	1.69	IO		
	5th	2.05	1.90	IO		
	Rf	1.79	2.18	IO		

Table 8. Seismic structure index (I_S) model b

Model	floor	$\frac{n+1}{n+i}$		$I_{Ac-i}.I_{C-i}$	I_{SCWB-i}	I_T	R	Ω_o	E_o	S_D	I_S
(b)	1st	15/15	1.00	1.33	1.00	1.00	8	3	3.54	1.00	3.54
	2nd	15/16	0.94	1.43	1.00	1.00	8	3	3.57	1.00	3.57
	3rd	15/17	0.88	1.55	1.00	1.00	8	3	3.64	1.00	3.64
	4th	15/18	0.83	1.69	1.00	1.00	8	3	3.75	1.00	3.75
	5th	15/19	0.79	1.42	1.00	1.00	8	3	3.00	1.00	3.00
	6th	15/20	0.75	1.58	1.00	1.00	8	3	3.16	1.00	3.16
	7th	15/21	0.71	1.77	1.00	1.00	8	3	3.37	1.00	3.37
	8th	15/22	0.68	2.01	1.00	1.00	8	3	3.66	1.00	3.66
	9th	15/23	0.65	2.33	1.00	1.00	8	3	4.06	1.00	4.06
	10th	15/24	0.63	2.77	1.00	1.00	8	3	4.62	1.00	4.62
	11th	15/25	0.60	3.25	1.00	1.00	8	3	5.20	1.00	5.20
	12th	15/26	0.58	3.86	1.00	1.00	8	3	5.94	1.00	5.94
	13th	15/27	0.56	4.36	1.00	1.00	8	3	6.45	1.00	6.45
	Rf	15/28	0.54	4.36	0.29	1.00	8	3	1.80	1.00	1.80

moment-resisting frame which is the result of multiplication of the modification factor of level shear capacity $\left(\frac{n+1}{n+i}\right)$, column dimension index (I_{Ac-i}) > 1, column type index (I_{C-i})=0.8 normal column (2<h0/D<6), strong column/weak beam index (I_{SCWB-i})=1 except for the roof floor=0.29, structural vibration period index (I_T)=1, structural system ductility index (R/Ω_0)=8/3 and S_D is the irregularity of building geometry because model b has a regular geometric shape thus the value = 1.

Table 9, I_{SO} is the seismic demand index which is the multiplication of the modification factor of level seismic demand $\left(\frac{n+i}{2n-i+1}\right)$, seismic response index (C_S/C_{Smin})=3.36 and the priority factors of building function (I_e)=1 (office). Table 10 shows that from the 1st floor to the 13th floor, except for the roof floor, the comparison is $I_S > I_{SO}$, which means that the column and beam dimensions have been quite-well designed hence ensuring the adequate rigidity, strength and ductility when a strong earthquake occurs, and it will only suffer light damage or IO (Immediate Occupancy).

Table 9. Seismic demand index (I_{SO}) of location model b

Model	floor	$\frac{n+1}{2n-i+1}$		I_{cs}	I_e	I_{SO}
(b)	1st	15/28	0.54	3.36	1.0	1.80
	2nd	15/27	0.56	3.36	1.0	1.87
	3rd	15/26	0.58	3.36	1.0	1.94
	4th	15/25	0.60	3.36	1.0	2.02
	5th	15/24	0.63	3.36	1.0	2.10
	6th	15/23	0.65	3.36	1.0	2.19
	7th	15/22	0.68	3.36	1.0	2.29
	8th	15/21	0.71	3.36	1.0	2.40
	9th	15/20	0.75	3.36	1.0	2.52
	10th	15/19	0.79	3.36	1.0	2.65
	11th	15/18	0.83	3.36	1.0	2.80
	12th	15/17	0.88	3.36	1.0	2.96
	13th	15/16	0.94	3.36	1.0	3.15
	Rf	15/15	1.00	3.36	1.0	3.36

Table 10 and Figure 2 are the research conducted on model b with pushover analysis resulted in the target displacement=0.474 m with drift ratio=0.85%. Based on FEMA 273, model b, located at the Earthquake Zone 6 with Soft Soil is in inelastic condition, and thus it is is able to resist the earthquake load up to the level of Immediate Occupancy (IO). At the IO level, there is possibility for the structural damage that can be repaired. The prediction on the proposed SVA procedure is relatively similar to the result of the research.

Table 10. Comparison between seismic structure index (I_S) and seismic demand index (I_{SO}) *as well as comparison between SVA and pushover analysis model b*

Model	floor	I_S	I_{SO}	SVA	Pushover analysis-ETABS	
					drift ratio	Performance level
(b)	1st	3.54	1.80	IO	0.85%	IO - LS
	2nd	3.57	1.87	IO		
	3rd	3.64	1.94	IO		
	4th	3.75	2.02	IO		
	5th	3.00	2.10	IO		
	6th	3.16	2.19	IO		
	7th	3.37	2.29	IO		
	8th	3.66	2.40	IO		
	9th	4.06	2.52	IO		
	10th	4.62	2.65	IO		
	11th	5.20	2.80	IO		
	12th	5.94	2.96	IO		
	13th	6.45	3.15	IO		
	Rf	1.80	3.36	LS		

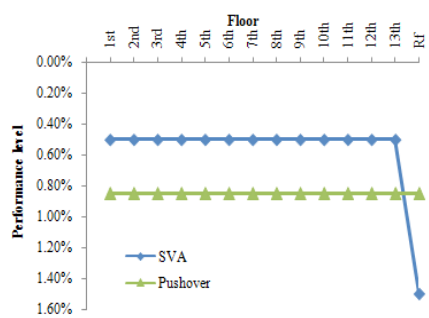


Figure 2. Comparison between between SVA and pushover analysis model b.

3.3. Model c [16]

Table 11, I_S value is the multiplication between E_0 and S_D. E_0 is the basic seismic structure index of the special moment-resisting frame which is the result of multipli-

cation of the modification factor of level shear capacity $\left(\frac{n+1}{n+i}\right)$, column dimension index (I_{Ac-i}) > 1, column type index (I_{C-i})=0.8 normal column (2<h0/D<6), strong column/weak beam index (I_{SCWB-i})=1 except for the roof floor=0.5, structural vibration period index (I_T)=0 since T_C=0.69 seconds > T_{max}=0.5 seconds, structural system ductility index (R/Ω_0)=8/3 and S_D is the irregularity of building geometry because model c has a regular geometric shape thus the value = 1.
<Insert Table 11 here>

Table 12, I_{SO} is the seismic demand index which is the multiplication of the modification factor of level seismic demand $\left(\frac{n+i}{2n-i+1}\right)$, seismic response index (C_S/C_{Smin})=1.81 and the priority factors of building function (I_e)=1 (office). Table 13 shows that from the 1st floor to the roof floor, $I_S< I_{SO}$. Actually, the column and beam dimensions had been well designed. However, it needs a combination with the shear wall structure, so it does not only guarantee the strength and ductility but also gives the adequate rigidity that makes the building will not be too flexible ($T_C>T_{max}$) and eventually the requirements on the security of the architectural elements and structure will meet.

Table 13 and Figure 3 are the research conducted on model c with pushover analysis resulted in the target displacement=0.648 m with drift ratio=1.78%. Based on FEMA 273, model c, located at the Earthquake Zone 6 with Hard Soil, is in inelastic condition, and therefore it is able to resist the earthquake load up to the level of Life Safety (LS) – Collapse Prevention (CP), which means that there is a possibility of moderate until severe damage. The prediction on the proposed SVA procedure is relatively close to the result of the research conducted.

3.4. Model d [17]

Table 14, I_S value is the multiplication between E_0 and S_D. E_0 is the basic seismic structure index of the moderate moment-resisting frame which is the result of multiplication of the modification factor of level shear capac-

Table 12. Seismic demand index (I_{SO}) of location model c

Model	floor	$\frac{n+1}{2n-i+1}$		I_{cs}	I_e	I_{SO}
(c)	1st	11/20	0.55	1.81	1.0	1.00
	2nd	11/19	0.58	1.81	1.0	1.05
	3rd	11/18	0.61	1.81	1.0	1.11
	4th	11/17	0.65	1.81	1.0	1.17
	5th	11/16	0.69	1.81	1.0	1.25
	6th	11/15	0.73	1.81	1.0	1.33
	7th	11/14	0.79	1.81	1.0	1.43
	8th	11/13	0.85	1.81	1.0	1.54
	9th	11/12	0.92	1.81	1.0	1.66
	Rf	11/11	1.00	1.81	1.0	1.81

Table 11. Seismic structure index (I_S) model c

Model	floor	$\frac{n+1}{n+i}$		$I_{Ac-i}.I_{C-i}$	I_{SCWB-i}	I_T	R	Ω_o	E_o	S_D	I_S
(c)	1st	11/11	1.00	1.19	1.00	0	8	3	0.00	1.00	0.00
	2nd	11/12	0.92	1.32	1.00	0	8	3	0.00	1.00	0.00
	3rd	11/13	0.85	1.48	1.00	0	8	3	0.00	1.00	0.00
	4th	11/14	0.79	1.69	1.00	0	8	3	0.00	1.00	0.00
	5th	11/15	0.73	1.98	1.00	0	8	3	0.00	1.00	0.00
	6th	11/16	0.69	1.81	1.00	0	8	3	0.00	1.00	0.00
	7th	11/17	0.65	2.27	1.00	0	8	3	0.00	1.00	0.00
	8th	11/18	0.61	2.94	1.00	0	8	3	0.00	1.00	0.00
	9th	11/19	0.58	4.14	1.00	0	8	3	0.00	1.00	0.00
	Rf	11/20	0.55	5.36	0.50	0	8	3	0.00	1.00	0.00

Table 13. Comparison between seismic structure index (I_S) and seismic demand index (I_{SO}) as well as comparison between SVA and pushover analysis model c

Model	floor	I_S	I_{SO}	SVA	Pushover analysis-ETABS	
					drift ratio	Performance level
(c)	1st	0.00	1.00	CP	0.91%	IO-LS
	2nd	0.00	1.05	CP		
	3rd	0.00	1.11	CP		
	4th	0.00	1.17	CP		
	5th	0.00	1.25	CP		
	6th	0.00	1.33	CP		
	7th	0.00	1.43	CP		
	8th	0.00	1.54	CP		
	9th	0.00	1.66	CP		
	Rf	0.00	1.81	CP		

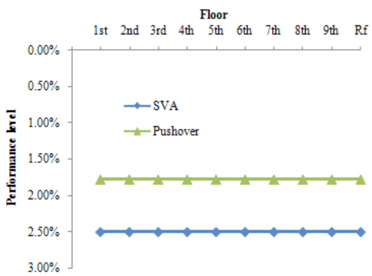


Figure 3. Comparison between between SVA and pushover analysis model c.

ity $\left(\frac{n+1}{n+i}\right)$, column dimension index (I_{Ac-i}) > 1, column type index (I_{C-i})=0.8 normal column (2<h0/D<6), strong column weak/beam index (I_{SCWB-i})=1 except for the roof floor=0.33, structural vibration period index (I_T)=1, structural system ductility index (R/Ω_0)=5/3 and S_D is the irregularity of building geometry because model d has a regular geometric shape thus the value = 1.

Table 15, I_{SO} is the seismic demand index which is the multiplication of the modification factor of level seismic demand $\left(\frac{n+i}{2n-i+1}\right)$, seismic response index (C_S/C_{Smin})=2.26 and the priority factors of building function (I_e)=1 (office). Table 16 shows that from the 1st floor to the 4th floor, except for the roof floor, the comparison is $I_S > I_{SO}$, means that the column and beam dimensions have been quite-well designed hence ensuring the adequate rigidity, strength and ductility when a strong earthquake occurs, and it will only suffer light damage or IO (Immediate Occupancy).

Table 16 and Figure 4 are the research conducted on model d with pushover analysis resulted in the target displacement=0.060 m with drift ratio=0.31%. Based on FEMA 273, model d, located at the Earthquake Zone of Banyumas with Hard Soil with S_S=0.7 g and S_1=0.25 g in inelastic condition, and thus it is able to resist the earthquake load up to the level of Immediate Occupancy (IO). At the IO level, there is possibility for structural damage that can be repaired. The prediction on the proposed SVA procedure is relatively similar to the result of the research conducted.

Table 15. Seismic demand index (I_{SO}) of location model d

Model	floor	$\frac{n+1}{2n-i+1}$		I_{cs}	I_e	I_{SO}
(d)	1st	6/10	0.60	2.26	1.0	1.36
	2nd	6/9	0.67	2.26	1.0	1.51
	3rd	6/8	0.75	2.26	1.0	1.70
	4th	6/7	0.86	2.26	1.0	1.94
	Rf	6/6	1.00	2.26	1.0	2.26

Table 14. Seismic structure index (I_S) model d

Model	floor	$\frac{n+1}{n+i}$		$I_{Ac-i}.I_{C-i}$	I_{SCWB-i}	I_T	R	Ω_o	E_o	S_D	I_S
(d)	1st	6/6	1.00	1.14	1.00	1.00	5	3	1.90	1.00	1.90
	2nd	6/7	0.86	1.42	1.00	1.00	5	3	2.02	1.00	2.02
	3rd	6/8	0.75	1.86	1.00	1.00	5	3	2.33	1.00	2.33
	4th	6/9	0.67	2.52	1.00	1.00	5	3	2.80	1.00	2.80
	Rf	6/10	0.60	3.20	0.33	1.00	5	3	1.04	1.00	1.04

Table 16. Comparison between seismic structure index (I_S) and seismic demand index (I_{SO}) as well as comparison between SVA and pushover analysis model d

Model	floor	I_S	I_{SO}	SVA	Pushover analysis-SAP2000	
					drift ratio	Performance level
(d)	1st	1.90	1.36	IO	0.31%	IO
	2nd	2.02	1.51	IO		
	3rd	2.33	1.70	IO		
	4th	2.80	1.94	IO		
	Rf	1.04	2.26	LS		

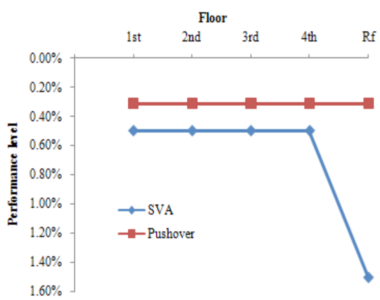


Figure 4. Comparison between between SVA and pushover analysis model d.

3.5. Model e [18]

Table 17, I_S value is the multiplication between E_0 and S_D. E_0 is the basic seismic structure index of the moderate moment-resisting frame which is the result of multiplication of the modification factor of level shear capacity $\left(\frac{n+1}{n+i}\right)$, column dimension index (I_{Ac-i}) > 1, column type index (I_{C-i})=0.6 slender column (6≤h0/D), strong column weak/beam index (I_{SCWB-i})=1 except for the roof floor=0.30, structural vibration period index (I_T) = 1, structural system ductility index (R/Ω_0)=8/3 and S_D is the irregularity of building geometry because model e has a regular geometric shape thus the value = 1.

Table 18, I_{SO} is the seismic demand index which is the multiplication of the modification factor of level seismic demand $\left(\frac{n+i}{2n-i+1}\right)$, seismic response index (C_S/C_{Smin})=1.26 and the priority factors of building function (I_e)=1 (office). Table 19 shows that from the 1st floor to the 3th floor, except for the roof floor, the comparison is $I_S > I_{SO}$, which means that the column and beam dimensions have been quite-well designed hence ensuring the adequate rigidity, strength and ductility when a strong earthquake occurs, and it will only suffer light damage or IO (Immediate Occupancy).

Table 19 and Figure 5 are the research conducted on model e with pushover analysis resulted in the target

Table 18. Seismic demand index (I_{SO}) of location model e

Model	floor	$\frac{n+1}{2n-i+1}$		I_{cs}	I_e	I_{SO}
(e)	1st	5/8	0.63	1.26	1.0	0.79
	2nd	5/7	0.71	1.26	1.0	0.90
	3rd	5/6	0.83	1.26	1.0	1.05
	Rf	5/5	1.00	1.26	1.0	1.26

Table19. Comparison between seismic structure index (I_S) and seismic demand index (I_{SO}) as well as comparison between SVA and pushover analysis model e

Model	floor	IS	ISO	SVA	Pushover analysis-SAP2000	
					drift ratio	Performance level
(e)	1st	3.20	0.79	IO	0.60%	IO
	2nd	2.99	0.90	IO		
	3rd	2.57	1.05	IO		
	Rf	0.69	1.26	CP		

Table 17. Seismic structure index (I_S) model e

Model	floor	$\frac{n+1}{n+i}$		$I_{Ac-i}.I_{C-i}$	I_{SCWB-i}	I_T	R	Ω_o	E_o	S_D	I_S
(e)	1st	5/5	1.00	1.20	1.00	1.00	8	3	3.20	1.00	3.20
	2nd	5/6	0.83	1.34	1.00	1.00	8	3	2.99	1.00	2.99
	3rd	5/7	0.71	1.35	1.00	1.00	8	3	2.57	1.00	2.57
	Rf	5/8	0.63	1.35	0.31	1.00	8	3	0.69	1.00	0.69

displacement=0.872 m with drift ratio=0.60%. Based on FEMA 273, model e, located at Ternate in the Earthquake Zone 4 with Moderate Soil is in inelastic condition, so it is able to resist the earthquake load up to the level of Immediate Occupancy (IO). At the IO level, there is possibility for structural damage that can be repaired. The prediction on the proposed SVA procedure is relatively similar to the result of the research conducted.

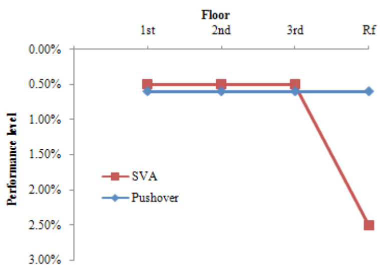


Figure 5. Comparison between between SVA and pushover analysis model e.

3.6. Model f [19]

Table 20, I_S value is the multiplication between E_0 and S_D. E_0 is the basic seismic structure index of the moderate moment-resisting frame which is the result of multiplication between the modification factor of level shear capacity $\left(\frac{n+1}{n+i}\right)$, column dimension index ($I_{Ac\text{-}i}$)<1 for the 1st to 4th floor while column dimension index ($I_{Ac\text{-}i}$) > 1 for the 5th-roof floor, column type index ($I_{C\text{-}i}$)=0.8 normal column (2<h0/D<6), strong column/weak beam index ($I_{SCWB\text{-}i}$)=1 except for the roof floor=0.25, structural vibration period index (I_T)=1, structural system ductility index (R/Ω_0)=8/3 and S_D is the irregularity of building geometry because model f has a regular geometric shape so that the value = 1.

Table 21, I_{SO} is the seismic demand index which is the multiplication of the modification factor of level seismic demand $\left(\frac{n+i}{2n-i+1}\right)$, seismic response index (C_S/C_{Smin})=3.33 and the priority factors of building function (I_e)=1 (office). Table 22 shows that from the 1st floor to the 11th floor has $0.5I_{SO} \le I_S \le I_{SO}$ (LS) while for the roof floor $I_S < 0.5I_{SO}$ (CP), means that the column and beam dimensions have not been well designed although the rigidity and ductility have been adequate but the strength of structure is less adequate so that there is a potential for moderate damage or LS (Life Safety) when a strong earthquake occurs.

Table 22 and Figure 6 are the research conducted on model f with pushover analysis resulted in the target displacement=0.65 m with drift ratio=1.36%. Based on FEMA 273, model f, which is located in Bobong City, North Maluku, with Moderate Soil with S_S=1.355 g and S_1=0.537 g is in inelastic condition which is able to

Table 20. Seismic structure index (I_S) model f

Model	Floor	$\frac{n+1}{n+i}$		$I_{Ac-i}.I_{C-i}$	I_{SCWB-i}	I_T	R	Ω_o	E_o	S_D	I_S
(f)	1st	13/13	1.00	0.58	1.00	1.00	8	3	1.55	1.00	1.55
	2nd	13/14	0.93	0.63	1.00	1.00	8	3	1.57	1.00	1.57
	3rd	13/15	0.87	0.70	1.00	1.00	8	3	1.61	1.00	1.61
	4th	13/16	0.81	0.77	1.00	1.00	8	3	1.68	1.00	1.68
	5th	13/17	0.76	0.87	1.00	1.00	8	3	1.78	1.00	1.78
	6th	13/18	0.72	1.00	1.00	1.00	8	3	1.92	1.00	1.92
	7th	13/19	0.68	1.16	1.00	1.00	8	3	2.11	1.00	2.11
	8th	13/20	0.65	1.00	1.00	1.00	8	3	1.72	1.00	1.72
	9th	13/21	0.62	1.16	1.00	1.00	8	3	1.91	1.00	1.91
	10th	13/22	0.59	1.38	1.00	1.00	8	3	2.18	1.00	2.18
	11th	13/23	0.57	1.72	1.00	1.00	8	3	2.59	1.00	2.59
	Rf	13/24	0.54	2.21	0.25	1.00	8	3	0.80	1.00	0.80

Table 21. Seismic demand index (I_{SO}) of location model f

Model	Floor	$\frac{n+1}{2n-i+1}$		I_{cs}	I_e	I_{SO}
(f)	1st	13/24	0.54	3.33	1.0	1.81
	2nd	13/23	0.57	3.33	1.0	1.88
	3rd	13/22	0.59	3.33	1.0	1.97
	4th	13/21	0.62	3.33	1.0	2.06
	5th	13/20	0.65	3.33	1.0	2.17
	6th	13/19	0.68	3.33	1.0	2.28
	7th	13/18	0.72	3.33	1.0	2.41
	8th	13/17	0.76	3.33	1.0	2.55
	9th	13/16	0.81	3.33	1.0	2.71
	10th	13/15	0.87	3.33	1.0	2.89
	11th	13/14	0.93	3.33	1.0	3.10
	Rf	13/13	1.00	3.33	1.0	3.33

Table 22. Comparison between seismic structure index (I_S) and seismic demand index (I_{SO}) as well as comparison between SVA and pushover analysis model f

Model	Floor	I_S	I_{SO}	SVA	Pushover analysis-SAP2000	
					drift ratio	Performance level
(f)	1st	1.55	1.81	LS	1.36%	IO-LS
	2nd	1.57	1.88	LS		
	3rd	1.61	1.97	LS		
	4th	1.68	2.06	LS		
	5th	1.78	2.17	LS		
	6th	1.92	2.28	LS		
	7th	2.11	2.41	LS		
	8th	1.72	2.55	LS		
	9th	1.91	2.71	LS		
	10th	2.18	2.89	LS		
	11th	2.59	3.10	LS		
	Rf	0.80	3.33	CP		

resist the earthquake load up to the level of Immediate Occupancy (IO) – Life Safety (LS), but according to drift ratio, it has already approached the LS, means that there is a potential moderate structural damage which is still possible to repair. The prediction on the proposed SVA procedure has relatively close the result of the research conducted.

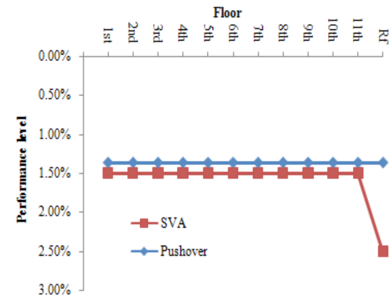


Figure 6. Comparison between between SVA and pushover analysis model f.

4. Conclusion

Based on the results of the research, there are some conclusions as follows:

1. The prediction on the proposed SVA procedure for model a (6 floors), d (5 floors), and e (4 floors) has a relatively similar result to which have been conducted by other researchers on the building models.
2. The prediction on the proposed SVA procedure for model b (14 floors), c (10 floors), and e (12 floors) has a relatively close result to which have been conducted by other researchers on the building models.
3. For the buildings with moment-resisting frame < 10 floors, the building performance is dominated by the dimensions of beam, column, and the ratio of height and width of the building, while for the buildings ≥ 10 floors, the building performance is dominated by the dimensions of beam, column and the height of building.

The purpose of the prediction on SVA procedure here does not look for exactly similar results to the more accurate results of the procedure analysis such as pushover analysis, but the result of SVA prediction is one level higher or lower than the accurate calculation is considered adequate because according to[3], the result of the SVA procedure can be used to underlie the potential status of the selected buildings and subsequently there are a list of the buildings which needs more detailed vulnerability assessment conducted by the structural experts.

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