Rapid and in-depth analysis for seismic risk evaluation

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Abstract. The high public demand on housing in urban areas requires the government of Indonesia to adopt a policy of encouraging the development of vertical housing. Cilacap has been allocated Rusunawa (low-income apartment) development in 2006. Evident from some earthquakes occurrence in recent years, however, Cilacap may be seen as an earthquake prone region which posing some risk to this type of vertical structures. The Appropriate strategy should be performed to evaluate the seismic risks of this local government owned four stories low-income apartment. This paper demonstrates two tier evaluation strategy; rapid evaluation and in-depth analysis and compares both results. First evaluation was conducted by means of Building Rapid Visual Screening (RVS) of FEMA 154 of the Rusunawa block A and B. The result was used further to calculate seismic risk score (SR) which exhibit the probability of the building damage given the Maximum Considered Earthquake (MCER) that will occur during the Rusunawa service life. The in-depth analysis was conducted by developing fragility function expressed in the form of fragility curves for the Rusunawa. The fragility shows the probability that certain damage states will be exceeded given the intensity of earthquakes which will occur during building service life. The fragility was developed as lognormal curves in which the building response to earthquake input was analyzed by means of pushover.

1. Introduction
Limited land for urban housing encourages the government to take a policy of vertical housing [1]. The city of Cilacap has been allocated Rusunawa (low-income apartment) development in 2006. It is a government-owned building that functions as a dwelling for people. However, as Cilacap is an area quite prone to earthquakes, therefore, the assessment of the seismic vulnerability of existing buildings, especially Rusunawa, is very important. The appropriate strategy should be taken to evaluate the seismic risks of this local government owned four stories low income-apartment.

The first tier evaluation was conducted by means of Building Rapid Visual Screening (RVS) of FEMA 154. The rapid visual screening (RVS) procedure has been developed to identify, inventory, and screen buildings that are potentially seismically hazardous [2]. RVS will provide a preliminary description of the risk of building against earthquake hazards [3,4]. The result was used further to calculate seismic risk score (SR) which exhibit the probability of the building damage given the Maximum Considered Earthquake (MCER) which will occur during the Rusunawa service life. Meanwhile, to assess the risk more accurately in-depth analysis may be necessary. The analysis should predict the building response over several earthquake intensity in the region. A pushover analysis is performed in this study to thoroughly estimate the maximum force and deformation that occurs and to
obtain information on which parts are critical. Many of research indicates that nonlinear static pushover analysis provides sufficient results for low-rise building [5].

2. Rapid Visual Screening
The RVS procedure uses an empirical methodology. It is based on a sidewalk survey of a building and a data collection form completed by the person conducting the survey. The inspector visually observes of the building from the exterior, and if possible, the interior.

There are five kinds of Data Collection Form based on seismicity region namely: Low, Medium, Moderately High, High, and Very High. Determination of Seismicity is based on the Response Spectral Acceleration Area of Maximum Considered Earthquake Risk (MCER) depicted in Table 1.

| Seismicity Region | Spectral Acceleration Response, SS (short-period, or 0.2 seconds) | Spectral Acceleration Response, S1 (long-period, or 1.0 second) |
|-------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Low               | Low less than 0.250g                                          | less than 0.100g                                              |
| Moderate          | greater than or equal to 0.250g but less than 0.500g          | greater than or equal to 0.100g but less than 0.200g          |
| Moderately High   | greater than or equal to 0.500g but less than 1.000g          | greater than or equal to 0.200g but less than 0.400g          |
| High              | greater than or equal to 1.000g but less than 1.500            | greater than or equal to 0.400g but less than 0.600g          |
| Very High         | greater than or equal to 1.500g                               | greater than or equal to 0.600g                               |

Data collection form consists of spaces to document building identification information, including the use and size of buildings, building photographs, sketches and documentation of building data related to seismic performance. Based on data collected during the survey, the score can be calculated. This score provides an indication of the seismic performance of buildings. The final score, S is an estimate of the probability of collapse if an earthquake occurs given a maximum-considered earthquake risk, MCER. Mathematically, if P shows the probability of collapse in the MCER shaking, then the S score is derived from FEMA 154 which satisfies the equation (1):

\[ S = -\log_{10}(P) \]  

For instance, a final score S of 2 implies there is a chance of 1 in 10^2, or 1 in 100, that the building will collapse if such ground motions occur.

3. Risk Score (SR)
Risk Score, denoted by SR, which measures building safety regarding how frequently collapse-causing earthquakes occur. It is intended as an estimate of the negative base-10 logarithm of the number of earthquakes that could cause building collapse during the service life of the building, which is commonly taken to be 50 years [6]. This is a different measure of performance from S. S has nothing to do with the design life of the building or the number of collapse-causing earthquakes while SR does.

To obtain Risk Score is to add the final score of S with PMFR (Risk Modification Factor). Table 2 shows that, for all seismicity regions between Moderate and Very High, one can add approximately 1.0 to the Final Score to get the Risk Score.
Table 2. Estimated value of PMFR (FEMA 155)

| No | Seismicity Region | PMRF |
|----|-------------------|------|
| 1  | Low               | 0.1  |
| 2  | Moderate          | 0.9  |
| 3  | Moderately High   | 1.2  |
| 4  | High              | 1.1  |
| 5  | Very High         | 0.9  |

4. Pushover analysis

The basic concept of nonlinear static analysis (pushover) is to provide an incremental certain static loading pattern in the lateral direction. This method is simple but the resulting information is able to describe the inelastic response of the building.

Pushover method employs two load cases, i.e. gravitation load and earthquake load, for the non-linear static analysis. A combination of dead load, super imposed dead load and live load was inputted as gravity load case in which each load was multiplied by a factor of 1. As the load was applied to a structural model, the response of the structure was recorded. Then, an around acceleration was inputted as subsequent load case with multiplier factor of 1 as a non-linear static load. This load case was applied with displacement control method. The initial condition for this loading condition was taken from previous gravity load case. The response of structure was then recorded in multiple steps a minimum number of 10 steps and maximum 100 steps. The maximum target was determined when the deviation of 4% times the total building height was reached by the program default [7]. The result of this pushover method is a capacity curve describing base shear force as a function of displacement.

5. Fragility Curve

The fragility curve characterizes the relationship between the probability of a demand parameter will cause a structure to experience a condition of damage that exceeds the limit condition of the prescribed damage states (limit state). This demand parameter can be Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) or spectral displacement for a certain period. The Federal Emergency Management Agency (FEMA) designs the manual document to explain and simulate the fragility analysis methods of building structures that became the approach method in the assessment of seismic losses.

To simplify damage states, the HAZUS methodology classifies the degree of destruction of buildings into four discrete deterioration conditions, e.g., slight, moderate, extensive, and complete, as illustrated schematically in Figure 1[8]. Each damage condition represents various building damage thresholds. For example, slight damage conditions extend from the limit of slight damage to moderate damage limits.
6. Research methods
This study implements Rapid Visual Screening FEMA 154. Data were obtained from: (1) field survey and (2) direct interview with the technical institution as building manager which has the knowledge of the building condition, documentation, and identification type of damage. Data Collection Form is completed for each building screened through execution of the following steps:
   a. Verifying and updating the building identification information;
   b. Walking around the building to identify the number of stories and shape, and sketching a plan and elevation view on the Data Collection Form;
   c. Photographing the building;
   d. Determining and documenting occupancy;
   e. Reviewing the soil type and geologic hazards, as identified during the pre-field planning process;
   f. Identifying adjacency issues, building irregularities, and any potential exterior falling hazards;
   g. Adding any comments about unusual conditions or circumstances that may affect the screening;
   h. Identifying the building material, gravity load-carrying system, and seismic force-resisting system to identify the FEMA Building Type (entering the building, if possible, to facilitate this process) and circling the Basic Score on the Data Collection Form;
   i. Circling the appropriate seismic performance attribute Score Modifiers (e.g., irregularities, design date, and soil type) on the Data Collection Form;

The dimensions of structural elements, material quality and structural shape are also required for the calculation of loading and modeling of structures.

Based on the as-built drawing and observation results, a structural model will be used as the basis for performance analysis of its structure.

7. Result and discussion
Block A and Block B of Rusunawa Tegal Kamulyan at Cilacap was the case study of the investigation. The building is located at 7.89 latitude and 109.024 longitude with Spectral Acceleration Response 0.989 for a short period and 0.391 for long-period. It is, therefore, categorized in the moderately high seismicity. Table 3 and 4 show evaluation with RVS.

| No | Data | Description |
|----|------|-------------|
| 1  | Building Identification Information | address, building name, use, latitude and longitude, and site specific ground motion values, name of the screener(s), and the date and time of the screening. It is desirable to document this information during the pre-field survey. |
| 2  | Photo | Photos are taken during the survey and as much as possible to show the entire building to identify compliance with pre-field data. |
| 3  | Sketches | Sketches are obtained from as-built drawing documents and verified in the field. |
| 4  | Soil type | Soil type is stiff soil obtained from Dinas Cipta Karya Tata Ruang as building manager. |
| 5  | Building Characteristics | The building has four stories. The use of the building is for housing with 48 units per block. Total building area of 2010 m². |
| 6  | FEMA building type | FEMA building Type Based on construction documents is a Concrete frame buildings with unreinforced masonry infill walls and in accordance with survey observations. The building belongs to the C3 type of building. |
| 7  | Modifier | Severe vertical irregularity because walls of the building do not stack vertically in plan. (out of plane set back) |
Plan Irrigularity: the building is double L shaped, with projections of more than 20 feet. (Reentrant Corner);
the exterior beams do not align with the columns in plan.

| No | Final Level Score | Description |
|----|-------------------|-------------|
| 9  | Basic score C3 = 1.4; V_{L1} = -0.8; P_{L1} = -0.6; Minimum score, S_{MIN} = 0.3 |
|    | The final level 1 score, S_{L1} = Basic Score + V_{L1} + P_{L1} |
|    | Because S_{MIN} \geq S_{L1} so S_{L1} = 0.3 |

10 Coment | There are many spalling in concrete beams |
11 Action required | the score SL1 less than cut of so detailed structural evaluation required. The RVS rating system is made with the assumption that the building is built of quality materials. Damage to structural elements has a significant impact on the expected performance of a building. |

Table 4. RVS Level 2 Rusunawa Tegalkamulyan Cilacap

| No | Data | Analysis |
|----|------|----------|
| 1  | Vertical Irregularity, V_{L2} | Setback: Vertical elements of the lateral system at an upper story are outboard of those at the story below causing the diaphragm to cantilever at the offset. (Score -1) Short column: there are infill walls or adjacent floors that shorten the column. (score -0.5) Split levels: There is a split level at one of the floor levels or at the roof (score -0.5) |
|    | V_{L2} = -1-0.5-0.5 = -2 (cap at-1.3) |
|    | V_{L2} = -1.3 |
| 2  | Plan Irregularity, P_{L2} | Torsional irregularity: Lateral system does not appear relatively well distributed in plan in either or both directions. (Score -0.8) Reentrant corner: Both projections from an interior corner exceed 25% of the overall plan dimension in that direction. Score -0.4 |
|    | P_{L2} = -0.8 -0.4 = -1.2 |
| 3  | Redundancy (M) | The building has at least two bays of lateral elements on each side of the building in each direction. Score +0.3 |
|    | M = +0.3 |
| 4  | Final Level Score, SL2 | S_{L2} = S' + PL2 + M \geq S_{MIN} |
|    | S' = (S_{L1} - V_{L1} - P_{L1}) = 0.3 -(-0.8)-(-0.6) = 1.7 |
|    | S_{L2} = 1.7 + (-1.3) + (-1.2) + 0.3 = -0.5 |

A negative score implies a probability of collapse greater than 100%, which is not possible. To address this, a Minimum Score, S_{MIN}, is provided. The
Minimum Score was developed by considering the worst possible combination.

In the first tier analysis using RVS, the Rusunawa building obtained a final score of 0.3. A Final Score, S, of 0.3 implies that there is a chance of 1 in $10^{0.3}$ or 1 in 2 that the building will collapse if MCER ground motions occur. It also implies that the probability of collapse of the building is 50.12% when an earthquake of MCER takes place. Further, the risk score, SR, of the building is 1.3 means 1/$10^{1.3}$ collapse-causing earthquakes per 50 years or 1 collapse-causing earthquake per 20 building design lifetimes. It also means the probability of collapse is 5.01%.

The second tier analysis was carried out as the RVS mandated the in-depth-analysis. Pushover analysis was implemented in this level by firstly developing a model of structure (figure 2). The analysis consists of two phases. The first phase of the structure was given a gravity load which is a combination of dead load and reduced live load. The second phase of the structure is given the lateral load of monotonic incremental from the acceleration of the soil. The intensity of lateral loading in the second stage continues to increase until the weakest component of the structure deforms and then continues until the structure collapse.

The computational program repeats the analysis was obtaining several the number of elements reaching the yield. At each loading step, internal force and deformation were calculated and recorded that would produce a capacity curve (figure 3). The structural response curve was then converted into a capacity spectrum in the format of Acceleration-Displacement Response Spectrum (ADRS). This spectrum was used further to develop seismic fragility curve.

Figure 2. Structural Model
In addition to estimating the maximum force and deformation that occurs, pushover analysis can also provide information on which building elements are critical when the earthquake occurs. Pushover analysis shows the occurrence of plastic hinges at each stage of the load increase. Plastic hinge prediction that occurs in the structure according to pushover analysis shows the plastic deformation was formed from the end of the beam at the corner of the building as shown in figure 4 and Figure 5.

Figure 3. Capacity Curve

Figure 4. First Step pushover analysis
The color-coded plastic deformation and brief qualitative explanation of the damage level is recapitulated in the Table 5 as follows:

| Hinges colour | Level | explanation                                         |
|---------------|-------|-----------------------------------------------------|
|               | B     | Linear limit, the first melting occurs              |
|               | IO    | Minor damage, the stiffness of the structure is still the same |
|               | LS    | Moderate damage, reduced structure stiffness        |
|               | CP    | Severe damage, the stiffness of the structure is reduced much |
|               | C     | The maximum limit of a capable shear force          |
|               | D     | Structures in collapse                              |
|               | E     | The structure is unable to resist shear             |

The fragility curve shows the probability of certain damage to a building when it subjects to a certain intensity of the earthquake. The fragility curves are arranged by the median value and the potential hazard parameters that can be either spectral displacement and spectral acceleration representing certain damage conditions. The method used to determine the median value of the damage is HAZUS-MH MR5 [9]. For a given level of building response, fragility curves distribute damage between four physical damage states: slight, moderate, extensive and complete. Each damage state represents a range of damage to the building with the range starting from threshold.

The procedure to determine the median of spectral displacement ($S_d$, $ds$) based on nonlinear static pushover analysis results. The recapitulation of the damage state is shown in Table 6.

| Damage states | $S_d$, $ds$ (m) | $S_a$, $ds$ (g) |
|---------------|-----------------|-----------------|
| Slight        | 0.006103        | 0.1112          |
| Moderate      | 0.009155        | 0.1571          |
| Extensive     | 0.039060        | 0.5004          |
| Complete      | 0.068966        | 0.5527          |
The analysis of fragility is continued by processing four statistically structural data sets to determine the size of the data distribution by computing the standard deviation. Representing uncertainty in the analysis, incorporating standard deviation (Beta) values describe the total variability of fragility curve damage states [10] as shown in the Equation 2.

$$β_{ds} = \sqrt{[(CONV [β_C, β_D])]^2 + [β_M(ds)]^2}$$  \hspace{1cm} (2)

where:
- $β_C$ = is the lognormal standard deviation parameter that describes the total variability of damage state, $ds$,
- $β_D$ = is the lognormal standard deviation parameter that describes the variability of the demand spectrum (values of $β_D$ = 0.45 at short periods and $β_D$ = 0.50 at long periods).
- $β_M(ds)$ = is the lognormal standard deviation parameters that describe the variability of the threshold of damage state, $ds$.

**Table 7.** Lognormal standard deviation of the damage states

| Limit State | $S_a$, $ds$ (g) | $β_M(ds)$ | $β_C$ | $β_D$ | $β_{ds}$ |
|-------------|-----------------|-----------|-------|-------|----------|
| Slight      | 0.11124         | 0.4000    | 0.5178| 0.45000| 0.4765   |
| Moderate    | 0.1572371       | 0.4000    | 0.5178| 0.45000| 0.4765   |
| Extensive   | 0.4974554       | 0.4000    | 0.5178| 0.45000| 0.4765   |
| Complete    | 0.5533506       | 0.4000    | 0.5178| 0.45000| 0.4765   |

The probability relationship with various demand parameters is shown in the fragility curve (fig.6) by means of the equation 3. The parameter representing the earthquake intensity measures used in the investigation is spectral acceleration [11].

$$P (ds|S_a) = Φ\left(\frac{1}{β_{ds}}\right)ln\left(\frac{S_a}{S_{a,ds}}\right)$$  \hspace{1cm} (3)

where:
- $Φ$ = cumulative function of probability,
- $β_{ds}$ = Lognormal standard deviation of any damage condition,
- $S_a$ = spectral acceleration,
- $S_{a,ds}$ = median value of spectral acceleration when structure is damaged.
8. Conclusion
The fragility curves shown in figure 6 may be used to evaluate a seismic risk of Rusunawa Cilacap rationally by demonstrating how much probability of certain type of damage will occur when a certain level of spectral acceleration takes place in the building due to ground shaking. For instance, when the building experience acceleration of 0.3 g, then from the curve it can be inferred that there will be approximately 93% probability the building will suffer moderate and slight damage, but there is only 10% chance that building will be damaged in extensive or even complete manner. Further, if it is expected that the building experience less than 50% probability of extensive damage, then the spectral acceleration of the building should be no more than 0.46 g. By using fragility curves the decision maker and stakeholder then may have a rational basis to take action in minimizing the seismic risk prior the earthquake.

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