Development of Building-Specific Approach to City Seismic Response Analysis for Metro Manila

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Abstract – *Information on the expected variability of maximum responses of buildings in cities of Metro Manila in the event of a strong earthquake can aid in disaster preparedness. A way to obtain such information is to combine the responses of individual buildings as influenced by different material properties and input ground motion. This study aims to develop a building-specific approach to city seismic response analysis for Metro Manila. Tools were developed for the tasks of processing feature data from GIS datasets, generation of building-specific input ground motion, automated MDOF model generation and analysis, and postprocessing of results. Input ground motion for each model was generated using the parameters, earthquake magnitude, distance to epicenter, and site/soil conditions. As an application example, a scenario earthquake analysis was conducted for five cities in Metro Manila considering C1-L, C1-M and C4-H building types (a total of 264,625 models). Results show that C1-M types for the city with Site Class D and located nearest to the fault obtained the highest mean and standard deviation of maximum story drift. Comparing the five cities, cities situated in Site Class D obtained higher mean of maximum story drift in all building types than in cities situated in Site Class C. The visualization of spatial distribution of buildings with varying story drifts allows for verifying the derived statistical information, as well as for direct comparison of the response of cities. Analysis of computation costs shows that for this application example, 6.5 hours of runtime (if running in single processor), 650 GB disk usage, and 50 GB of memory were required to simulate a scenario for a total duration of 18.4 seconds. These figures were estimated to be only 18% of the total cost if the whole Metro Manila is to be analyzed for one scenario earthquake using the building-specific approach.*

Keywords—building-specific approach, city seismic response analysis, large scale computing

I. INTRODUCTION

In the Philippines, many areas with dense population and businesses are located close to identified active faults. Some of these areas are even situated in soil types which may amplify ground shaking in the event of an earthquake. An example is Metro Manila, which is close to active faults and has varying soil types. In disaster preparation for its cities for expected strong earthquakes, information related to the number, type, and severity of damage to buildings are important. However, it is a challenge to account for the wide variability in building parameters, such as material properties, vintage, and structural design code used, in addition to local soil types and distance from faults. To aid the stakeholders, the Philippine Institute of Volcanology and Seismology (PHIVOLCS), guided by its in-house-developed tool, Rapid Earthquake Damage Assessment System, or REDAS software, developed an area-based approach which combines hazard information, exposure information, and fragility curves derived from historical and simulated data of damage [1]. This approach aims to quantify the distribution of damaged states per building type which are mapped per area defined by political boundaries.

With the availability of moderate class computers with multi-core processors and high memory, the simulation-based approach [2,3,4,5] is an emerging viable option. This approach uses concepts in mechanics of materials, numerical methods, and computing techniques to simulate the processes related to dynamic response of crust, soil, and building structures. This approach accounts for individual building's geometric and local material properties, thus leads to building-specific dynamic analysis to output maximum story drift (a parameter that is related to damage levels). An example of tools that applies this approach is the Integrated Earthquake Simulation (or IES) [2] program, which generates a virtual city and performs simulation of structure dynamic response among other disaster-related processes (such as earthquake wave propagation, tsunami inundation analysis, and agent evacuation simulation). Recently, Hori et al. [6] identified two main problems in application of IES for structure response analysis: (1) requirement of large computation; and (2) requirement of numerous analysis models for structures.

In application to seismic response analysis for cities of Metro Manila, employing building-specific approach gives several advantages. First, the dynamic analysis should be able to model the variability of resulting maximum story drift as influenced by varying material type, vintage, soil types, and distance from the fault. Second, its results (in the form of time-varying or peak values), which are obtained in all models, can be further processed to be used as inputs in other disaster mitigation studies such as: locating early response equipment, analysis of lifeline infrastructure and road network, and simulation of evacuation plans for a given earthquake scenario. Third, since results for building models can be visually represented in virtual city, effective communication to non-technical stakeholders can be achieved.

This study aims to develop a building-specific approach to city seismic response analysis for Metro Manila. We note that the general tasks used here are similar to those used by related simulation-based studies [3,4,5], although there are differences in terms of methods used for generation of shape models, input ground motion, and postprocessing, to account for the available data and local settings. Tools were developed for the tasks with consideration of large input and output data. The approach is then applied to scenario earthquake analysis of five cities in Metro Manila.

II. BUILDING-SPECIFIC APPROACH

The simplest model that can be used to simulate the dynamic behavior of buildings, specifically its first mode of vibration, is the single-degree-of-freedom model. For buildings with multiple stories, multi-degree-of-freedom (MDOF) model is often the choice, from which multiple modes of vibration can be considered. For these models, the required parameters are mass, stiffness, and damping, which can be used to compute for the fundamental period of vibration. For typical structures, the National Structural Code of the Philippines 2015 [7] also provides methods to estimate the fundamental period of vibration (see NSCP 2015 Section 208.5.2.2). Thus, using the three-dimensional (3D) shape and material property of a building, it is possible to estimate these parameters to generate the MDOF model per building.

The GMMA READY Project [8] is a hazard mapping project for community-based disaster risk management. One output of the project is a high resolution GIS dataset for Greater Metro Manila. The dataset contains features representing built structures, where each feature is characterized by a polygon with nodal coordinates and a corresponding elevation. The datasets were processed by PHIVOLCS to check the quality of features to define building footprints and heights. Because the features cover all building types of interest and capture regular and irregular shape of building footprint to as fine as 1.0-meter resolution, we used this dataset in this study for generating the 3D shape models from which the MDOF models will be derived. We note that this target resolution is the same as with the datasets used in related simulation-based studies [3,4,5], although in these studies the points used to generate the 3D shape models were generated from land-based surveys.

A toolset was then developed for this approach to perform the following tasks (see Figure 1): (1) processing the feature data points to generate the 3D shape models, (2) generating input ground motions, (3) MDOF model generation and analysis, and (4) postprocessing of results of each model. Each task processes the individual inputs and outputs of each model. Due to expected large computation cost in each task, the codes were developed in low level programming languages (C++ and Fortran), and computing techniques, such as data partitioning and parallel computing were implemented.

As shown in Figure 1, the main inputs are parameters that are known to influence the dynamic response of crust, soil and building structures. The main outputs are displacements and story drifts which can be used for estimation of damage.

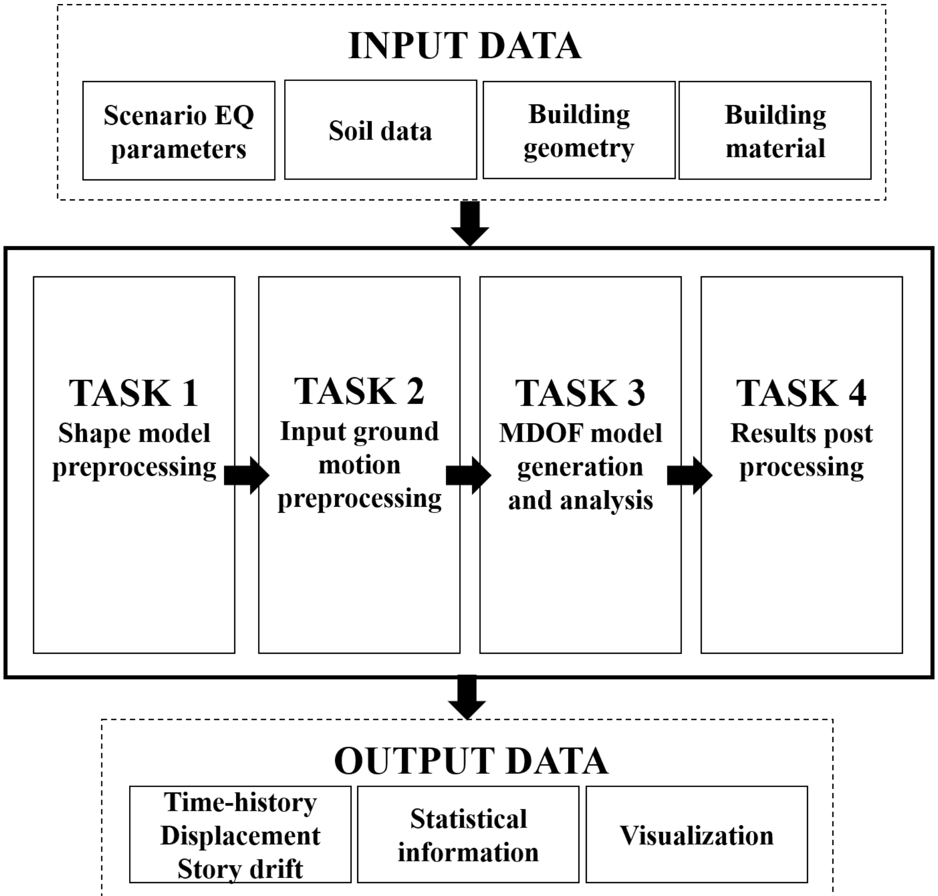

Figure 1. Main input and output data and the tasks related to the building-specific approach

In the first task, features were filtered according to the target building types to be analyzed. The latitude and longitude coordinates of nodal points describing the building footprints were converted to local coordinates, and building heights were computed from elevations. This task also includes partitioning of features to the number of available processors for parallel computing. The 3D shape model of a building is then generated, by first, dividing the height by a set floor-to-floor distance to mark the floor levels, and then, extruding the points of the features (representing building footprints) from the base up to the top floor level. As mentioned, this 3D shape model will be used to generate the MDOF model. In the second task synthetic ground motions for each building are generated. The main inputs for this task are the earthquake parameters and site/soil data. To compute the distance of a building to the source, the geometric centroid of building footprint is computed and measured from the epicenter. For the soil data, a lookup table of Vs30 values is used and the NEHRP site class [9] is then selected. For generating acceleration time-history data, a stochastic ground motion estimation tool based on Specific Barrier Model [10] is used. Mendoza and Tingatinga [11] earlier studied the calibration of this model for generating synthetic ground motions in the West Valley Fault. In the third task, the IES program [2] is called to generate the MDOF model from the 3D shape model, and then perform MDOF analysis using the input acceleration data. Here, the building types that follow the building typologies listed in [12] are set. In the fourth task, all data are gathered to a single folder where statistical information from building shape model (types, number of stories), time-history displacement, and story drift results are outputted. Visualization of models and results in virtual city is also included in this task.

III. APPLICATION EXAMPLE

The developed building-specific approach was applied to five cities in Metro Manila. These cities were selected to represent cities with different building types, local soil types and distance from the source. Table 1 lists the five cities with different setting of NEHRP Site Class. For setting the Site Class, we used the Vs30 data by Grutas and Yamanaka [13]. For reference, the average distances to the epicenter are also listed. For all cities, we considered only low- to high-rise structures for analysis, i.e. buildings with up to 15 floor levels. We also assumed that these buildings are composed of reinforced concrete material, and were designed as either moment-resisting frames (for buildings with 7 floor levels or less) or with shear walls (for buildings with 8 to 15 floor levels).

For the seismic event, we chose a hypothetical earthquake with epicenter along the West Valley Fault. Table 2 shows the main parameters for this earthquake. For each building model, two components (east-west, north-south) of acceleration with time interval of about 0.0045 second and total time steps of 4,096 were generated.

Table 1. Model Settings for Each City

City	NEHRP Site Class	Average distance from Epicenter (km)	Number of building models per type		
			C1-L	C1-M	C4-H
1	C	7.56	56,120	7,727	46
2	D	10.52	91,812	23,160	384
3	C	10.99	39,260	6,999	182
4	D	11.23	8,451	475	0
5	D	15.08	25,772	4,176	61

In running IES, MDOF models were grouped according to the following building types: C1-L: number of floor levels ranging from 1 to 2; C1-M: number of floor levels ranging from 3 to 7; and C4-H: number of floor levels ranging from 8 to 15. Each city was then analyzed for 4,096 time steps (a total duration of 18.4 seconds) using the input ground motion data. The outputs were the displacement and story drift of each node of the model per time step. From the computed maximum values, mean and standard deviation were computed for each building type and city.

Table 2. Parameters for the scenario earthquake in the application example

Parameter:	Value:
Epicentral Coordinates	(14.64798°, 121.0852°)
Depth	4 km
Magnitude, M_w	7.2

Figure 2 shows the building models in the five cities and the distribution of maximum story drift. Buildings in Cities 1 and 3, with setting of NEHRP site class C, showed relatively lower maximum story drift than the other three cities. City 2 obtained the highest number of models with high story drifts, followed by City 5, and then City 4. In Cities 2 and 5 the buildings with high story drift are distributed in almost all areas.

Figure 3 shows the mean and standard deviation (SD) of story drifts grouped according to building type. In all cities, C1-M type obtained the highest mean and SD. C1-L and C4-H types obtained close mean values, but C4-H has slightly lower SD. From these results it can be deduced that for buildings designed as moment-resisting frames (C1-L and C1-M), higher floors result to higher drifts. Buildings with shear walls (C4-H) are stiffer and result to low drifts. Comparing per city, Cities 1 and 3 obtained lower story drift values than other cities, in all building types, confirming the results shown in Figure 2. The computed SD are also slightly lower. Among all the cities, City 2 obtained the highest mean and SD. This is due to the city having the highest number of C1-M type buildings among all cities, a NEHRP site class corresponding to low Vs30, and close distance to the epicenter (relative to Cities 4 and 5). For Cities 2, 4, 5 with NEHRP site class D, the closer distance to the epicenter resulted to higher story drifts. For stiff buildings in Cities 1 and 3 with NEHRP site class C (C1-L and C4-H types), this parameter had no significant effect.

Tables 3, 4, and 5 show the computation cost of the demonstrative example. Table 3 is related to inputs. The total number of building models and setting of file partitions per city resulted to maximum of 15,000 building models per file (initial test runs showed that this number resulted MDOF models that costs about 2 GB of memory usage per processor). The generated shape models result to small file sizes. Relative to this, input ground motion files (generated in the third task) are much larger, which is due to multiplier of time step size. Table 4 is related to outputs, and shows that the combined displacement and story drifts per time step, and visualization files resulted to a significant disk usage (about 650 Gigabytes). Table 5 shows the computation time and memory cost. The total runtime of the five cities was about 6.5 hours if running using a single processor. The required memory was about 50 GB. Depending on the number of building models and discretization of shape models to MDOF models, the required computation time and memory may increase significantly, as shown for the case of City 2.

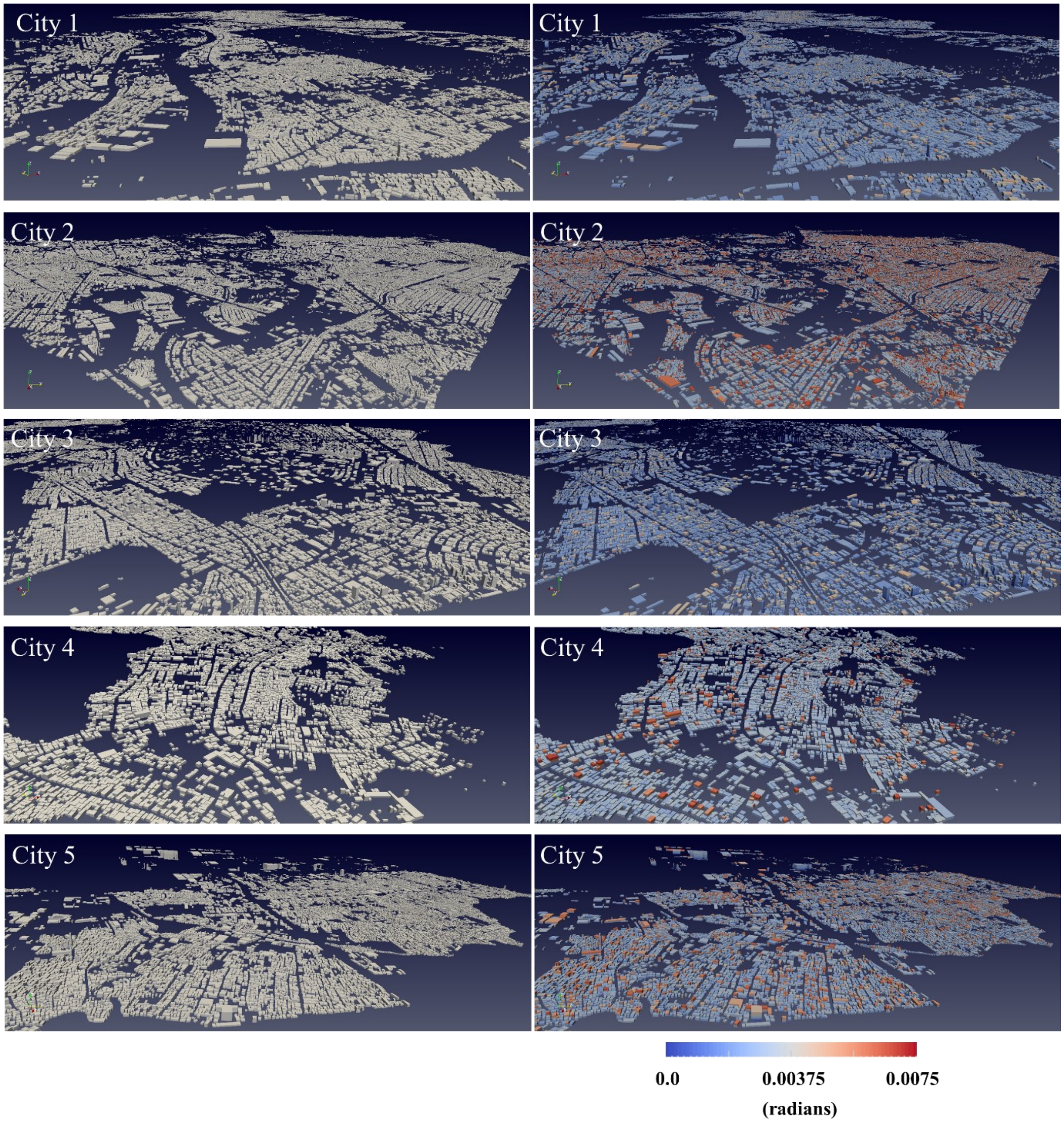

Figure 2 Visualization of each city: (left) distribution of building models; (right) distribution of maximum story drift of building models

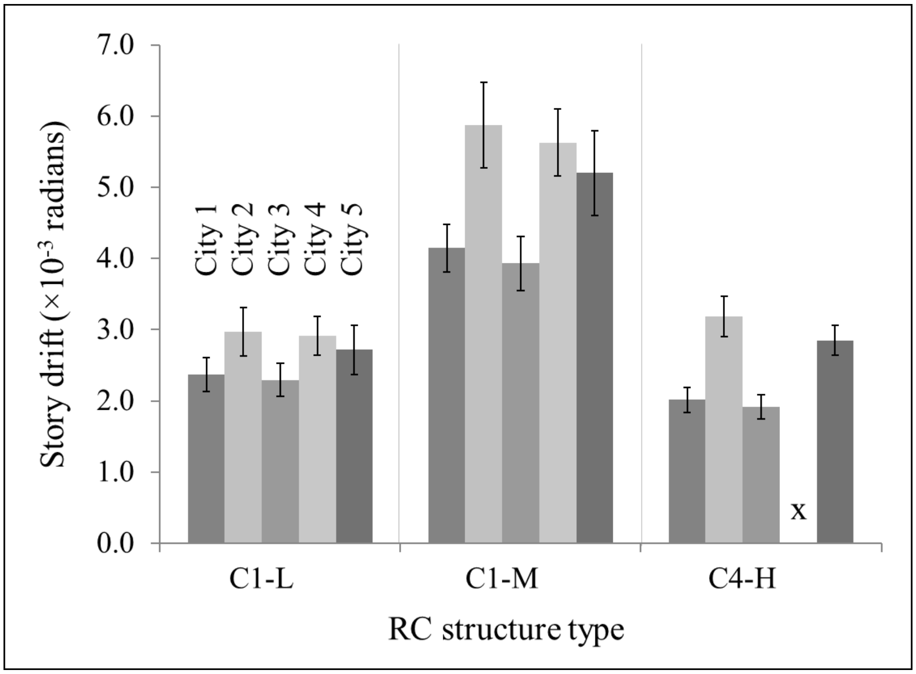

Figure 3 Mean and standard deviation of story drift values of different RC building types (symbol "×" means "No data" for that city)

Table 3. Cities and corresponding input data and disk usage

City	Total number of building models	Number of file partitions	Total size of all shape files (MB)	Total size of ground motion input file (GB)
1	63,893	5	2.89	3.19
2	115,356	8	4.65	5.51
3	46,441	4	2.07	2.26
4	8,926	1	0.35	0.43
5	30,009	4	1.25	1.45

Table 4. Cities and corresponding output data for 4,096 time steps

City	Total size of displacement and story drift results (in binary format) (GB)	Size of visualization data (in .vtk format) (GB)
1	7.98	139.26
2	14.84	263.37
3	6.10	105.27
4	1.01	17.20
5	3.71	64.31

Table 5. Cities and computation time in running tasks 2 and 3 for 4,096 time steps

City	Computation time in running task 2 using 8 processors* (minutes)	Computation time in running task 3 using 8 processors* (minutes)	Total memory cost in running task 3* (GB)
1	1.8	3.76	12.42
2	4.0	41.13	20.54
3	1.5	2.74	8.96
4	0.3	0.56	1.79
5	1.0	1.78	5.89

* Using computer with processor Intel Xeon CPU E31245 3.30GHz and 16GB RAM

With these results, it is of interest to estimate the required computation cost of applying the building-specific approach to all cities (and 1 municipality) of Metro Manila. Using the GIS dataset for each city, tasks related to 3D shape model generation were ran. The total number of generated models reached 1.46 million. Given that the number of building models analyzed in the demonstrative example is only 18% of this number, it can be estimated that the computation costs listed in Tables 3, 4, and 5, are expected to increase by up to 5.5 times. For this computational requirement, running the tasks in a large parallel computing environment, such as in DOST-ASTI CoARE HPC, is more suitable.

IV. CONCLUSION

This study described the development of building-specific approach to city seismic response analysis. Tools were developed for input data processing, fault-to-surface ground motion estimation, structure dynamic analysis, and postprocessing. The required inputs are parameters that are known to influence the dynamic response of soil and building structures. The main outputs are displacements and story drifts that are needed to analyze the variability of response of the different buildings in a city, and are used for damage estimation.

As an application example, low to high-rise building models of five cities in Metro Manila were analyzed for a scenario earthquake. The results show that the variation in story-drifts of buildings in a city depends on the different settings of site/soil condition, design (as either as moment-resisting frame or with shear walls), and distance to epicenter. The visualization of spatial distribution of buildings with varying story drifts allows for verifying the derived statistical information, as well as for direct comparison of the response of cities.

A way to improve the accuracy of the results of this approach is to use more realistic data of building geometry. Thus, current works are focused on improving the tools for the analysis of more complicated building types and configurations (as examples: generating shape models from engineering drawings in BIM format, and using 3D FEM models - see [14,15,16]). With the current available data (GIS data) to construct 3D shape models, the applicability of the approach is limited to providing preliminary inputs for detailed city response estimation, such as for identifying the buildings to be further analyzed in-depth using more sophisticated analysis tools. It is expected that by using the results for this purpose, there will be significant reduction in total computation cost than by using sophisticated analysis tool for all buildings in the city.

Lastly, the building-specific approach may offer opportunity for engineers, who have extensive experience in structural analysis and design, to be involved the local disaster risk reduction efforts by cooperating on how to generate reliable and efficient analysis models for specific target problems.

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