Estimating Damage Caused by Natural Hazards for the Insurance Industry in Puerto Rico

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Insurance companies have a pressing need to refine their estimates of expected damage in earthquakes, hurricanes and floods. The University, which needs financial support for its investigations on the resistance of structures subjected to natural hazards, has the expertise to help the insurance industry assess expected losses. The two needs came together at the University of Puerto Rico at Mayagüez (UPRM) Department of Civil Engineering as part of a project funded by the Insurance Commissioner of Puerto Rico (ICPR). This paper is an overview of the project, which includes earthquake hazard estimates, evaluation of expected performance of concrete and steel structures subjected to earthquakes and strong winds, flood resistance studies and alternative design and repair method studies.

Introduction

The insurance industry is a complex system for which engineers and other professionals make decisions about construction costs, risks and damage evaluations. Many people involved in this business do not have any formal education in the technicalities of structures or in natural hazards and their consequences. Academic researchers usually write for their peers, making it difficult for those without formal science or engineering education to understand research results. In this project, research has the end user in mind, so that information can be transferred, understood and used for practical tasks in insurance activities.

The Insurance Commissioner requested UPRM to develop a structured system to support the main insurance business stakeholders. The risks considered relate to natural hazards (hurricanes, earthquakes and floods) in typical scenarios affecting property on the island. The project encompasses the development of tools to assess risk within a framework defined by the ICPR and the insurance firms, and is organized in such areas as seismic risk and design; building performance in earthquakes and hurricanes, vulnerability of construction under wind and seismic excitation, building costs, and flood damage. Another area compiles information generated by the project to be used to calculate maximum probable loss.

Ground Motion and Liquefaction Potential Evaluation for Puerto Rico's Main Cities

Puerto Rico, located within the tectonically active zone between the North American and Caribbean plates, is recognized as having a significant seismic hazard, evidenced by the hundreds of moderate (M 4 to 5) events recorded in the last 30 years. Since the early Spanish settlements in the 16th century, at least five strong earthquakes have struck the island –1670 (M≈6), 1787 (M≈7.3), 1867 (M≈7.3), 1918 (M≈7.3), and 1943 (M≈7.5)– causing loss of life and significant property damage. The 1918 earthquake reportedly induced liquefaction in western Puerto Rico, killing at least 114 people and causing about $114 million in damage. The consequences of a future earthquake could be even worse, as the majority of the population of four million lives in coastal areas susceptible to liquefaction and tsunamis.

Despite the high seismic risk, research to adequately assess and mitigate the earthquake hazard in Puerto Rico lags behind other seismically active regions of the US, particularly in quantification of expected ground motion and liquefaction susceptibility for major cities. The UPRM project attempts to address this gap. The Ground Motion and Liquefaction sub-project involves compiling a geotechnical database of available borehole information, SPT and CPT data and groundwater information, complemented with shear wave velocity profiles from geophysical tests, where available.

This project develops the island's first geotechnical database of superficial soils in Puerto Rico's main cities: San Juan, Ponce, Mayagüez, Arecibo, Humacao and Caguas. Existing geotechnical boring, water well log data, geophysical test results, and geological information for each of these cities were solicited from public and private sources. The resulting database is the first step in the process to estimate design ground motion and to develop earthquake soil amplification maps. All the information is stored using ARC-GIS software. Figure 1 shows the geotechnical boreholes for the city of Mayagüez.

A liquefaction susceptibility study is then conducted for each city and liquefaction susceptibility maps prepared. These used the cyclic stress ratios determined using the site-specific geotechnical data coupled with the 1998 NCEER recommendations for the simplified liquefaction procedure originally proposed by Seed and Idriss in 1971. (Figure 2 presents the Mayagüez liquefaction susceptibility study.) These results may assist policy makers and the engineering design community to prepare for future seismic events in Puerto Rico.

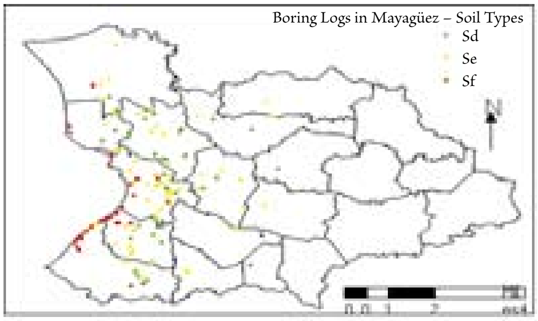


Figure 1: Boring logs in the city of Mayagüez.

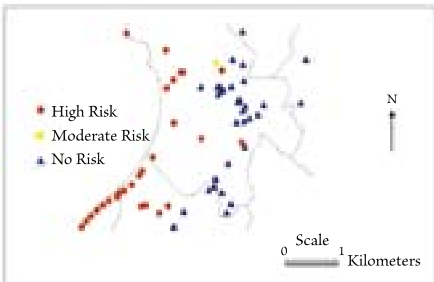


Figure 2: Liquefaction susceptibility study for the city of Mayagüez.

Parameters Affecting Earthquake Resistance

This project provides information necessary to estimate expected damage in buildings subjected to strong ground motion. The researchers attempt to determine the influence of typical structural features on earthquake resistance of both existing and new structures of reinforced concrete or steel.

From existing literature, buildings are preliminarily classified as residential, hotel, commercial, hospital, school, or industrial. Existing structure data compiled within each classification determines which geometric and structural parameters show more variation. Data from field studies and ARPE plans identify reasonable variations in the observed parameters, and are used to establish properties of typical structures. Using examples of typical existing buildings, normal parameter ranges for floor height, beam span, beam depth, element dimensions, site effect and others are established for particular categories. Elastic analyses, assuming cracked sections, are performed to obtain the calculated inter-story drifts for buildings subjected to design ground motions. Using the drifts, estimates of structural damage can be obtained using Algan's equations. Other parameters such as columns shortened by adjacent masonry walls and flexible stories are handled separately. Currently, typical reinforced one- and two-story concrete houses made of beams and columns or walls have been analyzed. Medium-rise buildings are under study to determine building period and expected drifts.

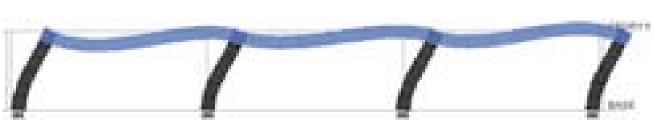


Figure 3

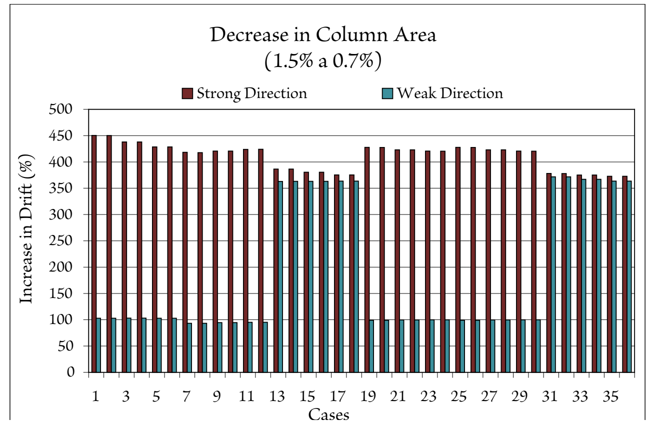


Figure 4

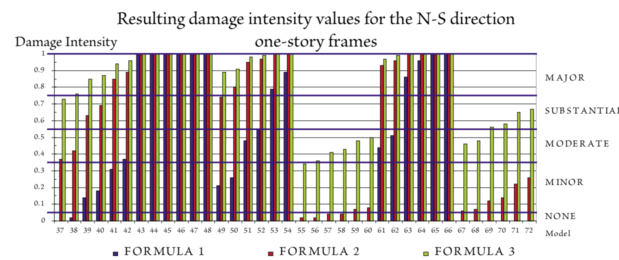


Figure 5

The following parameter variations were studied: Soil types C, D and E according to UBC 97; geometry in plan of rectangular layout (2:1, 1:1); column area as percentage of floor area (0.7%, 1.5%); column orientation (NS, EW, distributed); and roof height (8', 10', 12'). Roof lateral displacement and drift were obtained from the elastic analysis of models subjected to spectral earthquake loads. Figure 3 shows the displaced shape of a typical three-span frame. The most influential parameters of the response were column area, column orientation, and roof height. An example is the Figure 4 graph, showing the increase in drift with the decrease in column area for the different models.

The Figure 5 graph uses a damage intensity scale from 0 to 1, in which 1 represents total damage, 0.75 is substantial damage, 0.55 is moderate damage, 0.35 is minor damage, and 0.05 is no damage. The method provides for structural damage (formula 1, nonstructural damage of normal elements of, and nonstructural damage of, elements sensitive to lateral displacements).

Damage to Industrial Construction from Hurricanes

Research on the vulnerability of construction in Puerto Rico to hurricanes has been restricted in this project to a few building types: low-rise industrial buildings and multistory buildings with six floors or more. Insurance companies find it difficult to estimate policy costs for such buildings, which can be the source of large claims after a hurricane. Insurance companies avoid insuring wooden structures, and the cost of claims from concrete dwellings is not a real concern for them.

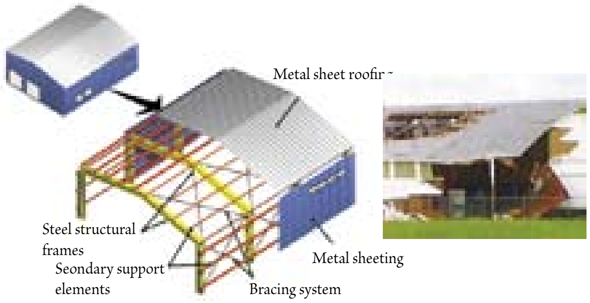


Figure 6: (a) Elements of industrial buildings considered in this research. (b) Example of failure in industrial building due to a hurricane.

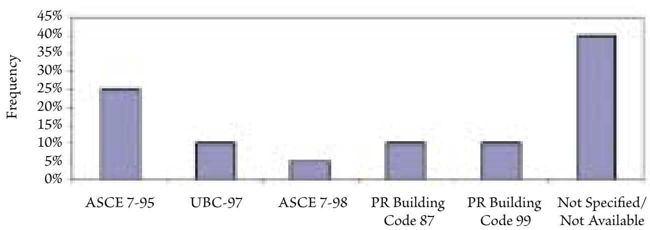


Figure 7: Wind design codes used for the industrial buildings in the project database

Figure 6 (a) shows a schematic representation of a low-rise industrial building. The large exposure surfaces to wind in this type of building constitute the primary difference from other construction.

During hurricanes, industrial buildings may experience several different forms of failure, including buckling of the roof or sidewall panels, pull-out of connections between the panels and the main resisting frame, and failure of connections between the columns and the foundation. An example of failure due to hurricanes is shown in Figure 6 (b). Although models and tools for structural analysis and design codes are already available, it is the risk estimates for such structures that the insurance industry requires. The two ingredients needed are 1) the probability of occurrence of hurricanes with given intensities (which are derived from recurrence studies) and 2) frequency of the different types of industrial buildings (which are derived from inventories).

Because no inventories are available in Puerto Rico for industrial buildings (or for other building types), part of the research was devoted to developing a small inventory. Construction plans were obtained with the help of ARPE (Administración de Reglamentos y Permisos de Puerto Rico). Of 20 projects reviewed, 17 were designed after 1999. Of primary interest are the identification of the structure, wind design procedures used (codes used), parameters required to estimate wind loads, and construction procedures used. Figure 7 shows an example of wind information used in the designs.

Failure modes such as buckling of the roof or sidewalls are computed during the project using finite element analysis. Examples of these are shown in Figure 8. Details are given in López and Godoy (2005) for the buckling of several panel configurations.

Finally, information about the mean return period of hurricanes for Puerto Rico was used. For example, contours of maximum wind speed for a 100-year return period are shown in Figure 9. The studies support the assumption that just one zone can be considered for the island because changes in expected events from zone to zone are small.

The information collected or produced as part of the research is currently used to generate fragility curves for each type of construction considered.

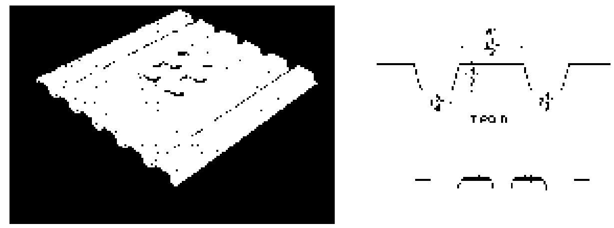


Figure 8: Buckling mode for type B cold-formed folded plate for wind pressures (From López and Godoy, 2005).

Figure 9: Contours of maximum wind speed for 100 year return period.

Experimental Study of the Earthquake Vulnerability of Typical Residences

Resistance to earthquakes of existing structures is of particular importance to insurance companies in Puerto Rico. A large number of residences (of one and two stories) are constructed with reinforced concrete walls oriented longitudinally and masonry walls, transversally (see Figure 10). Since no information was available on the resistance of these structures in the weak direction, five structures were constructed to represent typical residences with typical details that emphasize: the connection between the footing and reinforced concrete/masonry wall, horizontal and vertical reinforcement of the concrete/masonry wall, and the connection between the roof and reinforced concrete/masonry wall. Figure 11 shows the typical construction details of the specimens in this project. Tests establish capacities along the weak axis. Figure 12 illustrates the failure mechanism observed during the tests of the first two specimens; Figure 13 shows the preliminary experimental results obtained during the tests of these two specimens.

As it can be seen, the lateral capacity of the specimens increases significantly when a concrete block wall is included inside the frame. Preliminary computations show that without the concrete block wall, the overall lateral capacity of the house will be less than the lateral demand produced for this type of structure during an earthquake.

Figure 10. Typical construction of residences

Figure 11. Construction of the specimens in the UPRM Structural Laboratory

Figure 12. Failure mechanisms of the first two specimens tested: (a) joint failure of specimen 1 (without concrete block wall), (b) concrete wall failure of specimen 2 (with concrete block wall).

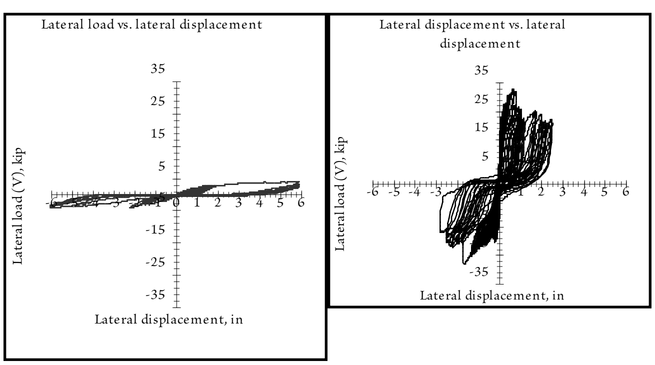


Figure 13. Preliminary experimental results of the first two specimens. (a) specimen without masonry concrete wall. (b) specimen with concrete block wall.

Elastic Design of Reinforced Concrete Buildings

Puerto Rico's building codes incorporated modern seismic provisions in 1987. In other locations buildings designed without these provisions have been severely damaged or suffered moderate damage of structural elements and severe damage of elements considered as non-structural, but that might impair the use of the building. Others designed under current code regulations have also suffered severe damage or even collapse during an earthquake event. Current building codes allow cracking and yielding of structures in a large earthquake, but prevent collapse. However, such cracks, yielding and lateral deformation may affect the immediate and future use of the building, which could be at serious risk for structural failure.

Many structures, such as hospitals, special government agencies or schools used as shelters must be in full service during and after a major natural event such as a hurricane or an earthquake. Buildings are designed to resist elastically the forces produced by the maximum wind velocity specified for a region; however, the forces induced by the maximum earthquake specified for the region are usually much stronger than the wind forces. Designing the building to resist earthquake forces elastically could represent a large increase in construction costs.

Many hospitals and schools designed before the 1987 Puerto Rico building code revisions were designed for gravity loads, wind loads and moderate earthquakes, and do not satisfy modern seismic codes. Attention is now on retrofitting to improve seismic performance, and on proposing new regulations in the code so that structures of this type can perform elastically during an earthquake event.

This paper presents part of the research at the UPRM of seismic performance of buildings designated as full-service, directed at developing regulations to enforce the use elastic forces in the design of these structures. As part of this process, typical buildings are modeled to study their behavior under earthquake code elastic forces, so that strengthening can be recommended where needed. Detailed cost estimates are prepared to determine the cost of retrofitting after construction versus adding structural elements before construction.

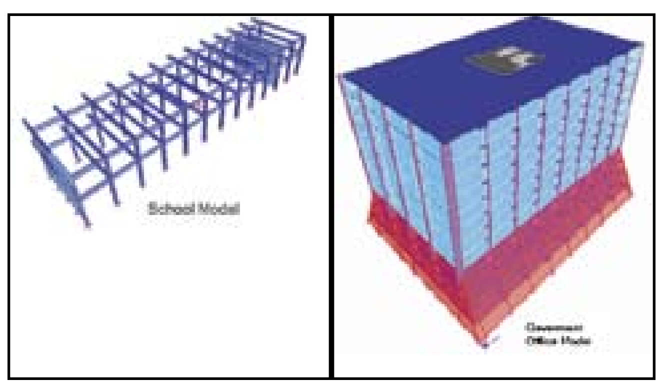


Figure 14: (a) School Model. (b) Model of Government Office Building.

The investigation involves preparing a complete structural model of each building using the information from construction drawings; analysis of the existing structure using the elastic forces obtained from the code requirements with a reduced ductility factor of R=2; design verification of the structural elements, including the foundation, to determine adequacy; analysis of the proposed structure with the addition of structural elements to comply with the new forces; determination of the cost estimate of the new elements, including the foundation, and determination of percentage of increase relative to the total cost estimate; determination of the cost estimate of the new elements to be incorporated in the existing structure, including demolition, sequence of construction and foundations.

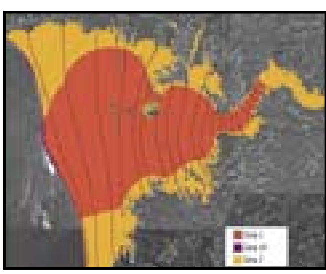
Two models have been completed, the school building model and the government office building. The hospital building is in the modeling process.

Flood Effects on Structures

Flood actions may directly, cause damage or even structural failure of buildings. Flood action analysis allows more accurate estimates of potential flood events and effects, clearing up many current uncertainties.

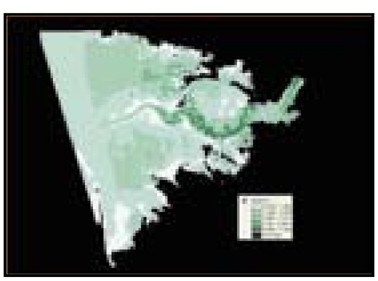
The main objectives of flood research are to estimate the vulnerability of buildings and building elements due to riverine and coastal floods, and to determine the probable maximum loss due to catastrophic flood events.

The main methodology focuses on the development of various algorithms to identify and select spatial flood risks based on flood insurance maps. Flood levels and velocities are identified and flood depths are generated.



a. FIRM

b. Topography



c. Flood Depth

Figure 15: Flood Level Generated from FIRM and Topographic Maps

The structural components of buildings are identified and characterized at specific flood sites. The structural failure of the building elements are analyzed for the resistance of materials, structural elements, and connections. The failure modes are analyzed and selected by comparing the resistance of structural materials and the resistance of the connections. The magnitude of the forces are compared with the resistance of the structural elements and connections in buildings in order to estimate building vulnerability.

Five action stresses will be considered which are caused by hydrostatics, hydrodynamics, waves, buoyancy, debris impact, and soil scour.

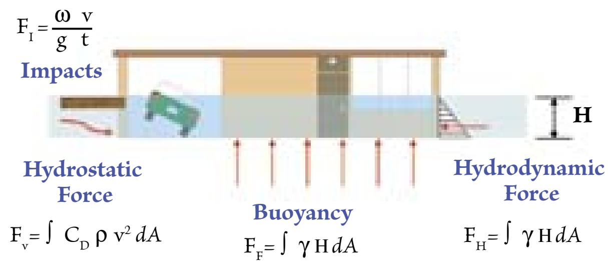


Figure 16: Flood loads acting on a building

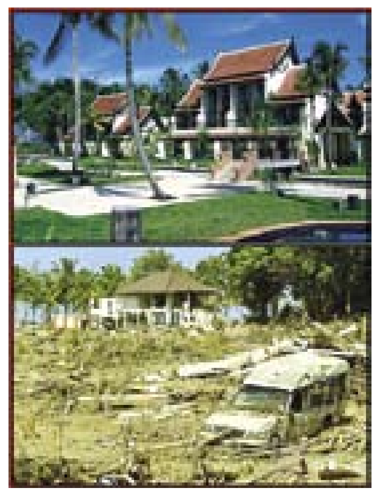


Figure 17: Flood devastation

Cost Estimates of Construction for Puerto Rico

Two components make up maximum probable loss: the loss model and the cost estimate. Since the structures damaged by a natural disaster are repaired or rebuilt, the cost estimate must be directed towards a structure's repair or reconstruction cost. A survey was made among contractors, designers and owners to obtain Puerto Rico cost data, which was categorized according to the classification shown in Table 3.

Central tendency measures, percentiles and variation coefficients were obtained from the classified information and compared with data from: *Building Construction Cost Data*, *National Building Cost Manual*, and *Bids Construction Report*. Factors were estimated to adjust the national average costs from these publications to the costs indicated by our survey.

A cost index was developed to provide a means of updating the results without having to completely redo the survey. To update the index, a smaller survey is made of the principal cost components identified in our survey, including labor and materials. Since it is not practical to include all labor and material items involved in construction projects as part of the index, categories with the highest costs were selected. The labor component in the index includes the amount paid to carpenters, rodmen, masons, and labor, while the material component includes the cost of large quantities of concrete, reinforcing steel, ceramic floors, and cement.

The costs from the survey combined with the adjustment method that could be used in the future provide an estimate of current construction cost. Previous studies (R.S.Means, 2002, Guzmán 1998) have developed a relationship between current construction costs and repair and reconstruction cost of structures. A literature review of these studies was made and factors were estimated to convert current construction costs to repair or reconstruction costs of structures. The factor for repairing structures is 1.89 and the factor for replacement of structures is 1.13, meaning that the repair cost estimate is the cost estimate based on current cost multiplied by 1.89. Similarly, the repair cost estimate is the cost estimate based on current costs multiplied by 1.13.

Classification	Use
Commercial	Bank
	Care center for the elderly
	Hotel
	Office
	Retail sales
Educational	School
	Classrooms
	University
Parking	Individual
	As part of a project
Residential	Apartments > 3 stories
	Apartments (walkup)
	One-family house
Industrial	Treatment plant
	Utility building
	Manufacturing
Other	Basketball court (school)
	Community center
Repair	School
	Hotel

Table 1: Cost Categories.

Detailed information and survey results are found in Botero (2004).

Integrating Insurance Solutions

The structural, geotechnical, and socio-economic components of the Puerto Rico Insurance Project were discussed in previous sections. Integrating the results from those components in an intuitive, multi-level insurance solution software required consultation with various user groups, a process still underway at this writing, thus this section provides only an overview of the first generation software, not the final product.

Figure 18: Interface Menu.

Structure menus provide selection options within residential, commercial, institutional and industrial use groups. The selection is aided by photographs depicting various building types. Three levels of input in each section provide for varied levels of user expertise. Figure 20 shows first-level menus for two residential types. The wide use of metal roofs in Puerto Rico, which is not limited to wood-zinc houses, and the practice of building houses on gravity columns are reflected in these two menus. Calculations for first level input are based on fragility curves developed by the structural groups. The second level option uses simplified response analysis algorithms to improve on the first level predictions. The third level option is for engineers only, and requires detailed structural input. The last two levels are not available for all building classes. Buildings with high insurance values are likely candidates for a more refined analysis.

The Policy option deals with liability issues resulting from the actual versus the insured values of structures. The Analysis menus provide event-driven financial analysis options for earthquakes, floods, and hurricanes. The life cycle cost analysis is also available under this option. The cost parameters from the previously reported surveys are used in these calculations. The Report menus generate risk analysis summaries in user specified formats to be used as part of an insurance document.

There are a number of computer programs available today estimating potential losses from disasters. Of those, HAZUS, developed by the Federal Emergency Management Agency, is the most well known. By design, these programs focus on regional losses, providing a big picture approach. In developing the Insurance Solutions program, the focus was shifted to individual buildings. Although the user will still have the option of analyzing his entire inventory for various event scenarios, the emphasis on small components is where the strength of this program lies.

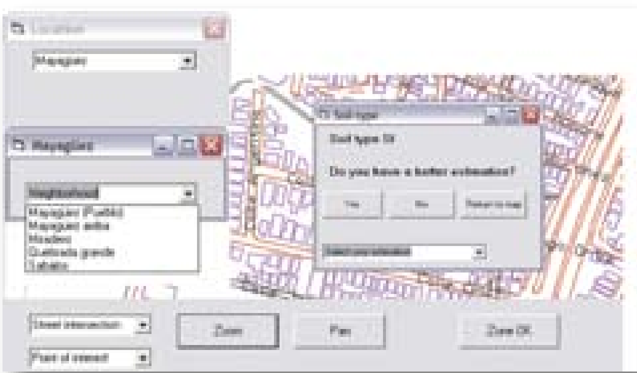


Figure 19: Location Menus.

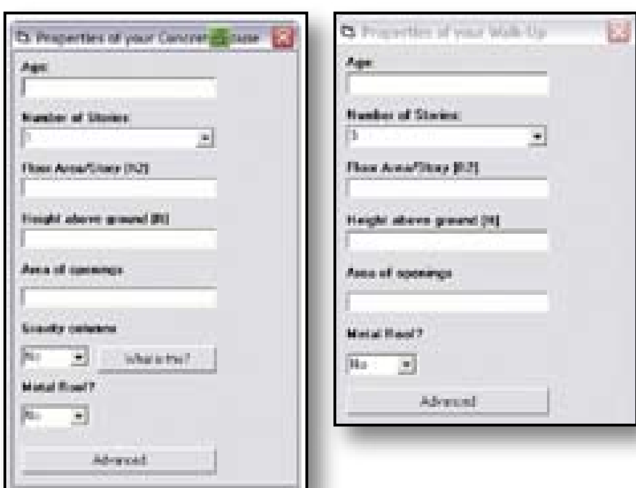


Figure 20: Sample building classification menus.

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