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Seismic Analysis and Comparison of Vertical Irregular Building Cases Using Response Spectrum Method

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Abstract - Preliminary seismic risk assessment tools are used to screen existing buildings against potential seismic hazards. Buildings that perform poorly are prioritized for detailed evaluations to determine its condition. The risk of a building can be defined as the product of Hazard, Vulnerability, and Assets. Hazard is the earthquake itself. Vulnerability are building characteristics that make it more susceptible to the hazard. Assets are elements that add value to the structure such as building population. Vertical irregularities such as soft stories are considered in assessments but is much generalized. The National Structural Code of the Philippines (NSCP) defines soft story irregularities based on the reduction of stiffness in adjacent stories. Since the study is used for an ocular preliminary risk assessment of existing buildings, the soft story definition is simplified. In the study, it is assumed that the properties and number of structural members for each story is constant. Thus, soft stories may be defined by simply determining the height of the stories. The study is also limited to a single soft story at the first story. The severity of the soft story is varied by increasing the height of the soft story. A static pushover analysis is utilized to determine the performance of the building under different irregularity conditions. The output of the study may be used to improve existing level 1 seismic risk assessments. Due to the limitations of a static pushover analysis, the study only covers low-rise buildings as permitted by the NSCP. Though it is recognized that a dynamic time history is more suitable, a pushover analysis is sufficient due to the preliminary assessment nature of the objective. The study has found that one of the primary concerns in vertical irregularities is the localization of seismic demand. For soft story buildings, the concentration of seismic demand is where the soft story is located. Data from the pushover analysis is translated into score modifiers for the varying soft story severity which may be used for preliminary risk assessment tools.

Keywords- Spectrum method, vertical irregular, Seismic Design

I. Introduction

Earthquakes are considered to be one of the most unpredictable and devastating natural hazards. Earthquakes pose multiple hazards to a community, potentially inflicting large economic, property, and population loss. One of the measures used in order to combat or reduce the devastating effects of earthquakes is through the seismic risk assessment of existing buildings.

Several procedures have been developed in order to allow communities to prevent and mitigate losses in the event of an earthquake. One such technique is assessing existing buildings to determine which buildings are safer if an earthquake is to occur. However, the amount of structures is too large and would take a significant amount of time and resources to be assessed in detail. A preliminary assessment is then introduced in order to determine which buildings should be prioritized for a detailed assessment. One such tool is the American tool FEMA154 by the Applied Technology Council and Federal Emergency Management Agency (ATC 2002) [1]. It should be emphasized that preliminary assessment procedures are merely tools for prioritization and cannot actually determine if a building is definitely safe from earthquakes.

The FEMA154 have become the model for a number of rapid visual screening tools of several countries. Canada, India, New Zealand, and several others, followed the framework of FEMA154, developing their own rapid visual screening tool for potential seismic hazards to suite local structural codes and conditions.

In preliminary seismic risk assessments, there are several parameters considered such as the soil type, seismic zoning, structural system, material type, height, irregularities, and etc. These assessment tools are widely used throughout different countries and accepted as an effective tool for risk assessment. Still, improvements to the assessment tool can still be introduced which allows it to be more refined. One such improvement that can be introduced is in the area of vertical irregularities. Vertical irregularities are basically building characteristics that demands for more complex design due to the different seismic demand experienced. An example of a vertical irregularity are buildings with soft stories. This can be further broken down into the different types of irregularities as well as their severity for a more refined assessment tool.

I.1. Pushover Analysis

Pushover analysis is one of the methods available for evaluating buildings against earthquake loads. As the name suggests, a structure is induced incrementally with a lateral loading pattern until a target displacement is reached or until the structure reaches a limit state. The structure is subjected to the load until some structural members yield [2]. The model is then modified to account for the reduced stiffness of the building and is once again applied with a lateral load until additional members yield. A base shear vs. displacement capacity curve and a plastic hinging model is produced as the end product of the analysis which gives a general idea of the behavior of the building.

Although it is acknowledged that other types of analysis such as the dynamic time-history analysis is more accurate, the preliminary assessment nature of the objective would allow a simple static pushover analysis to be used. Several studies have also utilized this type of analysis in studying irregular buildings [3, 4, 5, 6, 7]
There are several documents available that provide guidelines when performing a nonlinear static analysis (static pushover analysis). These documents offer guidelines on things such as the computation of the target displacement, and things to consider for a proper analysis such as the modelling rules. The ATC-40 document by the Applied Technology Council is followed in this study [8].

The building analyzed go through various performance levels which describes a limiting damage condition for a building. As the displacement of the building increases, so does the damage as illustrated in figure 1. The performance levels are commonly defined as follows,

- Immediate Occupancy IO: Damage is light and structure retains most of its original strength and stiffness. There may be minor cracking on the structural members.
- Life Safety LS: Substantial damage to the structure and the structure may have lost a large portion of its strength and stiffness.
- Collapse Prevention CP: Severe damage and little strength and stiffness remains. Building is unstable and is near collapse.

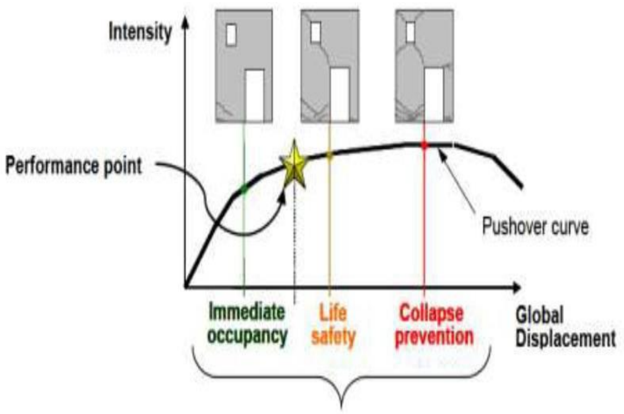

Fig. 1. Performance Levels

1.2 Response-spectrum analysis

Response-spectrum analysis (RSA) is a linear-dynamic statistical analysis method which measures the contribution from each natural mode of vibration to indicate the likely maximum seismic response of an essentially elastic structure. Response-spectrum analysis provides insight into dynamic behavior by measuring pseudo-spectral acceleration, velocity, or displacement as a function of structural period for a given time history and level of damping. It is practical to envelope response spectra such that a smooth curve represents the peak response for each realization of structural period. Response-spectrum analysis is useful for design decision-making because it relates structural type-selection to dynamic performance. Structures of shorter period experience greater acceleration, whereas those of longer period experience greater displacement. Structural performance objectives should be taken into account during preliminary design and response-spectrum analysis.RSA provides insight into how damping affects structural response. A family of response curves may be developed with variable levels of damping. As damping increases, response spectra shifts downward. The International Building Code (IBC) is based on 5% damping. This accounts for incidental damping from hysteretic behavior, which is not explicitly modeled during RSA. Viscous dampers do not affect structural stiffness, are not modeled during RSA, and are not accounted for in the IBC provision for 5% damping.

All response quantities are positive, therefore RSA is not suitable for torsional irregularity. A static lateral-load procedure is best for measuring accidental torsion. The same applies when considering uplift and compression during foundation design. Modal response may be combined using SRSS, CQC, ABS, or GMC methods. CQC is best when periods are closely spaced, with cross-correlation between mode shapes. SRSS is suitable when periods differ by more than 10%. Ritz vectors are recommended for RSA because this formulation is computationally efficient. Only pertinent mode shapes which occur in the horizontal plane are identified. Eigen vectors use the full stiffness and mass matrices, which also account for vertical modes. Eigen formulation is useful when considering floor vibration, out-of-plane vibration of shear-wall systems, etc. Eigen application is also useful for locating modelling errors.

Using SAP2000, **response-spectrum curves** may be generated from a user-defined time-history record through the following process:

- Define the time-history function through Define > Functions > Time History Menu.
- Define the time-history load case through Define > Load Cases > Add New Load Case.
- Run the time-history analysis.
- Select a fixed joint, then display the ground-motion response-spectrum curves for that joint by selecting Display > Show Response Curves, as shown in Figure 2:

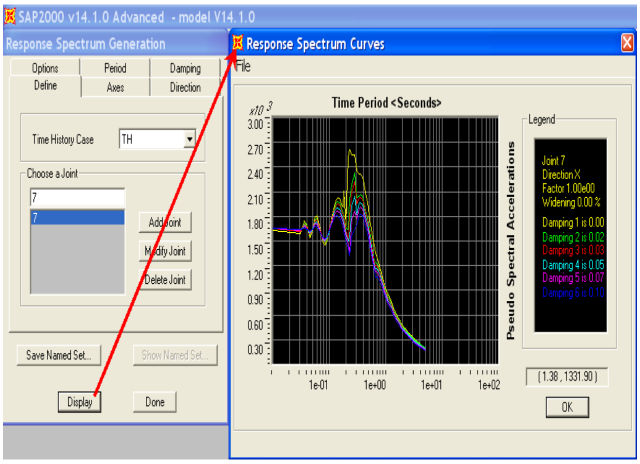

Figure 2 - Response-spectrum curves

Response-spectrum analysis (RSA) is a linear method which does not consider nonlinear assignments during formulation. Links represent another nonlinear assignment which does not affect RSA. RSA uses effective stiffness and effective damping according to the stiffness used in the corresponding modal analysis case. Stiffness may be based on zero initial conditions or that at the end of the nonlinear case. These options are shown in Figure 3:

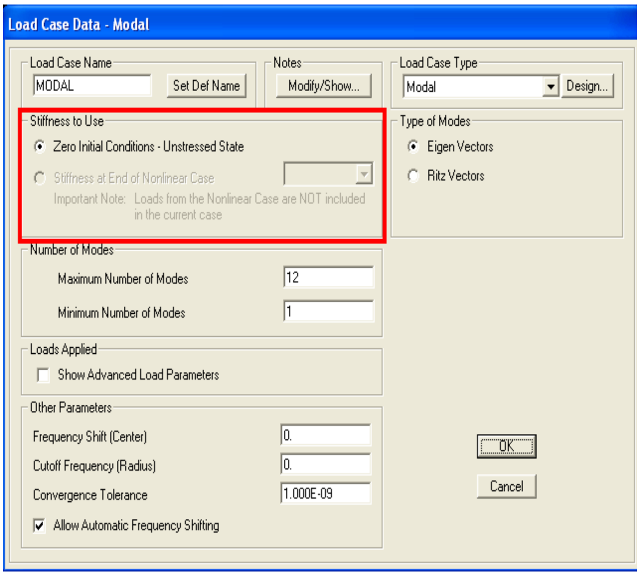

Figure 3 – Stiffness

II. Methodology

A static pushover analysis using SAP2000 was utilized in the research. Due to the NSCP code limitation in using this method of analysis, only a low-rise 5 story building was modelled [9]. A concrete frame building with 3 bays at 6 meters each is modelled. The number of bays vary in actual buildings but based on a survey of over 100 random low story buildings around Manila, Philippines, 3 bay concrete buildings are the most common. A story height of 3 meters is kept constant throughout each story and model except when the irregularity is introduced.

The model is also constructed considering code provisions as well as guidelines given by the ATC-40 document. Section sizes are determined so that it will be able to accommodate every type of model. The model is made so that the fundamental period of vibration of the building does not exceed 1.0s to ensure the first mode of vibration dominates. Other limits such as the maximum inter-story drift limit of 2.0% is also observed. Figure 2 shows the geometry of the regular building model considered.

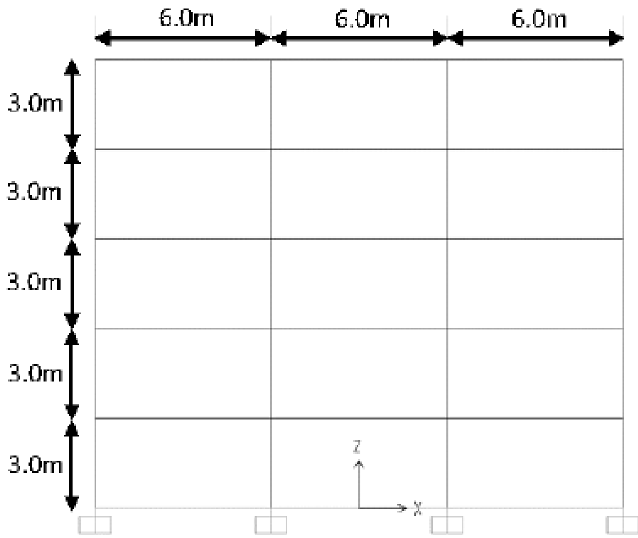

Fig. 2. Regular Building Model

Default SAP2000 hinges are used in the analysis. M3 hinges are assigned on beam ends and P M2 M3 hinges are assigned on column ends as per ATC-40 recommendations. A triangular codal type of loading is consider in the analysis wherein the loading on a story is a function of its mass and height from the ground. The model is pushed to a target displacement determined automatically by SAP2000 using ATC-40 recommendations. This target displacement is the displacement experienced by the building given the design earthquake.

There are numerous possible configurations of soft stories in a building. However, this study would only be limited to soft stories located at the first story since this is the most common case. Soft stories are determined when the stiffness of a story is less than 70 percent of an adjacent story. Since the study is used for a rapid ocular assessment, soft story indicators that can be easily assessed visually are utilized to introduce the irregularity. Two parameters that can be easily inspected through visual means are openings as well as considerably larger story heights. Since the effects of openings on the stiffness of a story is difficult quantify, only the story height is considered. It is also assumed that the number of structural members as well as its properties remain constant all through each story. Table1 shows the SR equivalent of each modified first story height. Figure 3 shows the geometry of the soft story building model.

Table 1. First Story Height (m) Soft Story Ratio Equivalence.

First Story Height	SR
3.38	1.43
3.50	1.59
4.00	2.37
4.50	3.38
5.00	4.63
5.50	6.16
6.00	8.00

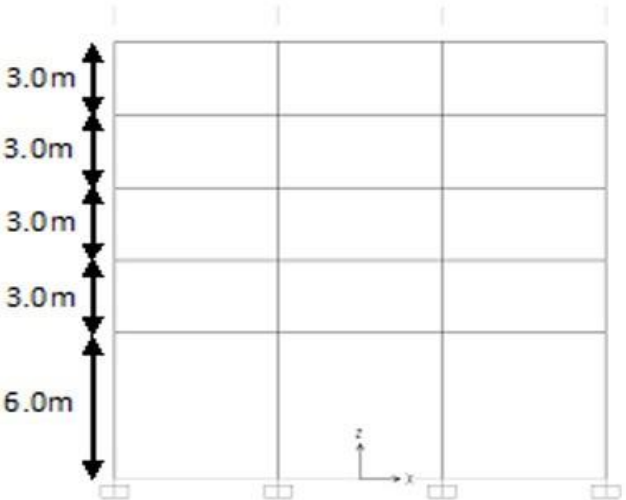

Fig. 3. Soft Story Building Model

III. Results and Discussions

The plastic hinge formation as well as the seismic design of the building is shown in the paper. The data gathered are some of the important seismic indicators in analyzing buildings. All data are gathered using SAP2000.

I.2. Plastic Hinge Formation
Plastic hinge formation is one of the primary data analyzed by researchers to identify location of the building where larger potential damage may occur. Assigned plastic hinges reach a specific hinge rotation limit and go through different damage states. ATC-40 recommends limit states but default SAP2000 hinge limits are adopted in the study. Figure 4 shows the SAP2000 color legend indicating the increasing damage severity of the hinges.

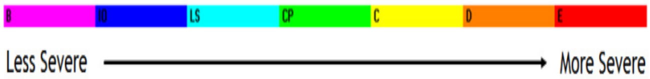

Fig. 4. Hinge Severity Legend.

I.3. Seismic Design
In the design of buildings, it is highly recommended that the geometry of the building to be regular and symmetric and for good reasons. A regular and symmetric building would likely result to a simpler design and would thus reduce the risk of errors in design. Depending on the type of irregularity, the complexity of the design increases. Although, a properly designed building should be able to withstand design forces, an irregular building increases the risk of a poor design by the engineer.

In the particular case of a soft story irregularity, the seismic demand for the first story increased. Section sizes for both regular and irregular (SR = 8.0) building were made uniform to a section of 350mm x 350mm. The regular building required a steel ratio of roughly 4.312% while the irregular building required a significantly larger amount of reinforcements to the point that it exceeds the structural codes limit of a steel ratio of 8% for columns.
Design moment for the regular and irregular structure are 160.401 KN-m and 221.713 KN-m respectively. This is a 38.22% increase in the required moment for the design. The design axial force on the other hand, was reduced from 968.429 KN to 482.247 KN for the irregular building which equates to a 50.20% decrease. Comparing the design results of the regular and irregular building, the force concentrations of the irregular building seems to be located on the long first story columns. If not designed properly, this is where local failure would most likely occur. The same conclusion can be drawn from past damage reports of buildings with a soft stories on the bottom floor.

I.4. Vulnerability Index
The vulnerability index approach was chosen instead of simply checking the individual seismic demand forces such as the moment and shear because it is less tedious. Checking for each beam and column of the building would be rather time consuming. Furthermore, simply checking the states of the plastic hinges allows any interaction among the structural members to be taken into account. ATC-40 hinge recommendations are followed.
The score modifier of each irregular building model comes down to the difference in distribution of the local vulnerability index relative to the regular building considered. The local vulnerability index of each frame of the building considered is determined using equation 5 and the distribution of the local vulnerability relative to the entire building vulnerability is determined.

It can be seen that the hinge formations are more severe. This indicates that the seismic load experienced by the irregular building is significantly greater. In can also be observed that the damage became localized on the lower frames. The damage on the upper frames are less severe. In the regular building, the 4^{th} and 5^{th} frame attained a VI_{Loc} of 0.1125 and 0.09375 respectively. While in the irregular building, the 4^{th} and 5^{th} frame VI_{Loc} of 0.0280125 and 0.0280125 respectively. While the bottom frames experienced greater damage. The first frame alone increased from 0.225 to 0.4875. A summary of all the local vulnerability indices determined for all soft story cases can be seen under table 2. Model names are notated as the height of the soft first story in meters.

The Table 3 shows the distribution of the local vulnerability indices determine through equation 5. As the irregularity increases in severity (S_R), in can be observed that an increasing percentage of the damage is observed on the soft first story. This shows that there is a concentration of hazard along the building. In the case of soft stories, the hazard is concentrated on the first story where the irregularity is located.

Table 2. Soft Story Building Local Vulnerability Indices.

Local Vulnerability Index								
Loc/Case	**Regular**	**Soft (3.4m)**	**Soft (3.5m)**	**Soft (4.0m)**	**Soft (4.5m)**	**Soft (5.0m)**	**Soft (5.5m)**	**Soft (6.0m)**
1st Frame	0.2250	0.2250	0.2250	0.2906	0.3047	0.3797	0.3047	0.4875
2nd Frame	0.1125	0.1125	0.1125	0.1125	0.1125	0.1156	0.1125	0.1500
3rd Frame	0.1125	0.1125	0.1125	0.1125	0.1125	0.1125	0.1125	0.1219
4th Frame	0.1125	0.1125	0.1125	0.0938	0.0750	0.0938	0.0750	0.0281
5th Frame	0.0938	0.0813	0.0750	0.0500	0.0281	0.0563	0.0281	0.0281
Total	0.6563	0.6438	0.6375	0.6594	0.6328	0.7578	0.6328	0.8156

Table 3. Soft Story Building Local Vulnerability Distribution

Vulnerability Index Distribution								
Loc/Case	**Regular**	**Soft (3.4)**	**Soft (3.5)**	**Soft (4.0)**	**Soft (4.5)**	**Soft (5.0)**	**Soft (5.5)**	**Soft (6.0)**
1st Frame	34.29	34.95	35.29	44.08	48.15	50.10	48.15	59.77
2nd Frame	17.14	17.48	17.65	17.06	17.78	15.26	17.78	18.39
3rd Frame	17.14	17.48	17.65	17.06	17.78	14.85	17.78	14.94
4th Frame	17.14	17.48	17.65	14.22	11.85	12.37	11.85	3.45
5th Frame	14.29	12.62	11.76	7.58	4.44	7.42	4.44	3.45

Table 4 shows the increase in the VI_D for each irregular frame relative to its respective regular frame. Equation 6 is used to determine the increase in VI_D, VI_F. Increasing the S_R shows an increase in VI_F of the first story which is also where the soft story is located. The largest VI_F indicates the increase in local hazard which in turn can be used as the basis of the score modifiers for the irregularities.

Table 5 is the proposed score modifiers which is simply based on the VI_F shown in table 3. The varying S_R is divided into three ranges which may also be categorized as low, medium, and high risk. The varying S_R is divided according to the largest VI_F for the given irregular case.

The score modifier proposed is simply multiplied to the score of a building assessed and thus increasing the priority ranking of the building. As an example, a building is given a score of 3.0 considering other parameters such as soil type and fault distance. If the building is a regular building, then its final score would be 3.0. But if the building is an irregular soft story building whose S_R is a 2.8, the scoreis multiplied by a 1.50 modifier which results to a final score of 4.50, thus making the building a higher priority. If the S_R is only a 1.6, then only a value of 1.30 needs to be multiplied to the score.

Table 4. Soft Story Building Local Vulnerability Factors.

Vulnerability Index Factor						
Regular	**Soft (3.4)**	**Soft (3.5)**	**Soft (4.0)**	**Soft (4.5)**	**Soft (5.0)**	**Soft (5.5)**
1.00	1.02	1.03	1.29	1.40	1.46	1.40
1.00	1.02	1.03	1.00	1.04	0.89	1.04
1.00	1.02	1.03	1.00	1.04	0.87	1.04
1.00	1.02	1.03	0.83	0.69	0.72	0.69
1.00	0.88	0.82	0.53	0.31	0.52	0.31

Table 5. Soft Story Building Score Modifiers.

Proposed Score Modifiers			
Risk	**Low**	**Medium**	**High**
S_R	1.4 - 2.3	2.4 - 6.0	6.1 - 8.0
Modifier	1.30	1.50	1.70

IV. Conclusion

Upon analysis of the modelling results for the soft story building, it can be seen that the main cause for soft story buildings to be more susceptible to earthquakes is the localization of seismic forces. Though the total demand on the building is smaller due to the increased height, uneven demands on the areas of the building results to a local hazard. The forces are concentrated on the segment of the building where there is a reduction in stiffness which is at the location of the soft story. This can be observed through the development of the plastic hinges, the story drift of the buildings, as well as the design. These seismic parameters show a localization of seismic demand.

The risk of the building is increased due to the increased hazards of specific areas. The increase in risk is also dependent on the amount or the severity of soft story of the building and thus the soft story irregularity modifier is further categorized to consider its severity.

It is recognized that any building that is designed properly will be able to withstand seismic excitation without incurring considerable damage. Building structural designers should take careful note of this area when designing soft story buildings.

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