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DESIGN AND EVALUATION OF VERTICAL EVACUATION BUILDING AT KELUMBAYAN USING TSUNAMI MODELLING

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ABSTRACT: The Sumatran Fault and the Krakatau Volcano on Sunda Strait, Indonesia, has produced earthquakes and tsunamis on the region. One of the cities in this region that has high potential to be affected by future disaster is Kelumbayan. A solution to minimize the casualties due to tsunami is by constructing a Vertical Evacuation Building (VEB), which acts as a shelter and rescue building. Hence, the design of the VEB must ensure that it can resist large earthquakes and withstand tsunami impacts. Currently, there is no local code regarding tsunami, hence the design of such structure should be evaluated. This study conducts the design and evaluation of a VEB in Kelumbayan using a simulation of tsunami propagation. Based on the tsunami depth and forces from the modelling, also the number of people to be sheltered, the VEB structural model is developed. The 4-story reinforced concrete structure utilizes a special moment frame system, with applicable loads for the shelter, including earthquake and tsunami loads. The structural performance of VEB is then evaluated using non-linear static pushover analysis. The result shows that forces due to tsunami are greater than those of earthquake, thus defining the capacity of structural members. The analysis shows that the structure performs satisfactory under the design seismic load, hence can be used as a tsunami shelter. In conclusion, the design of VEB complies with the applicable building codes and is adequate for its function.

Keywords: Kelumbayan, Structural performance, Tsunami, Vertical evacuation building

1. INTRODUCTION

As part of the ring of fire, Indonesia has experienced many earthquakes and tsunamis. One of the prone areas to such disasters is the Sunda Strait region. Records show that several earthquakes followed by tsunamis have occurred due to the eruptions of the Krakatau Volcano, and the tectonic activities of nearby Sumatran Fault [1].

One of the cities in the region with high potential to be affected by future disaster is Kelumbayan, Tanggamus Regency, Lampung. The district area is approximately 200 km^2, with a population of 11,129 people. A tourist destination area, Desa Kiluan Negeri, is also located in Kelumbayan, and it has a high economic impact for the district [2].

Kelumbayan's geographical location with shallow bays surrounded by hills, and nearby seismic sources, will intensify the impact of the tsunami. Hence, an effort to minimize the casualties due to tsunami is conducted. One possible solution is constructing a Vertical Evacuation Building (VEB). Acting as a shelter and rescue building, the VEB allows the community to reach a safe elevation within the evacuation time when a tsunami happened. The VEB is deemed to be useful especially for a tsunami with a close source that does not provide enough time for evacuation (the warning time is less than 30 minutes from the earthquake as the first warning of an impending tsunami) [3].

Fig.1 Kelumbayan District, Lampung (Google Earth)

The VEB for tsunami disaster evacuation have been studied at several location in Indonesia. The utilization of public buildings in Padang City as VEB has been evaluated, and it is found that the structural conditions of these buildings need to be improved to be used as a tsunami shelter [4]. Previous research of design procedure for VEB in Painan City reveals that the building must be designed such that it can survive when large earthquakes occur, then should be able to resist tsunami load without collapse [3]. Thus, the design not only should meet all requirements for seismic resistant structures, it also should show adequate performance and suffer no or minor damage under the design earthquake. Hence, the design of the VEB must ensure that it can resist large earthquakes and withstand tsunami impacts. Several international building codes have procedures regarding design for tsunami loads, specifically for structures to be used as tsunami shelter [5-7].

Currently, the design procedure regarding tsunami loads is not available in the local building codes. Therefore, it is deemed to be necessary to establish the tsunami loads and design procedure that can be used to design the VEB structure in Kelumbayan District. Furthermore, the tsunami loads should also be based on the maximum probable hazard in the region.

2. RESEARCH SIGNIFICANCE

The design of buildings with tsunami loading is very few in Indonesia. Moreover, the available local building codes do not specifically include tsunami loads in the design procedure. Therefore, in this study, a design on VEB in Kelumbayan was conducted with applicable loads (including earthquake) using local codes [8-9], and the design for tsunami load was carried out using recommendations from an international building code [5]. This approach has been applied on a different location, albeit with limited evaluation on the structural performance [3]. Thus, this research aims to further evaluate the VEB structural performance regarding its adequacy to be used as a tsunami shelter, using tsunami loads and design procedures from FEMA P-646 [5].

3. TSUNAMI AND MITIGATION SCENARIO

Tsunami forces are often catastrophic and impose great impacts on the buildings in coastal areas. Studies revealed that the tsunami wave can reach far inland with a substantial inundation depth, as shown by the thickness of sediment deposits in the affected region [10]. To obtain the tsunami forces used in the structural design, several tsunami parameters need to be determined. Previous study shows that conducting a simulation of tsunami propagation is important for obtaining these tsunami parameters [11-12]. Thus, a simulation of tsunami propagation was carried out to obtain the tsunami loads for the VEB in Kelumbayan District. The simulation was also critical for determining the optimum locations of the VEBs.

3.1 Tsunami Hazard

To obtain the maximum considered tsunami, various scenarios were evaluated. From all possible earthquake mechanisms, the Sunda Strait megathrust subduction zone provides the most severe tsunami scenario for Kelumbayan District [13]. The parameters for the megathrust were Mw = 8.7, with the length of the segment of 290 km. Regarding focal mechanism, the parameters are depth of 30 km and dip angle of 15° [14]. The tsunami was analyzed using 500 m x 500 m grids, with 100 m x 100 m nesting for the site. The Manning's coefficient, which represents the roughness or friction applied to the flow, is 0.02 with a fluid density of 1128 kg/m^3.

Based on the scenario, the generated tsunami may reach up far towards inland, up to approximately 4 km. The first wave arrives on the coast 22 minutes after the rupture, and the maximum velocity in the urban area was 5 m/s. The average inundation depth in the city area is approximately 1 – 5 m,

Fig. 2 shows the modelling of the tsunami wave arrival in the region, using the most severe scenario. The wave was generated at the Sunda Strait megathrust subduction zone. As the tsunami wave travelled towards inland, the height increased and peaked as it hit the coastal areas perpendicular to the direction of the wave. The study shows that the tsunami wave reached up to 5 m at Kelumbayan.

Fig. 3 provides a closer look at the level of inundation in the region. The hillside was inundated by 1 -3 m, and the coastal area was inundated by 3 – 5 m. This scenario is used in the study, with regards to the maximum evacuation time, and the tsunami loads. The tsunami loads were calculated using procedures given in [5].

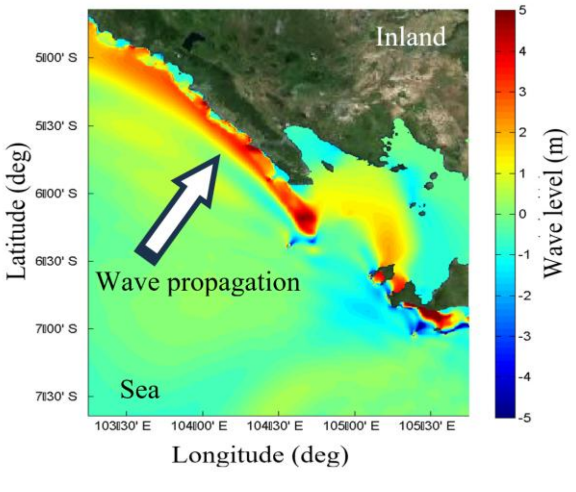


Fig.2 Tsunami wave arrival modelling at Kelumbayan District

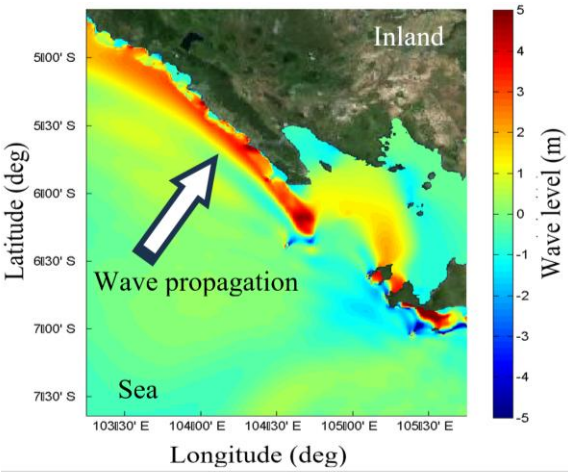


Fig.3 Depth of Tsunami Inundation at Kelumbayan District

3.2 VEB Locations and Capacities

From the results of tsunami modelling, it was assumed that 30 percent of the population would be affected by the tsunami. The assumption was based on the inundated area and the possibly affected population. Considering the number of people to be sheltered during tsunami, five VEB structures were planned for Kelumbayan District. Each VEB is a regular reinforced concrete building with a layout plan of 24 m x 24 m, based on the typical available open space for public facilities in the region. The VEBs are designed as multi-function facilities with each floor to be used for various activities. In addition, the upper floors are to be used as the refugee area.

The optimum locations for these VEBs were determined based on the maximum walking distance for average people within 20 minutes, that is approximately 1.2 km. The 20 minutes time limit is based on the arrival of the first wave from tsunami modelling. Therefore, each VEB is ideally located such that people within 1.2 km radius can access the VEB. The highly populated area and center for economic activities also affect the VEB locations, as more people are expected to use the shelter.

Reviewing the geography and demographic conditions, five locations were selected for the sites of VEBs. These locations were considered optimal for saving most lives, with all VEBs being well separated and in the vicinity of dense population. All VEBs were also placed in the coastal region, that would be highly affected by the tsunami. Fig.4 shows the locations of all VEBs at Kelumbayan.

For each VEB location, the maximum inundation elevation was calculated to determinate the minimum elevation of the refugee area. The modelling reveals that maximum inundation depth was found to be 5 m; thus the 1st and 2nd stories were assumed to be inundated, and the tsunami loads were calculated with this level as a reference.

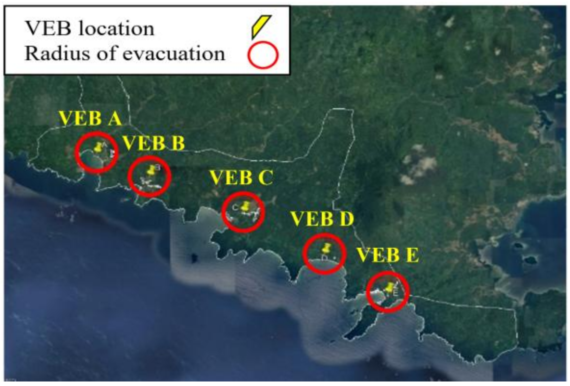


Fig.4 VEB Locations at Kelumbayan District

Although almost all the Kelumbayan District was affected by the tsunami, it is assumed that only 30 percent of the population was critically affected. With the addition of tourists to the region, it is assumed that approximately four thousand people would need to be sheltered. Considering the various density of the region, the required capacity of each VEB would also vary. The code [5] requested that the area required for VEB is 0.93 m^2 per person, hence the required area for each VEB was estimated. Next, the height of each VEB was calculated, with the assumption that roof floor was also used as a refugee area. To simplify, it is assumed that all VEB would have a similar plan layout, that is 24 m x 24 m, thus the required number of stories could be determined. Table 1 provides the estimated height and the number of stories of each VEB.

Table 1 VEB Capacity and Number of Stories

VEB	Number of People	Required Refugee Area (m^2)	Number of Story for Evacuation
A	641	656	2
B	945	987	2
C	1149	1175	3
D	230	235	1
E	912	933	2

4. MODELLING OF VEB STRUCTURE

The VEB to be modeled and evaluated was VEB in location C, as it was deemed to be the most critical facility. This VEB is of a 4-story reinforced concrete structure, with the 3rd, 4th, and roof floors to be used as refugee area.

Based on the previous assumption, the plan layout elevations were designed such that the building has no structural irregularities. The building consists of four spans on both axes with 6 m span width, and 4 m story heights for all floors (Fig. 5). The floor plans show locations of columns and beams that are typical for all floors. Two types of columns were utilized, Column 1 for story 1 and 2, and Column 2 for story 3 and 4. Two types of beams were also used, with Beam 1 identified with green lines, and Beam 2 with grey lines in Fig. 5.

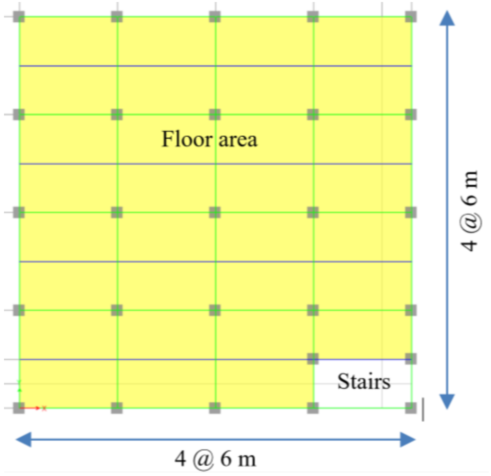


Fig.5 Plan Layout of VEB Structures

The VEB structural system is a special moment frame, which acts as a lateral resisting system. Table 2 shows the material properties, for both concrete and reinforcement bars for each type of structural element. The dimensions and detailing of those structural members are presented in Table 3 and Table 4 respectively.

Table 2 Material Properties

Material	Specification
Concrete for column	fc' = 35 MPa
Concrete for beam and plate	fc' = 30 MPa
Steel reinforcement	fy = 400 MPa

Table 3 Dimensions of Structural Elements

Elements	h (mm)	b (mm)
Column (story 1 and 2)	750	750
Column (story 3 and 4)	650	650
Beam 1	600	350
Beam 2	300	200
Plate	150	8

Table 4 Detailing of Structural Elements

Elements	Longitudinal Rebar	Transverse Rebar
Column (story 1 and 2)	16D32	4D13-100
Column (story 3 and 4)	16D29	4D13-100
Beam 1	8D22/7D22	2D13-100
Beam 2	2D19/2D19	2D10-100
Plate	D13-200	D13-200

Fig.6 shows the structural model of VEB, with beams, columns, slabs, and stairs. In this model, the floor slabs are assumed to be semi-rigid diaphragms.

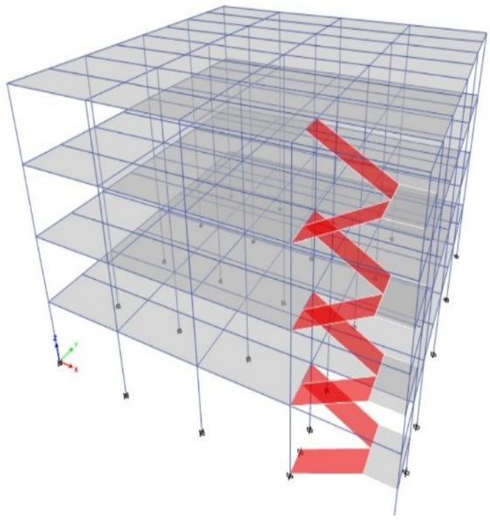


Fig.6 3D Modelling of VEB at Kelumbayan District

The VEB building design loads and their combinations followed SNI 1727-2020 [8], with additional applicable loads for shelter. The loads considered were dead load, live load, rain load, wind load, as well as earthquake load and tsunami load. The live load was taken as 4.79 kN/m^2, as governed by the building's function.

The seismic load for VEB was calculated based on SNI 1726-2019 [9]. Fig. 7 shows the response spectra for Kelumbayan District, that were obtained from http://puskim.pu.go.id/Aplikasi/desain_spektra_indonesia_2011/, for site class D. The spectral parameters were as follows: S_S = 1.47, S_1 = 0.66, F_a = 1.00, and F_v = 1.70.

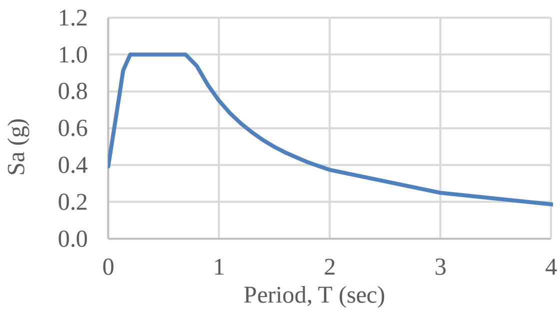


Fig.7 Response Spectra for Kelumbayan District

As an essential facility with risk category IV, the seismic design category (SDC) for the VEB was selected as D, with an importance factor (I_e) of 1.5. The response modification factor (R) was 8 for special moment frame structure. From the analysis, the total seismic weight of the structure was found to be 20,638 kN.

The tsunami load was calculated based on FEMA P-646 [5]. The tsunami forces consist of hydrostatic force, buoyant force, hydrodynamic force, impulse force, debris impact force, damming debris force, uplift forces on elevated floors, and extra gravity force. All forces were then applied to the structural model using the load combinations given by FEMA P-646 to obtain the tsunami loads resultant (Ts).

5. STRUCTURAL ANALYSIS OF VEB

The structural analysis reveals that the VEB fundamental period was 0.274 sec, and the first two modes were translational modes. Using procedures from the code, the seismic load was calculated, and the design seismic base shear was 4,749 kN.

The procedure for designing structure for seismic load was continued. Checking on irregularities confirmed that the structure was regular, and the VEB building satisfied drift limitations. The effect of P-Δ was also evaluated, along with the redundancy factor. Everything shows that the design of VEB complies with codes [8-9].

Next, the design procedure for tsunami load was conducted following FEMA P-646 [5]. Table 5 shows the tsunami forces calculated for the model, which consist of hydrostatics (F_h), buoyancy (F_b), hydrodynamics (F_d), impulse (F_s), debris impact (F_i), damming debris (F_{dm}), uplift (F_u), and additional retained water (F_r). The applications of these forces to the model were also provided. These forces were then used to calculate the tsunami load resultant (T_s) using load combinations from the code.

Table 5 Summary of Tsunami Forces

Type		Location	Forces
Hydrostatic	F_h	Corner column	113 kN/m
		Exterior column	226 kN/m
Buoyancy	F_b	Corner column	679 kN
		Exterior column	1358 kN
		Interior column	2716 kN
Hydrodynamics	F_d	Corner column	37 kN/m
		Exterior column	74 kN/m
Impulse	F_s	Corner column	56 kN/m
		Exterior column	112 kN/m
Debris Impact	F_i		678 kN
Damming Debris	F_{dm}		37 kN/m
Uplift	F_u		0
Additional Retained Water Loading	F_r		0

The load combination for tsunami forces to obtain the tsunami load was based on [5].

$$F_b + F_u + F_s + F_d + F_i + F_h \quad (1)$$

$$F_b + F_u + F_{dm} + F_d + F_i + F_h \quad (2)$$

$$F_b + F_u + F_r \quad (3)$$

The tsunami loads resultant (Ts) is the maximum load obtained from the above combinations. It should be noted that no combination of tsunami and earthquake loads were considered, as it is very unlikely to occur simultaneously.

The analysis reveals that the forces from tsunami was much more than forces from other loads, including earthquake (Table 6). The larger base shear due to tsunami force implies that the structure requires larger lateral load capacity than regular earthquake resistant structure. The maximum moments at columns and beams also show that these forces due to tsunami were much larger. Hence, the capacities of structural elements were governed by the tsunami load, not by the seismic load.

Table 6 Comparisons of Forces Due to Earthquake and Tsunami Load

Forces	Earthquake	Tsunami
Base Shear	4749 kN	21,757 kN
Max. moment at Column	1015 kNm	2549 kNm
Max moment at Beam	341 kNm	462 kNm

Based on the results of the analysis, the detailing of structural members was completed. Using the configuration of the structural elements and detailing as presented earlier, the internal forces were obtained and used for checking the member capacities. Fig. 8 presents the moments on typical floor plates due to gravity load.

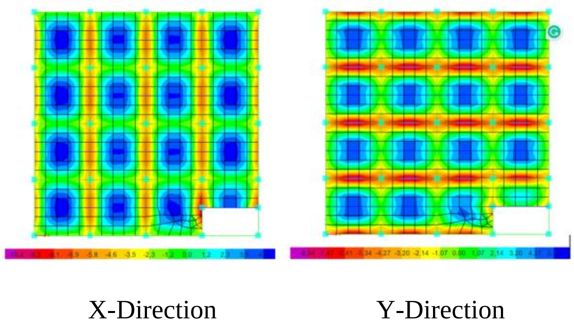
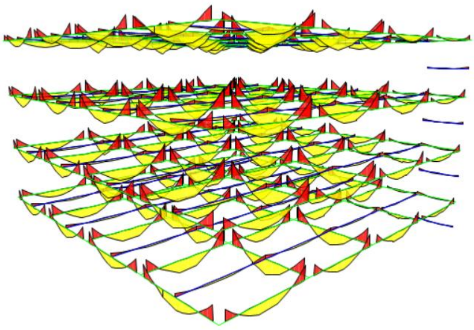


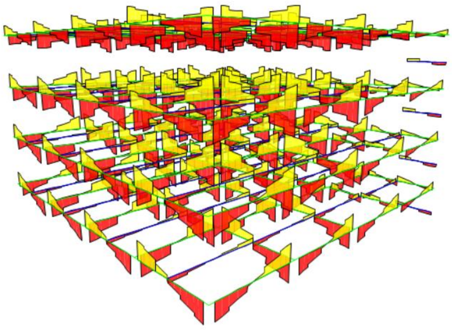
Fig.8 Moment on Floor Plate Due to Gravity Loads

The internal forces (moment and shear) developed on beams and columns due to combination with the tsunami load are presented in Figure 9 and 10 respectively.

The analysis reveals that all members were adequate in resisting all applicable loads. Next, the structural performance was evaluated using the nonlinear static pushover analysis to evaluate whether the structure can be used as a tsunami shelter.

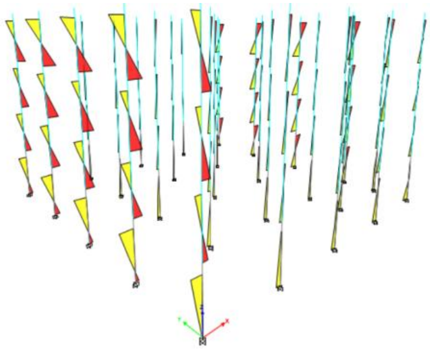


(a) Flexural Moment

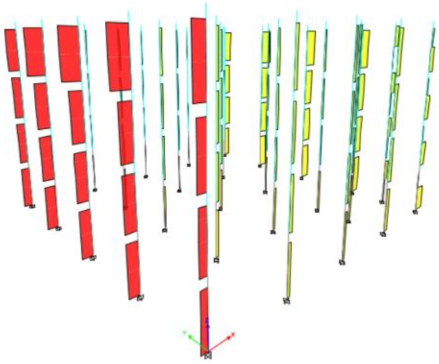


(b) Shear Force

Fig.9 Internal Forces on Beams Due to Combination with Tsunami Loads



(a) Flexural Moment



(b) Shear Force

Fig.10 Internal Forces on Columns Due to Combination with Tsunami Loads

It should be noted that the design followed all requirements for the special moment frame system, including requirements for detailing, and the strong-column-weak-beam concept. Therefore, it is expected that the structure will have some ductility and overstrength.

6. PERFORMANCE EVALUATION OF VEB

The VEB is expected to withstand large earthquakes with minimal or no damage, since the building is to be used for a shelter for the tsunami following the earthquake. To evaluate the structural performance under the design earthquake, a nonlinear static pushover analysis was conducted. The procedure is a performance-based design approach and is explained in FEMA 356 [15] as well as FEMA 440 [16].

According to [15-16], the structural performances can be categorized into 3 levels, namely:

1. *Immediate Occupancy (IO):* structure retains its original strength and stiffness, negligible damage.
2. *Life Safety (LS):* significant structural damage but not result in the collapse of structure, severe component damage, major cracks, and visible structural deformation.
3. *Collapse Prevention (CP):* damage to the core of the structure, possible significant degradation of the stiffness and lateral strength of the structure, large permanent lateral deformation. The building is on the verge of collapse.

To conduct the nonlinear static pushover analysis of VEB structure, plastic hinges were assigned on beams and columns ends. The backbone curves for the plastic hinges were developed according to [16].

Fig.11 presents a portion of the demand capacity spectra obtained from the pushover analysis, emphasizing on the elastic condition. The performance point is the intersection of the capacity curve and the demand curve on the capacity demand spectra, and it provides an estimation of the structural performance under the design seismic load.

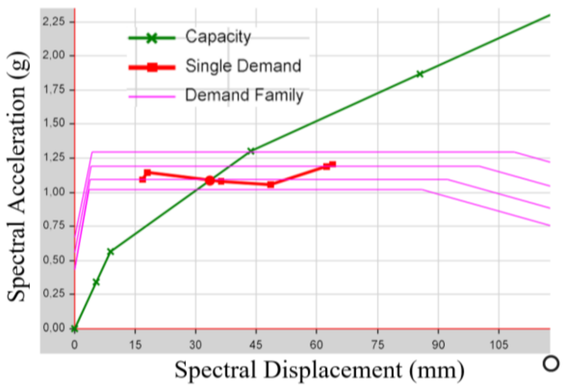


Fig.11 Demand Capacity Spectra for VEB

The pushover analysis reveals that the first plastic hinge was developed on a beam element on the 3rd story. The performance point, which represents the structural performance under the design seismic load, was reached at a displacement of 66.3mm. At this point, plastic hinges occurred on some elements, mostly beams, as expected, but with only a few hinges developed and a low level of yielding. Fig. 12 shows the development of plastic hinges up to performance point, with very early stage (indicated by green color).

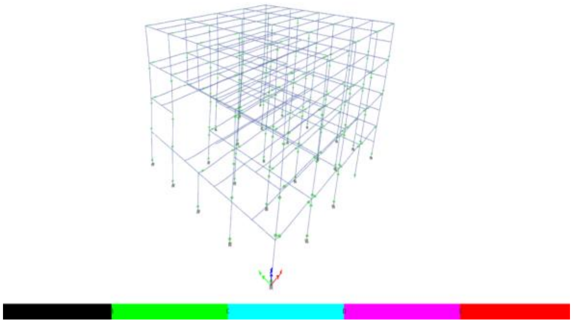


Fig.12 Development of Plastic Hinges of VEB Structure at Performance Point

From the capacity curve, the deformation for each performance level (IO, LS, CP) was obtained. Next, comparing the deformation at the performance point to these levels, the VEB performance can be estimated. Table 7 presents the deformations for various performance levels (IO, LS, CP), and the deformation at the performance point. The deformation due to the design earthquake load is smaller than the deformation for IO level (Table 7). Since the structural design was governed by the tsunami load, which was much larger than the seismic load, the structure remains fairly elastic with small deformation under the design earthquake load. Therefore, the performance of VEB structure is estimated to be at *Immediate Occupancy* (IO) level for the design seismic load, and the VEB structure is expected to perform satisfactorily as a shelter.

Table 7 Performance Level of VEB

Performance Level		Δ (mm)
Collapse Prevention (CP)	Δ_{max}	158.6
Life Safety (LS)	0,75 CP	119.0
Immediate Occupancy (IO)	0,67 LS	79.7
Performance Point (PP)		66.3
VEB Performance Level: *Immediate Occupancy* (IO)		

After the VEB was found to be adequate to resist the design seismic load, the next step was to evaluate VEB capacity in resisting the tsunami load. FEMA P646 [5] allows typical buildings to be damaged up to *Collapse Prevention* (CP) performance level due to tsunami load. As such, the structure may experience severe damage but is not permitted to collapse under the design tsunami forces. However, the code also states that the VEB structure as a shelter should have a performance level of *Immediate Occupancy* (IO) under the maximum considered tsunami. This means that the structure should have minimum damage due to tsunami loads.

The structural analysis using the final member design reveals that VEB structure could resist the tsunami loads. Using internal forces calculated from load combinations with tsunami load, all members were found to have adequate capacity. The results obtained in this study were in line with those of previous study [3].

The analysis reveals that the developments of plastic hinges on structural members under these loads were in the early stage. Hence, the performance level of VEB under the maximum considered tsunami is also *Immediate Occupancy* (IO). Therefore, the VEB was found to be adequate to be used as a tsunami evacuation building.

This study confirms that the design using tsunami load based on [5] and seismic load based on [9] provides an approach in designing tsunami shelter in Kelumbayan district. The design procedure from [5] is found to be useful and satisfactory for designing VEB in this study. The analysis reveals that the VEB structure was able to withstand the design seismic load with minimum damage and was adequate in resisting the design tsunami load, thus can be used as a tsunami shelter.

7. CONCLUSIONS

The Vertical Evacuation Building (VEB) for Kelumbayan district was designed using all applicable building loads based on local building codes [8-9], and tsunami loads as well as tsunami design procedure based on FEMA P-646 [5].

The study found that the tsunami load was much larger than the seismic load, thus governing the structural capacity of VEB. Designing VEB using tsunami loads yields a structure that also complies with all requirements for seismic resistant structures.

The nonlinear static pushover analysis reveals that the VEB structure was near elastic under the design seismic load, with minimum damage occurred. The development of plastic hinges was in the early stage on beams, and the structure showed large reserve capacity beyond the performance point. The performance level of VEB structure was found to be *Immediate Occupancy* (IO) level. Therefore, the VEB satisfies the performance targets required by regulations as an earthquake-resistant building and can be used as a shelter for tsunami. The study confirmed that the procedure given in [5] can be used in conjunction with the local building codes for designing VEB structures in Indonesia.

8. ACKNOWLEDGMENTS

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