DEVELOPING A GLOBAL BUILDING INVENTORY FOR EARTHQUAKE LOSS ASSESSMENT AND RISK MANAGEMENT

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ABSTRACT :

We discuss the development of a global database of building inventories for pre-earthquake risk analysis and for use in near-real-time post-earthquake loss estimation for the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) system. On a country-by-country level, the inventory contains estimates of building types categorized by material, lateral force-resisting system, use, and occupancy characteristics. The database draws on and harmonizes numerous sources: (1) UN statistics, (2) UN Habitat, (3) national housing censuses, (4) the World Housing Encyclopedia and (5) other pertinent literature.

KEYWORDS: Casualty Estimation; Building Inventory

1. INTRODUCTION

Rapid earthquake impact assessment capabilities can be used to inform planning and response decisions, to mitigate the disastrous impact after an earthquake, and to potentially save human lives through better coordinated response efforts. The U.S. Geological Survey's (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) system already produces ShakeMaps shortly after all global earthquakes ($M > 5.5$), and is now adding rapid loss-estimation capabilities (Wald et al., 2008). PAGER in its present form provides rapid estimation of human exposure to severe ground shaking which forms a critical input for its users to understand the possible impact of an earthquake. Yet, the impact of an earthquake in terms of human casualties is largely dependent on performance of the regional building stock and the occupancy rates at the time of earthquake. For example, multistory, precast-concrete framed buildings caused heavy casualties in the 1988 Spitak, Armenia earthquake (Bertero, 1989); adobe/mud construction in Bam was responsible for more than 80% of the casualties during the Bam, Iran earthquake in 2003 (Kuwata et al., 2005); weaker masonry and reinforced-concrete framed construction designed for gravity loads with soft first stories dominated losses in the Bhuj, India earthquake of 2001 (Madabhushi and Haigh, 2005), and adobe and weak masonry dwellings in Peru controlled the death toll in the Peru earthquake of 2007 (Taucer et al., 2007). Clearly, the presence of vulnerable building stocks in the affected regions is likely to be responsible for future earthquake casualties and it remains a primary societal concern. However, despite of these hard learnt lessons around the globe and bleaker future trends (Bilham, 2004), there are no comprehensive efforts globally for developing building inventories of sufficient quality and coverage to adequately address characterize future earthquake losses. In fact, limitations to inventory data generally have significant impact on other aspects of earthquake loss and risk estimation analyses (ATC, 1985; Coburn and Spence, 1992; Bommer et al., 2002; Steimen et al., 2004; FEMA, 2006). Such an inventory is vital, both for earthquake loss mitigation as well as for earthquake disaster response purposes. While rapid post-earthquake loss estimation is the primary motivation of this work, we hope that the global building inventory database described herein will find widespread use for pre-disaster mitigation efforts as well.

Various inventory data do exist. Shakhramanian (2000) discusses an effort by EMERCOM of the Russian Federation to develop the global loss modeling software 'Extremum'. It includes a global inventory that characterizes building stocks according to seismic resistance, but the software, its underlying data, and the means to compile them are unavailable for public use or scrutiny. The inventory data needs of PAGER have a much wider geographic scope than required in previous studies. We have performed a short but intensive search to document i) what data exist internationally pertaining to the nature of the building stock, ii) process of data development and its coverage, and iii) sources of information from which the data may be gathered. Owing to paucity of data globally, buildings have been broadly classified into residential and nonresidential types based on functional use. The methodology consists of the identification of data sources; attribute mapping, quality assessment and rating, synthesis of data, and where necessary, the assignment of inventory distributions to the countries lacking data. Our approach employs a structure type category system that combines FEMA 356 (FEMA, 1998, ASCE, 2000), EERI's World Housing Encyclopedia (2007), and EMS-98 (European Seismic Commission Working Group on Macroseismic Scales, 1998). The first source addresses most engineered construction in the developed world. The World Housing Encyclopedia provides resolution of various categories of unreinforced masonry. The EMS-98 system deals with European structure types that do not appear in the US. It also includes a quality assignment (low, medium, high) and data vintage, to acknowledge varying confidence in the available data and our interpretation of it. Some of the potential candidates identified for PAGER building inventory database development are i) the housing data compiled by the statistical agency of the United Nations (UN, 1993); ii) data on durable housing compiled by UN Habitat (2007) based on the Demographic and Health Survey (DHS); iii) data compiled by Population and Housing Censuses of individual countries (UN, 2005); iv) the World Housing Encyclopedia (WHE) database developed by the Earthquake Engineering Research Institute (EERI, 2007); and v) country-specific published literature (e.g., post-earthquake reconnaissance surveys, reports/research articles on earthquake loss estimation studies). As shown in Table 1, a high rating reflects data compiled from engineering or telephonic surveys, field visits for ground-truth, or data compilations from local engineering experts; medium rating refers to data compiled by general field surveys and assignments not based on engineering standards; low rating refers to data compiled by non-engineering agencies that are not specifically meant for engineering risk analysis.

Table 1. Summary of data sources and parameters associated with their quality and coverage.

Sr. No.	Source of Data	Building Stock	Quality	Global Coverage and Rating
1.	**World Housing Encyclopedia** (EERI 2007)	**1. Residential:** a. Construction type b. Occupancy	 High Medium	110 residential construction types in 37 countries developed by EERI's World Housing Encyclopedia (WHE). Overall medium rating assigned to the data obtained from this source.
2.	**UN Database**	**1. Residential:** a. Construction type b. Occupancy	 Medium Low	44 countries with construction type description based on external walls and type of housing units. About 110 countries with average occupancy estimated based on total building stock. Overall low rating assigned to the data obtained from this source.
3.	**Census of Housing**	**1. Residential:** a. Construction type b. Occupancy **2. Non-residential:** a. Construction type b. Occupancy	 Medium Low Medium Low	197 countries conducted housing census in 1990. Most of the Census surveys do not include information about non-residential building inventory. Overall medium rating assigned to the data obtained from this source.
4.	**Published Literature**	**1. Residential:** a. Construction type b. Occupancy **2. Non-residential:** a. Construction type b. Occupancy	 High Low Medium Medium	About 10 countries have been identified that contain high quality information e.g., research articles and reports. Overall high rating assigned to the data obtained from this source.
5.	**PAGER-WHE Project**	**1. Residential:** a. Construction type b. Occupancy **2. Non-residential:** a. Construction type b. Occupancy	 High Medium High Medium	To date, a database of more than 25 countries has been compiled by an expert judgment survey followed by review of database by EERI. Overall high rating assigned to the data obtained from this source.

2. METHODOLOGY

We performed a short but intensive search to understand what building stock data exist internationally and understand how the data were gathered and what sources were used. Among the different databases, housing type data were most commonly available from official census agencies of a country which provide country level distribution of housing units by predominant construction material (Figure 1). The description of construction material such as metal, brick, block or concrete, provides useful information about likely construction type. However such information needs to be mapped to standard construction types and then processed before it could be used for engineering risk analysis.

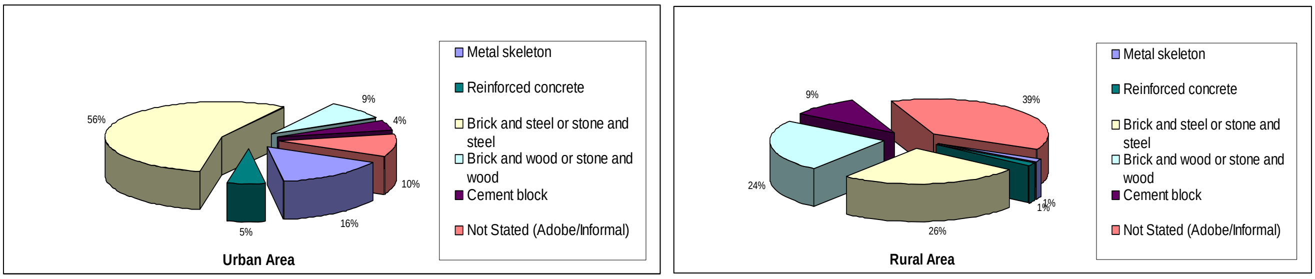

Figure 1. Distribution of building inventory for Iran (Source: Statistical Center, Iran).

Based on our findings, the PAGER inventory development was divided into three phases:

1. Database identification, preparation and confidence rating,
2. Data aggregation and quality ranking, and
3. Data assignment for missing entries

Figure 2 provides an overview of the PAGER inventory development methodology. In the first phase, we identify various databases that provide building stock distributions for individual countries; we map the raw description about construction material or building types in terms of PAGER construction types; and then rate them for further synthesis. After preparing the individual databases, in Phase-II, we merge them and pick the highest rated (quality) information to produce single database. In the last phase, we identify and develop data for missing elements of the matrix by identifying the most appropriate neighboring or analog country. The framework of present inventory development methodology is not entirely new and is in many ways analogous to the ATC-13 (ATC, 1985) and HAZUS (FEMA, 2006) inventory development methodologies.

2.1. Phase-I: Database identification, preparation and confidence rating

Phase-I consists of searching country-specific data from the various inventory data sources identified in Table 1 and then processing the raw data via attribute mapping. We also assign qualitative ratings to each data source to be used for a later phase of inventory compilation. After identifying country-specific construction type data from several sources, we map the raw data into the PAGER structure-type classification using the attribute mapping scheme discussed in detail by Jaiswal and Wald (2008a). Table 2 illustrates the inventory data gathered through the Demographic and Health Survey by the UN-Habitat for Colombia and its mapping to PAGER structure types.

Table 2. Distribution of Housing Unit by Construction material for Colombia (Source: UN-Habitat, 2007)

Sr. No.	Main Wall Material	Mapping to PAGER Structure Type	% Units
1	Zinc, canvas, plastics; Without Walls	INF	0.19
2	Adobe (mud bricks)	A	1.69
3	Compact dirt/mud	M	0.80
4	Bricks/polished wood/pre-manufactured material	UFB	92.60
5	Planks; Bamboo, straw, other plants	W	2.42
6	Bamboo with mud plaster	W2	2.30

The inventory development procedure is based on housing unit fractions rather than building fractions of particular structure types. Some of the data sources (e.g., published literature, EERI database) provide building inventory distribution by building rather than dwellings; in such cases, we have identified them separately and converted into fraction of dwelling stock by the equivalent number of units or by volume rather than their numbers (Jaiswal and Wald, 2008a). In cases where inventory information was available for sub-country regions rather than country-level (e.g., scenario study conducted by Faccioli et al., 1999 for Catania; post-earthquake reconnaissance conducted by Tobita et al., 2007 for Bam earthquake), they were used as a proxy to represent a particular country, but that assumption was reflected by a lower confidence level assignment used in the inventory model.

Most of the databases that have been identified for PAGER inventory development provide only residential building/dwelling stock data. In the absence of non-residential inventory distribution, certain predefined classification schemes based on engineering judgment have been used to convert the raw data into the equivalent occupancy categories. For example, the fraction of people working in various types of facilities such as administrative, commercial, banks, academia, and other facilities with similar usage, given in the database were classified into the non-residential category, whereas people residing in single or multi-family dwellings could be grouped into the residential category. In order to estimate the exact fraction of people in non-residential dwellings, we first compiled the data on average occupancy (number of persons) per dwelling irrespective of the construction types in different countries using global databases such as UN (2001) and UNECE (2006). Details of estimating the fraction of population in three different occupancy categories (residential, non-residential, and population in transit) by time of day are described in detail in Jaiswal and Wald (2008b). Mapping of raw data on construction types to a more standard classification system was necessary for combining data from several different sources.

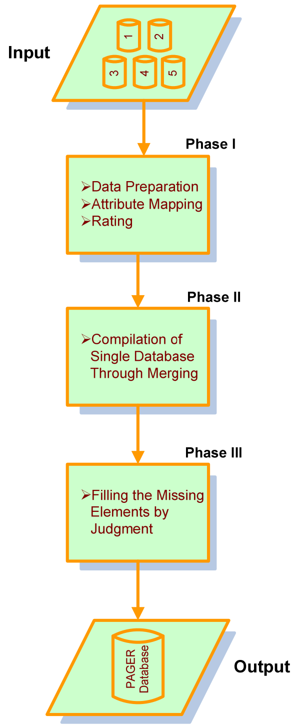

Figure 2. Schematic overview flowchart of the PAGER inventory development methodology.

Ideally the construction type classification should be based on the knowledge of the structural system, load transfer mechanism, the predominant construction material used, and the performance during past earthquakes. However, most of the raw inventory data did not provide building-specific information and hence it was necessary to adopt broad construction type classification based on material used for the construction of walls and roofs. More details about construction type classification are given in Jaiswal and Wald (2008a). We assigned ratings for each of the identified data sources based on simple PAGER attribute rating criteria (high, medium, or low) and rated all the entries in a given database using this scheme. Any missing information is assigned with "null" whereas all useful information is entered using the PAGER attribute mapping scheme. At the end of this phase, each raw data source and the relevant information contained therein was identified, rated, and compiled for further processing in Phase-II.

2.2. Phase-II: Data prioritization, merging, and country assignments

It consists of the development of single inventory matrix that covers the structure and occupancy related information at the country level by selecting the best quality attributes from the various individual databases processed in the previous phase. For each country, if only a single database provides information for a certain attribute, we assign it directly in the PAGER inventory matrix along with its rating. If none of the databases provide information for a certain attribute of a country, we assign the missing information based on an a priori country-pairing described in the next phase. If multiple databases are available for a particular country and attribute, then selection of appropriate attribute assignment is carried out in a two step process according to both its rating and vintage. We sort the attribute assignments according to their rating and select attributes that have higher rating. For a particular country, if attribute has multiple databases assigned with the same rating, we sort the assignments according to database vintage, retaining the most recent data. If attributes with similar ratings and vintage exist, we chose the attribute based on heuristics i.e., published literature data supersedes World Housing Encyclopedia reports or expert judgment surveys, and UN-Habitat (2007) data supersedes UN (1993). The outcome of this exercise is selection of a single attribute assignment for a chosen attribute type and country. Attribute data with "Null" or missing entries are carried forward for further processing in the Phase-III procedure. The output of Phase-II consists of a single inventory database matrix compiled from several individual data sources based on PAGER prioritization and classification criteria.

2.3. Phase-III: Data development for missing entries and synthesis

In the last phase, we occupy any non-exhausted attributes (i.e., "null" entries) by either assigning all the PAGER attributes for a particular country based on predefined criteria (normally from attributes of a neighboring country) or a few attributes due to lack of specific information in the available databases. Despite the use of several data sources during PAGER inventory development, more than fifty percent of countries across the globe have no direct information about building inventory distribution at the end of Phase-II. This step is aimed at developing a first-order estimation of the distribution of housing types in countries that otherwise have no information. It is quite common to have similar construction practices and building characteristics among neighboring countries that have similar population growth pattern, climates, lifestyles, and social and economic characteristics. In the absence of any regional data or inventory for the region/country, we needed an approach that could facilitate the process of selecting the most appropriate neighbor and perform country-pairing. Porter and Jaiswal (2006) compiled a first order vulnerability ranking scheme by which to group countries or a geographic regions of the world were classified into five vulnerability regions. Each of the vulnerability regions was assumed to have relatively uniform vulnerabilities across boundaries. The building stock and infrastructure belonging to region 1 was assumed to be the least vulnerable (e.g., California, New Zealand), and region 5 countries to be highly vulnerable (e.g., China, Iran, Pakistan). Among many factors, building codes and their enforcement, and the performance of buildings during past major earthquakes were of primary concern while performing regionalization. Countries with few inherently lethal pre-code buildings are assigned as a part of region 1. Countries with poor engineered construction are assigned as region 3. Predominance of adobe and rubble masonry as being part of the country's building stock was generally considered to be equivalent of region 5. Levels 2 and 4 are intermediate. The assignment of vulnerability level is illustrated in Porter and Jaiswal (2006). Although the scheme is broad, non-quantitative, and based on subjective judgment, it is being used only to select the best neighboring country for assignment of building inventory. Among all the neighboring countries, we selected the country that has same PAGER vulnerability region code (Porter and Jaiswal, 2006) as of the vulnerability code of missing country. If there are no countries with same vulnerability code and/ or more than one country with same PAGER vulnerability code, we use the data from country that has highest rating. In case of countries that have same ratings, we selected the neighbor that has highest quality and most recent data and replace the data of the missing country element with the information from the chosen country (Jaiswal and Wald, 2008a). The outcome of the Phase-III procedure is a PAGER inventory matrix with the distribution of population by residential and non-residential dwellings in urban and rural areas of the world (Figure 3). The inventory database provides 35 countries with high quality of data, 11 countries with medium quality and 201 countries with low quality data. There are 72 countries that contain data from one of the first four sources in Table 1 and 22 countries which have WHE-PAGER survey data.

3. IMPLEMENTATION CHALLENGES

Most of the data were available in variable formats such as HTML and spreadsheets, and published literature in the form of DOC or PDF reports/journal articles and required significant efforts to bring them into uniform digital format. Due to large variations of the data quality and sources across countries, it was important to rate the data quality and then select the best data using a consistent approach at the country level. Raw data contained variable nomenclature used for the description of construction types across databases and countries. We conducted limited Internet-based, country-specific research and reviewed the published literature to identify common building types and construction practices; however this effort was limited and could be further improved with additional country-specific information sources.

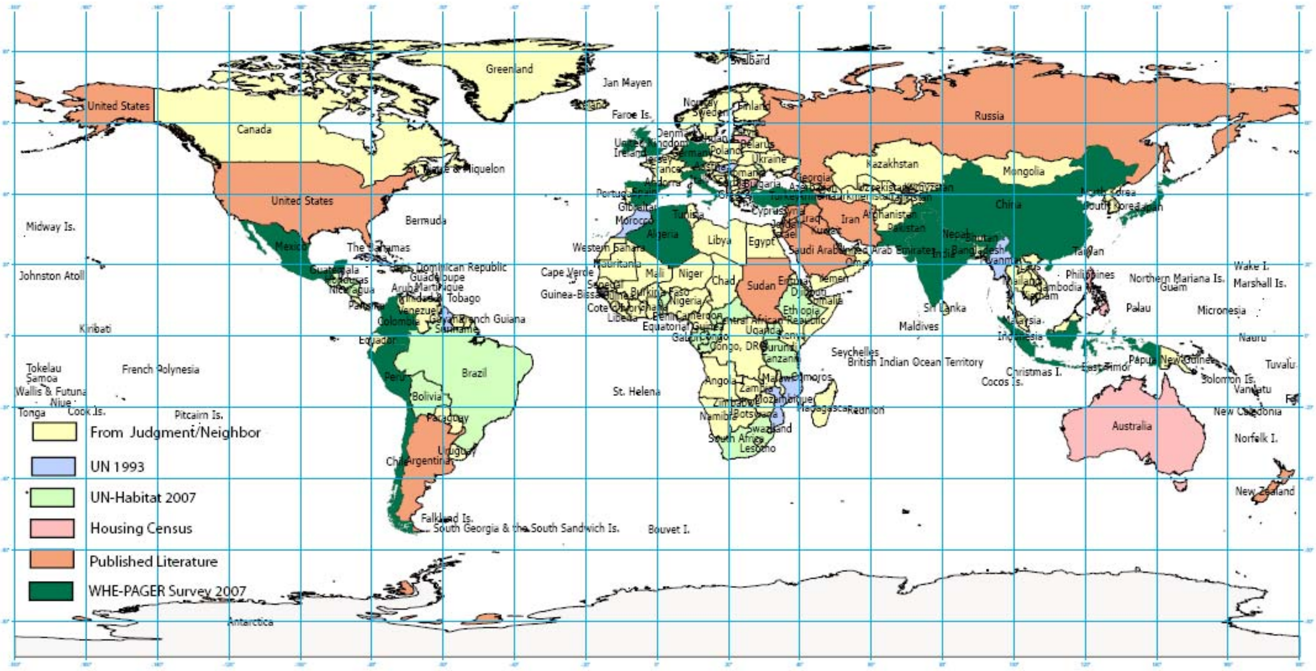

Figure 3. Global coverage of PAGER building inventory database with data compiled from various sources.

4. LIMITATIONS

We identified key data sources that provide building inventory information at a global scale and developed a unique building attribute mapping scheme for each of the data sources in order to map the raw data into uniform PAGER structure types. The mapping scheme developed has been specifically designed with the expectation of future enhancements from new and improved inventory data sources. Since the attribute mapping has been applied globally, based on a limited understanding of regional construction practices, it is possible that further access to country-specific published and unpublished reports or recent research articles will help improve the existing mapping scheme. For many countries, the building inventory data was either unavailable or incomplete. The use of a country-pairing scheme to identify the “best analogue” depending on data quality and vintage allowed the development of default inventory distribution for such countries.

5. WEB DELIVERY AND SCOPE OF FUTURE UPDATING

The inventory developed within the framework of the PAGER system requires routine updating of country/region specific information as higher quality data become available. The database is being made available online at http://pubs.usgs.gov/of/2008/1160/downloads/PAGER_database.xls, which will allow engineers and professionals to download and analyze the data and also to suggest appropriate modifications if necessary, based on recent research or knowledge in their respective countries. The feedback received from respective country experts will be used to upgrade the current, default PAGER inventory databases as is appropriate. The present investigation indicated that for many countries, the inventory data is extremely limited or non-existent. However, future research with continued improvements in the data compilation efforts will improve the data quality and also fill missing data identified here. One such effort is the WHE-PAGER project, which is an ongoing collaborative effort initiated by a group of experts from World Housing Encyclopedia (WHE) and PAGER project for better estimation of building inventory and building vulnerability worldwide (Porter et al., 2008). Emphasis was given in constraining inventory and vulnerabilities for countries identified by this study as being at high in risk, yet poor in data. The WHE-PAGER survey resulted in a development of comprehensive inventory specific information for 25+ countries in a standardized format covering various aspects of human occupancy pattern, construction types and its vulnerability for individual countries (www.world-housing.net). The growing responses of professionals during the survey, especially from earthquake prone countries, have clearly demonstrated the need of such open exchange.

6. SUMMARY AND CONCLUSIONS

The methodology described in this paper provides a simple, cost-effective framework for the development of a global, country-wide, residential building inventory database which aggregates various data sources of variable data quality and vintage. The main purpose of the inventory compilation is for earthquake casualty assessment for the USGS PAGER system. Even though better quality building data exists for various countries, much of it is proprietary, being available to either insurance or re-insurance agencies, country-specific research institutions, or private industry. Often, such data are focused on insured (and likely engineered) properties and thus may not be useful for overall country-wide inventory and impact assessment. Results from our general approach stand as a framework and global default model for which we readily concede portions of which must be replaced with higher quality and higher resolution data as they become available. Following broad conclusions can be obtained from the present investigation:

1. The investigation provides a step forward motivates the development of more refined databases with higher resolution and more rigorous country-specific data collection efforts.
2. The proposed framework provides a globally consistent approach for treating a variety of diverse datasets obtained from sources with varying level of uncertainty, quantity, and quality to produce a single, consistent global inventory dataset for earthquake loss estimation and risk management.
3. The investigation demonstrates that although substantial efforts have been made in recent housing census surveys by respective countries, several limitations must be overcome before the data generated from such surveys can be effectively utilized for earthquake loss estimation and risk mitigation efforts.
4. The investigation demonstrates that there is a strong need to seek an exercise which can encourage open data development and sharing mechanisms at global scale by adopting globally consistent data formats. This will potentially help in improving the quality of building inventory data (especially non-residential buildings) and can also be used for PAGER and other loss estimation needs.

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