DEVELOPMENT OF STATIC AND DYNAMIC MODELING APPROACHES USING FRAME MODELS FOR CITY SEISMIC RESPONSE ANALYSIS

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Abstract: Methods that can estimate the city response to seismic events are valuable tools that can assist in disaster risk reduction efforts. With the increasing availability of large computing resources, physics-based approaches that can be used for this purpose are becoming more practicable. This study aims to develop static and dynamic modeling approaches for city seismic response analysis. For both modeling approaches, tools were developed to generate and analyze models that are suitable to the available GIS and BIM data. To check the accuracy of the developed tools, validation tests were conducted by comparing with commercial software that is commonly used in structural analysis and design in the Philippines. Validations for static and dynamic analysis show that the results of the developed tools are within 6% and 8% of the results that were computed using a commercial software, respectively. These results are considered acceptable given the low computation cost per building in the developed approaches. As a demonstrative example, two cities in Metro Manila were considered for scenario earthquake analysis. Low to midrise reinforced concrete structures were analyzed and floor displacements were computed. From these results, maximum responses were obtained and visualized in city-level. Another example was conducted with the aim to compare the computed period of vibration with that of a previous study that performed experiment on a three-story building in Metro Manila. Results show that for the considered standard model of the building, the periods of vibration can be closely estimated by the developed tool.

Keywords: City seismic response analysis, finite element method, static and dynamic analysis

1. INTRODUCTION

In community disaster mitigation planning and preparation, determining the number of affected structures and the critical areas in the city for different earthquake scenarios can provide relevant inputs for resource allocation and in developing effective evacuation and recovery plan. At present, the area-based approach is commonly-used to estimate the response of different cities to earthquake scenarios. This approach combines data on hazard, exposure, and vulnerability, through maps and pre-computed vulnerability and fragility curves (Bautista et al., 2011). Because most of the data are processed from validated exposure information and recorded damage, the approach is considered empirical and reliable for damage estimation. However, extending the applicability of this approach to model the dynamic behavior of individual structures is difficult, because area-based approach is not fully-developed to account for the influence of geometry, material properties, and site conditions. An alternative approach is to analyze the response of individual buildings in the city, as in the simulation-based approach (Hori et al., 2018).

Simulation-based approach aims to estimate the overall response of a city to an earthquake scenario by combining the peak responses of individual buildings. Its reliability in estimation relies on taking into account the effect of each building's geometry and material properties to its dynamic response. One advantage of this approach is that multiple analysis can be performed to study the variability in response given the variability in material properties or input loading. This results to a large database of responses which can be used in assessing the structural integrity of buildings following an earthquake event.

A major challenge in using simulation-based modeling for seismic response of cities is the significant computer resource that may be required to process and store information. There are many related studies using available data, such as GIS data to generate analysis models (Homma et al., 2014; Fujita, et al. 2015, Quinay & Ichimura, 2016, Quinay et al., 2018). These studies show that even with the use of GIS data, with lower resolution compared to building drawings, there is still a need to develop in-house tools to manage the computation, especially for the analysis of large cities. Thus, it still remains a challenge to use building drawings as models for use in city seismic analysis.

This study aims to develop a computationally-efficient approach for city seismic response analysis. Two modeling approaches are proposed: static and dynamic modeling. The static modeling approach aims to provide a means for rapid estimation of building's response from calculated base shear due to the seismic demand. The dynamic modeling approach aims to determine the dynamic properties, such as natural period of vibration of the building. For both modeling approaches, tools were developed to generate and analyze models suitable to the available GIS and BIM data. The tools were also implemented with computing techniques to anticipate the large computation cost of analyzing up to thousand structures in the target city.

2. THE STATIC AND DYNAMIC MODELING APPROACHES

In numerical modeling, the resolution of available data can limit the accuracy of the analysis model that can be generated. For city seismic response analysis, it is important to tailor the modeling approaches according to the available data. In the case of Metro Manila, GIS data are widely available, but digitized engineering drawings are relatively few.

2.1 Static Modeling Approach

The static modeling approach aims to provide a means for rapid estimation of building's response due to the seismic demand. For this purpose, the required level of detail of the analysis models is generally not high, and the widely-available GIS data may be used. The GIS data considered here have resolutions as fine as in the order of a meter. This resolution is fine enough to describe the shape of the building footprint. Together with available height information, the three-dimensional geometry of the structure can be approximated, including details, such as the number of floor levels, or building type. In the approach developed in this study (see Figure 1), template models – each representing particular building types in the target area, are generated. The template models are generated as BIM models, where details in geometry and material properties may be easily inputted. BIM is used here to anticipate the wide availability of BIM for building structures in Metro Manila in the future. A tool was developed to automatically generate frame models from the BIM template models (Fader & Quinay, 2018). The frame models are composed of line elements with six-nodal degrees of freedom. Frame models are fixed at the base (ground level), and the horizontal force loading, representing earthquake loading, are computed from base shear that are redistributed to floor levels. The results of the static analysis are displacements and story drifts, which can be compared to threshold values to classify the structure as requiring further analysis.

2.2 Dynamic Modeling Approach

The dynamic modeling approach aims to determine the dynamic properties, such as natural period of vibration of the building. Because of the demand for higher resolution models in this approach, it is suited for building models with available structural details, such as engineering drawings (see Figure 2). For this approach, a three-dimensional solid finite element model is generated and dynamic analysis is performed using a time-varying input. In this analysis, it is expected that there is a significant jump in the computation cost, and it is important to introduce computational techniques in order to realize the computation in practical time.

The model generation follows the finite element mesh generation approach of Ichimura et al. (2007) wherein the mesh of tetrahedron and hexahedron elements are placed strategically in the model to generate high accuracy in modeling complicated geometries while reducing the computation cost. This is achieved by using the octree technique and multiresolution grid. In their approach, the model's three-dimensional geometry is already defined before the meshing procedure. In this study, the mesh and geometry are fixed at the same time, and instead, uses a level set approach to combine and trim elements to generate the desired cross sections (Carangan, 2018; Carangan & Quinay, 2018).

For the dynamic analysis, the displacement, $\boldsymbol{u}^{n+1}$ at time, {*n+1*} is solved using the Equation (1):

$$\left(\boldsymbol{K} + \frac{2}{\Delta t}\boldsymbol{C} + \frac{4}{\Delta t^2}\boldsymbol{M}\right)\boldsymbol{u}^{n+1} = \left(\frac{2}{\Delta t}\boldsymbol{C} + \frac{4}{\Delta t^2}\boldsymbol{M}\right)\boldsymbol{u}^{n} + \left(\boldsymbol{C} + \frac{4}{\Delta t}\boldsymbol{M}\right)\dot{\boldsymbol{u}}^{n} + \boldsymbol{M}\ddot{\boldsymbol{u}}^{n} + \boldsymbol{f}^{n+1} \qquad (1)$$

where, $\boldsymbol{K}, \boldsymbol{M}, \boldsymbol{C}$ are the stiffness, mass, and damping matrices. The vectors $\{\boldsymbol{u}\}$, $\{\dot{\boldsymbol{u}}\}$, $\{\ddot{\boldsymbol{u}}\}$ and $\{\boldsymbol{f}\}$ refer to the displacement, velocity, acceleration, and external force vectors, respectively. Δt is the time increment and n is the time step. The boundary conditions are time-varying displacements inputted at the bottom of the model. Viscous absorbing boundaries were placed at the bottom and side surface of the soil part of the model to truncate the infinite domain.

2.3 Implemented computational techniques

All developed tools were coded in low-level programming languages (C and Fortran). The computations were designed wherein the building data can be partitioned according to the number of available processors. To achieve this, distributed-memory approach through Message Passing Interface (MPI) was implemented. Thus, all model generation (line and solid elements), analysis, and postprocessing, are done in parallel. A simple partitioning of building model data based on the number of nodes was used to reduce the imbalance in computation load for each processor, and also to achieve almost the same runtime.

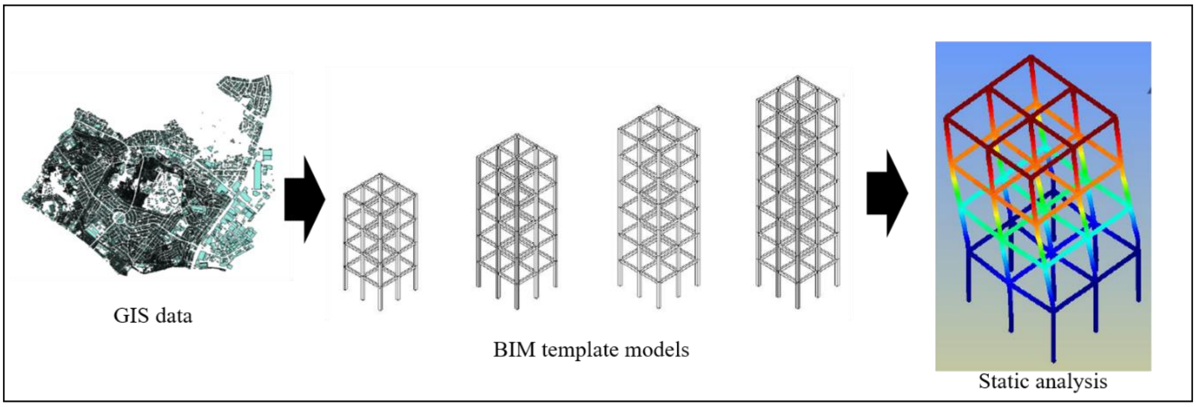

Figure 1. Procedure for the static modeling approach

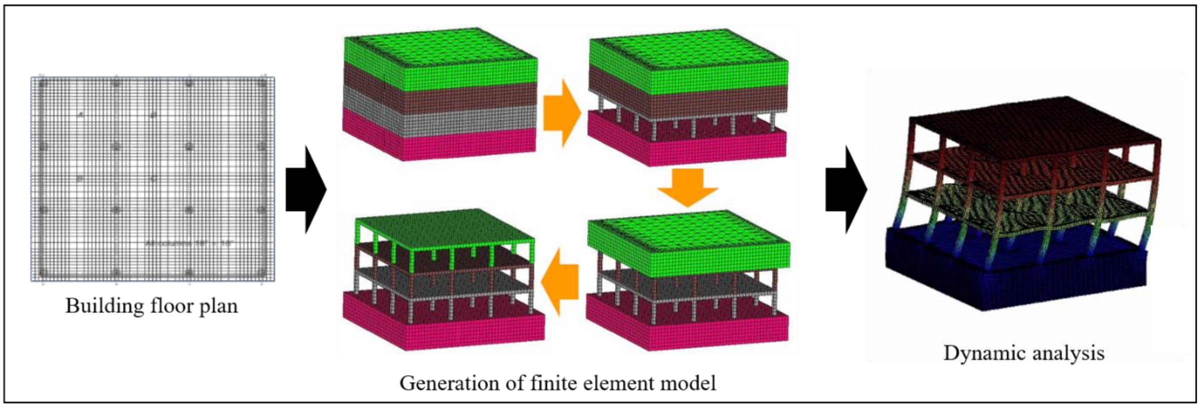

Figure 2. Procedure for the dynamic modeling approach

3. VALIDATION OF GENERATED ANALYSIS MODELS

Validation of the models generated by static analysis code was conducted by comparing the resulting displacement with that of a commercial software (CS) used for structural analysis and design. For the load settings, the static earthquake loads used in CS and FEM are the same. Figure 3 shows the displacements and deformed shape of the models. For a 5-story structure, the difference in the displacement values, with respect to CS results, ranged from 0.20 – 5.73% for the top-floor nodes.

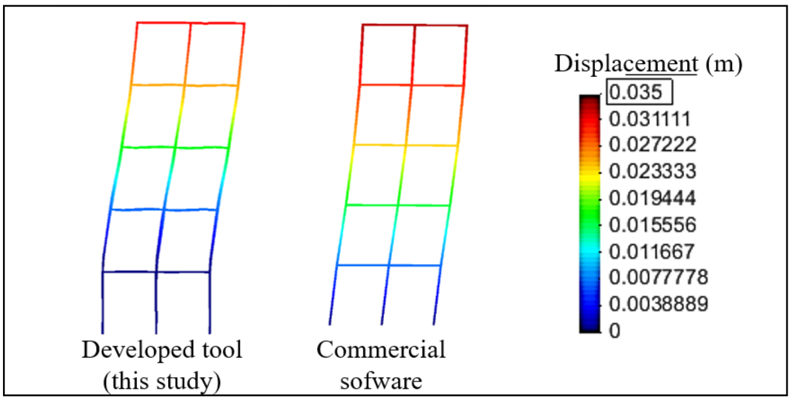

Figure 3. Comparison of results of static analysis code developed in this study and commercial structural analysis software

Validation for the developed dynamic analysis code was also conducted by comparing the results for the displacement (in frequency domain) between the code and CS. The same input dimensions and material (concrete) was set. Multiple cases with input loadings of Ricker wavelets of increasing center frequency were conducted. The time-varying displacement results are then postprocessed by Fast Fourier Transform to determine the amplitude-frequency distribution corresponding to each loading case.

Figure 4 shows the analysis models and a comparison of a nodal response at the top floor. The graph shows the results after inputting a Ricker wavelet with 1.1 Hz center frequency. Red line is the response of the 3D model generated by this study, and the black line is the response of the CS model. In all the tests, the obtained maximum relative difference of results is 7.91%.

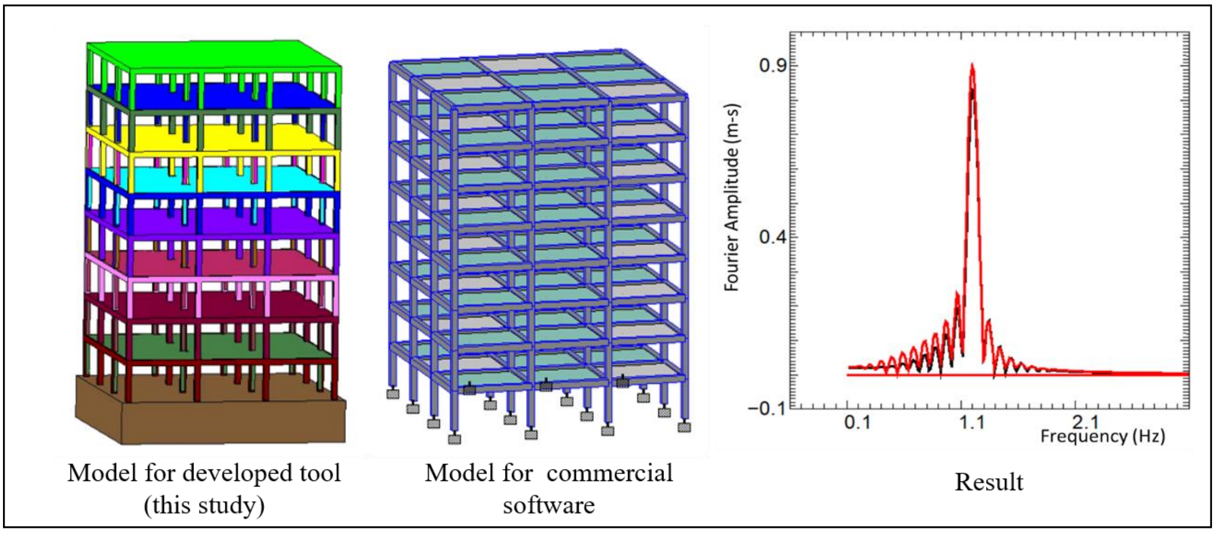

Figure 4. Analysis models and comparison of results of dynamic analysis code developed in this study and commercial software (CS) (red line is computed by this study while black line is computed by CS).

4. DEMONSTRATIVE EXAMPLES

Two cities in Metropolitan Manila were considered for a scenario earthquake analysis. A Mw 7.2 hypothetical earthquake was set to compute for the input seismic load for each building model. For this study, only low- to mid-rise concrete structures in the city were considered. Table 1 shows distribution of this building material type with varying floor levels in the two cities. City 1 has a total of 3,036 structures, while City 2 has 924. For generating the analysis models, we used the information from GIS dataset output of GMMA READY Project 2013. Templates of building models corresponding to those present in the GIS data were generated. To compute for the input floor horizontal loading, we used the NSCP 2015 static force procedure. An important parameter in determining the lateral load is the natural period of the building. The magnitude of the floor loading includes the selfweight of the structure as well as superimposed loadings.

Figure 5 shows the results of the analysis. For City 1, the obtained maximum displacement is about 6 cm. While for City 2, the maximum is about 3 cm. Post computations show that the frame models exhibited higher displacements and story drifts with increasing floor height. Moreover, as shown for City 1, there are clustering of buildings that obtained displacements ranging from 1.5 cm to 3 cm. Whereas, in City 2, buildings with similar displacements are more scattered throughout the whole city.

Table 1. Distribution of building floor levels of the two cities

No. of floors	No. of buildings	
	City1	City 2
2	2,209	838
3	559	72
4	192	13
5	60	0
6	16	1

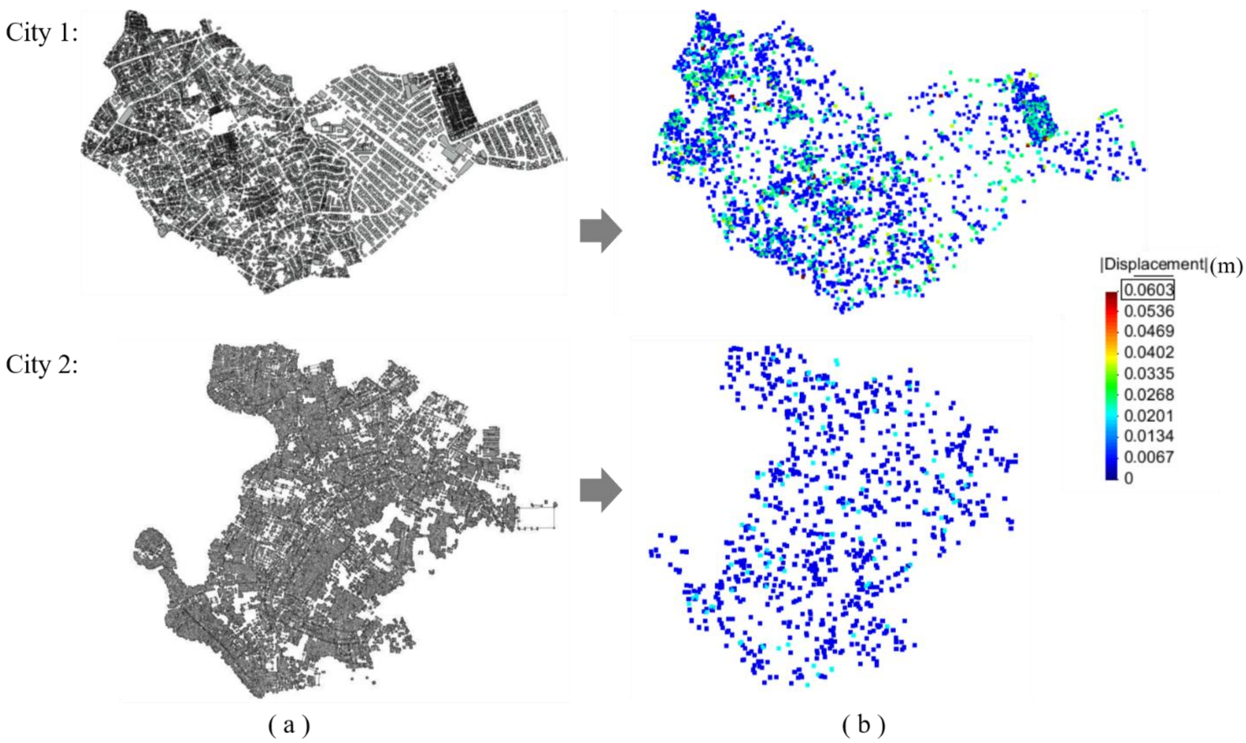

Figure 5. Result of scenario earthquake modeling: (a) visualized raw GIS data ; (b) generated building models and response to the scenario earthquake

To check the applicability of the developed dynamic analysis code, a three-story school building in Metro Manila, which was previously instrumented for a study in determining the period of vibration (Kubo et al., 2004), was considered for analysis. Given the standard floor plan and structural design, the analysis model (structure and soil) was constructed (see Figure 6). The model was subjected to multiple inputs of Ricker wavelets of increasing center frequency. Table 2 shows the comparison of the period derived from experiment and computed in this study. As shown, the obtained period for the longitudinal direction closely matched with that of the experiment. However, in the case of the transverse direction, there is a large difference (33.8%), which is attributed to possible inconsistencies in material properties and member geometries of the analysis model and the constructed building. Since the model generated in this study is based on the standard design for that particular building type, the actual settings of the building as constructed in the field remains to be further verified.

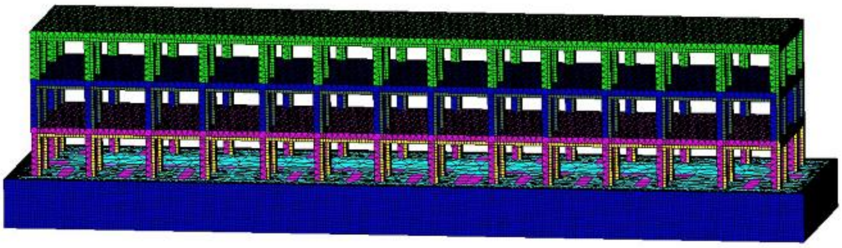

Figure 6. The finite element model of the thee-story building used for validation test of dynamic analysis code

Table 2. Periods derived from experiment and computed in this study

Direction	Experiment (s) (Kubo et al., 2004)	Computed (s) (This study)	Difference (%)
Longitudinal	0.24	0.22	6.2
Transverse	0.15	0.20	33.8

5. CONCLUSIONS

This study aimed to develop static and dynamic modeling approaches for city seismic response analysis. For both modeling approaches, tools were developed to generate and analyze models applicable to the available GIS and BIM data.

To check the accuracy of the developed tools, validation tests were conducted wherein the results obtained from these tools were compared with those of commercial software that are commonly used in structural analysis and design. Validations for static and dynamic analysis show that the results of the developed tools are within 6% and 8% of the results that were computed using a commercial structural analysis and design software, respectively.

As a demonstrative example, two cities in Metro Manila were considered for scenario earthquake analysis. Low- to mid-rise reinforced concrete frame structures were analyzed and floor displacements were computed. From the results, maximum story drifts were computed, and visualized in city-level to compare the responses of the two cities. Another example conducted was on the computation of the period of vibrations of a three-story building in Metro Manila. Results show that for the considered standard model of a three-story building, the periods of vibration can be closely estimated.

The developed modeling approaches are continuously being improved to be capable in handling the computation of other structure types, such as tall buildings with dual systems, hybrid, and makeshift structures that are local to Metro Manila cities. Moreover, with many buildings in the cities that are now being installed with sensors for health monitoring, the recorded data can be used to validate the analysis models.

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