EARTHQUAKE LOSS ESTIMATION FOR INDIA BASED ON MACROECONOMIC INDICATORS

P.K. DUNBAR[1], R.G. BILHAM[2], M.J. LAITURI[3]

[1] *National Geophysical Data Center, NOAA, E/GC1,*
325 Broadway, Boulder, CO 80305-3328, USA

[2] *Department of Geological Sciences, University of Colorado,*
Boulder CO 80309-0399, USA

[3] *Department of Earth Resources, Colorado State University,*
Fort Collins, CO 80523-1482, USA

1. Introduction

1.1. BACKGROUND

Preliminary results from the 2001 India census indicate that the population is now 1,027,015,247 [1], making India the second most populous country in the world [2]. The United Nations projects that by the year 2050, India will be the most populated country in the world with over 1.5 billion people [2]. India has also experienced some of the most devastating earthquakes ever recorded. Examples of earthquakes within the last 100 years and numbers of fatalities and damage are listed in Table 1 [3]. To reduce deaths and economic loss from earthquakes in India, it is important to understand where areas of high population density and high seismic hazard intersect.

TABLE 1. Devastating India Earthquakes from the National Geophysical Data Center's Significant Earthquake Database

Year	**Location**	**Deaths**	**Loss***
1905	Kangra	19,000	Unknown
1934	Bihar-Nepal	10,700	Unknown
1993	Latur	9,782	1,300
2001	Gujarat	18,000	4,600

*US $million

1.2. OBJECTIVES

The objective of this study is to apply a method of earthquake loss estimation based on a macroscopic index of exposure and population distribution [4] to India. The results of this study will be compared with other seismic hazard maps for India that were produced using more traditional loss estimation methodologies.

2. Review of Seismic Hazard Assessment for India

Some regions of India have experienced large earthquakes and others have no known history of the occurrence of earthquakes. In addition, some areas experience earthquakes frequently and others at long intervals of time. Since there is a wide variation in the seismic hazard in terms of the intensity of ground motion and frequency of occurrence, it would not be economical to construct all manmade structures to withstand very large earthquakes. Therefore, India has been divided into zones with respect to the severity of expected earthquake ground motion. Zones on the first seismic hazard maps were based on earthquake epicenters and intensities. Earthquake intensities are numerical values assigned to the effects of earthquakes on people and their works, and on the natural environment. Intensities are often evaluated using the Modified Mercalli Intensity Scale of 1931, which contains levels of effects ranging from intensity I, barely perceptible, to intensity XII, total damage. Intensity values are plotted onto maps and contours (lines) outlining areas of equal intensity are drawn to create isoseismal maps. The isoseismal maps are then used to define zones of seismic hazard.

2.1. INDIA SEISMIC HAZARD MAPS

The first national seismic hazard map of India was compiled by the Geological Survey of India (GSI) in 1935 [5]. In 1962, a second national seismic hazard map was published by the India Standards Institution (ISI). This map was based primarily on earthquake epicenters and isoseismal maps drawn by the GSI [5]. The map included earthquakes of magnitude 5 and greater with Modified Mercalli Intensities (ranging from V to IX) superimposed onto the map to create the zones. The zones in the 1962 map ranged from Zone 0 (no damage) assigned to a large region around Hyderabad in the state of Andhra Pradesh; to Zone VI (extensive damage) assigned to a small region around Shillong in Meghalaya and the northern region of Arunachal Pradesh.

The 1966 revision of the India seismic zoning map used geological information for regions of earthquake activity and tectonic maps that delineated fault systems [6]. The next major revision of the map was in 1970. After the magnitude 6.5 Koyna earthquake in 1967, which was in a region that had been assigned to Zone 0 in previous maps, Zone 0 was abolished in recognition of the fact that it was not scientifically sound to depict any region of India to have the probability of an earthquake equal to zero [5]. In addition, most of zones V and VI were merged into one zone. Therefore, the total number of zones was reduced from seven to five. The map was again revised in 1984 and is in use today [7].

The current Bureau of Indian Standards (BIS) seismic zonation map (Figure 1) was retrieved from the India Meterological Department (IMD) Web site:

http://www.imd.ernet.in/section/seismo/static/seismo-zone.htm. The relationship between zones and maximum intensities are shown in Table 2.

Another way of looking at seismic risk is based on the expected horizontal ground acceleration. Acceleration is measured relative to the acceleration due to gravity (g, 9.8 m/sec^2). Ground accelerations of 0.1 are considered capable of causing damage. Khattri [8] prepared a probabilistic seismic hazard map for India and adjacent areas that depicted contours of peak accelerations in rock in percent g with a 10% probability of exceedance in 50 years.

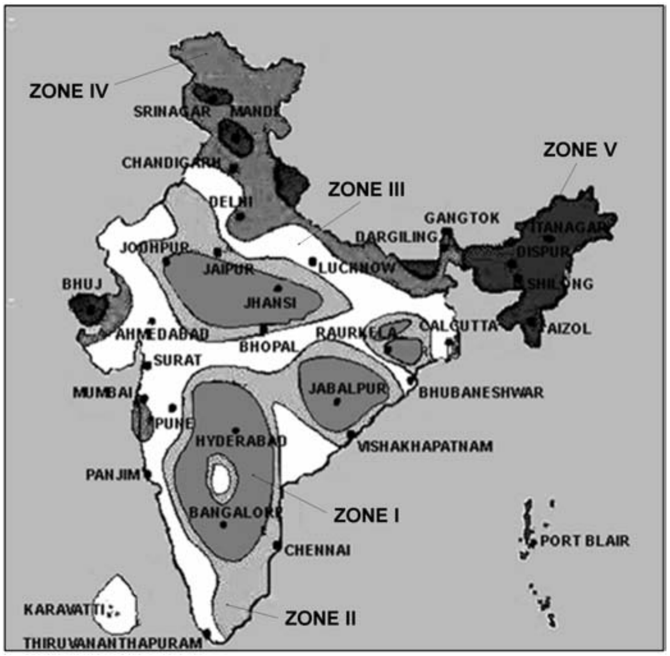

Figure 1. Seismic zoning map of India (from India Meteorological Department).

TABLE 2. Bureau of Indian Standards Seismic Zones and Maximum Intensities

Seismic Zone Designation	**Probable Maximum Intensities (Modified Mercalli Scale)**
I	V
II	VI
III	VII
IV	VIII
V	IX or more

In 1997, the Ministry of Urban Development of the Government of India published the first *Vulnerability Atlas of India* [9]. This atlas provides hazard maps for the natural hazards earthquakes, cyclones, and floods. Maps for all of India and for each State and Union Territory are included. Within each State and Union Territory, the vulnerability is indicated at the district level. The vulnerability was determined from the 1991 census that included numbers and percentages of building types in the rural and urban areas of each district. The building types were broken down into seven categories ranging from buildings with stone walls to bamboo thatch. Information on the vulnerability of the buildings to various earthquake intensities was then combined with the seismic hazard for each district to produce an earthquake hazard map for each State.

3. Earthquake Loss Estimation Methodologies

Earthquake loss can be described as the combination of the hazard, the exposure, and the vulnerability. The hazard refers to the frequency and severity of the threat or hazard. The exposure describes the people, property, systems or functions at risk of partial or total loss when exposed to hazards. Finally, the vulnerability describes the susceptibility to losses due to the exposure to the hazard. An earthquake loss estimate is a forecast of the effects of a hypothetical earthquake. A loss study may include estimates of deaths and injuries; property losses; loss of function in industries, lifelines, and emergency facilities; homelessness; and economic impacts. All earthquake loss estimation studies involve two components: the seismic hazard analysis and the vulnerability analysis.

3.1. SEISMIC HAZARD ANALYSIS

The seismic hazard analysis involves the identification and description of the earthquake to be used for evaluating losses. Most studies use one or more earthquakes to define the shaking hazard, without consideration of the probability that those events will occur. The most common form of this method uses the largest earthquake known to have occurred in a region, and this event is termed the historical maximum earthquake [10]. This approach is based on the premise that if an earthquake has occurred once, it can occur again. For example, Shinozuka *et al.* [11] conducted a loss estimation project for the Memphis, Tennessee region. Memphis is located in the New Madrid Seismic Zone (NMSZ). The NMSZ, whose southwestern extension begins at Marked Tree, Arkansas, generated three earthquakes of magnitude 8.0 or greater in 1811-12. Based on these historical earthquakes, they estimated losses for the Memphis region from a scenario 7.5 moment magnitude earthquake with an epicenter at Marked Tree, Arkansas.

The more comprehensive description of the hazard consists of calculating the seismic shaking from many different possible earthquakes and assigning a probability of occurrence to each event. This leads to probabilities of occurrence for earthquake losses over a specific time period.

3.2. VULNERABILITY ANALYSIS IN TRADITIONAL LOSS ESTIMATES

In traditional earthquake loss estimates, the vulnerability analysis entails the analysis of the vulnerability of buildings and other manmade facilities to earthquake damage and the losses that may result from this damage. An inventory of the buildings and other facilities to be considered in the study must be collected and the relationships among intensity of ground shaking, resulting damage, and associated losses of each inventory category must be established. This is the most time-consuming and expensive aspect of a loss study [10] and in many areas of the world these data are often unavailable or inconsistent.

3.3. VULNERABILITY ANALYSIS IN LOSS ESTIMATION WITH GDP

Chan *et al*. [4] developed an earthquake loss estimation methodology that uses the Gross Domestic Product (GDP) of a country as a macroscopic indicator to represent the total exposure, instead of the detailed building inventory required in traditional loss estimation methodologies. GDP refers to newly created wealth, which measures the total output of goods and services for final use occurring within the domestic territory of a given country, regardless of the allocation to domestic and foreign claims [12]. Since the economic loss from an earthquake is closely related to the state of its economy, Chan *et al*. [4] found that the GDP could be used to estimate the economic loss in an earthquake. Their method combines seismic hazard, GDP, population data, published earthquake loss data, and the relationship between GDP and known seismic loss, to estimate earthquake loss. This methodology was employed in this study to create an earthquake loss estimation map for India.

4. Data

The data used in this study were the LandScan 2000 Global Population 30-arc-second Database, GDP for the year 2000 from the World Bank, the 6-minute Global Seismic Hazard Assessment Program Map, and the National Geophysical Data Center's (NGDC) Significant Earthquake Database. These data are described in the following sections.

4.1. LANDSCAN 2000 GLOBAL POPULATION 30-ARC-SECOND DATABASE

LandScan 2000 Global Population 30-arc-second Database (LandScan 2000) is a 30-arc-second global population database (Figure 2). It was developed by Oak Ridge National Laboratory for the United States Department of Defense for input into their Hazard Prediction and Assessment Capability software [13]. The population distribution represents an ambient population, which integrates diurnal movements and collective travel habits into a single measure. The population distribution is determined by calculating a probability coefficient for each 30-arc-second cell and then applying the coefficient to the best available census counts for each country [14]. The probability coefficient is based on the following input variables [15]:

- Road proximity determined from the National Imagery and Mapping Agency's (NIMA) Vector Smart Map series (1:250,000 scale);
- Slope of the terrain calculated from NIMA's Digital Terrain Elevation Data (DTED) Level 0, 30-arc-second Terrain Data;

- Land cover types determined from U.S. Geological Survey's (USGS) Global Land Cover Characteristics (GLCC) database derived from Advanced Very High Resolution Radiometry (AVHRR) satellite imagery (1 km resolution);
- Radiance-calibrated nighttime lights from the Defense Meteorological Satellite Program Operational Line Scanner processed by NGDC (Figure 3).

4.2. GROSS DOMESTIC PRODUCT

GDP for the year 2000 were obtained from the World Bank’s World Development Indicators (WDI). The WDI is an annual compilation of data about development that includes indicators on the people, environment, and economy for over 200 countries [12].

4.3. GLOBAL SEISMIC HAZARD MAP

In 1992, the Global Seismic Hazard Assessment Program (GSHAP) was launched by the International Lithosphere Program (ILP) with the support of the International Council for Science (ICSU) and endorsed as a demonstration program within the framework of the United Nations International Decade for Natural Disaster Reduction [16]. The program was conducted from 1992-1998 and a Global Seismic Hazard Map (Figure 4) was compiled by joining regional maps produced for different GSHAP regions and test areas. The map depicts the global seismic hazard as peak ground acceleration (PGA) with a 10% chance of exceedance in 50 years at 6-minute resolution. This corresponds to a return period of 475 years for the maximum likely regional earthquake [16].

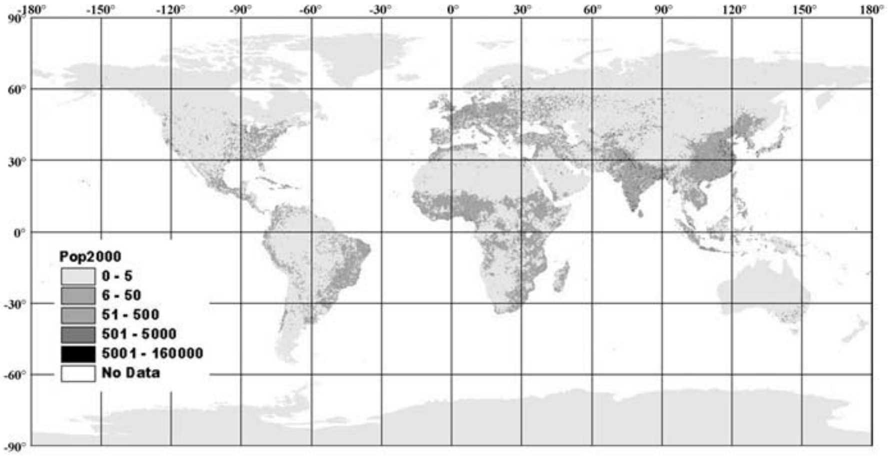

Figure 2. Landscan 30-arc-second Global Population Database 2000, developed by Oak Ridge National Laboratory for the United State Department of Defence

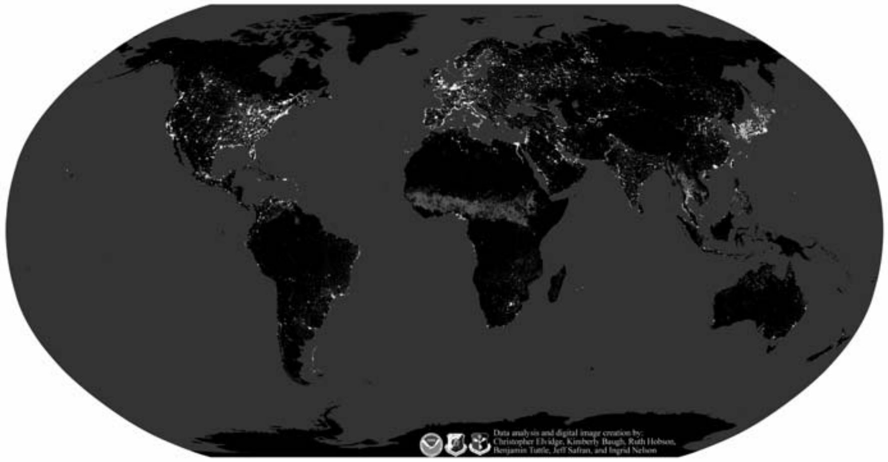

Figure 3. Stable nighttime lights (1994-1995) from the Defense Meteorological Satellite Program Operational Line Scanner processed by NGDC [17].

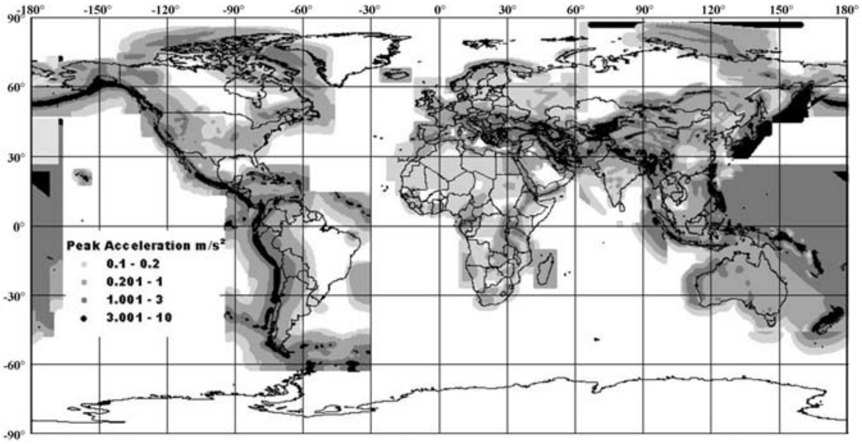

Figure 4. Global ground acceleration (pgs) with a 10% chance of exceedance in 50 years, corresponding to a return period of 475 years, Global Seismic Hazard Assessment Program (GSHAP), 1999.

The seismic hazard map for the region from 0-40° N and 65-100° E was compiled at the National Geophysical Research Institute, Hyderabad, India [7]. The results from this work were included in the seismic hazard map for Continental Asia [18]. Continental Asia was one of three regions (the Americas; Asia, Australia and Oceania; and Europe, Africa, and the Middle East) that were integrated into the final Global Seismic Hazard Map. The four main elements that the GSHAP program considered in compiling the global seismic hazard assessment were:

- Earthquake DataBase: the compilation of a uniform database of seismicity for the historical (pre-1900), early-instrumental (1900-1964) and instrumental periods (1964-today). For India and the adjoining areas, the National Oceanic and Atmospheric Administration, NGDC [19] catalog was merged with local catalogs. Duplicates, aftershocks, and earthquakes without any magnitudes were removed [7]. Intensities, Gutenberg surface-wave magnitudes (M_S), Beijing surface-wave magnitudes, and body-wave magnitudes (m_b) were all converted to moment magnitudes [17].
- Earthquake Source Characterization: the creation of a master seismic source model to describe the spatial-temporal distribution of earthquakes. The tectonic features for the India region were compiled from the following: "A Generalized Tectonic Map of India", "Tectonic Map of the Himalayan Arc region", "Tectonic Map of India" published by Oil and Natural Gas Commission, "Sketch Map of Major Tectonic Features of Southeast Asia", the "Map of the Tibetan Region" showing fault plane solutions of moderate earthquakes and active faults, and some unpublished material [7]. For seismotectonic considerations, the Indian region was divided into two major provinces: the Himalayan arc and other plate boundary regions and the Indian Shield region [7]. Based on the seismicity and distribution and tectonic trends, the region 0-40° N and 65-100° E was ultimately delineated into 86 zones [7].
- Strong Seismic Ground Motion: the evaluation of ground shaking as a function of earthquake size and distance. Since no reliable estimates of attenuation values were available for the Indian region, the attenuation relation from the 1979 Imperial Valley California earthquake was used [7].
- Computation of Seismic Hazard: the computation of the probability of occurrence of ground shaking in a given time period, to produce maps of seismic hazard and related uncertainties at appropriate scales. These values were computed using the FRISK88M software and the peak ground acceleration values were contoured with a contour interval of 0.05g [7]. The hazard map indicates that the majority of the plate boundary region and the Tibetan plateau region have hazard levels of the order of 0.25g with highs of 0.35-0.4g in the seismically active zones such as the Burmese arc, Northeastern India, and Northwest Himalaya/Hindukush region. In the Indian shield region, the regional seismic hazard is mostly of the order 0.1 g with some areas like Koyna depicting a hazard of 0.2g.

4.4. NGDC SIGNIFICANT EARTHQUAKE DATABASE

The NGDC Significant Earthquake Database contains information, including fatalities and dollar damage, on more than 5,000 destructive earthquakes from 2150 B.C. to the present. The events must meet at least one of the following criteria: moderate damage (approximately $1 million or more), 10 or more deaths, magnitude 7.5 or greater, or Modified Mercalli Intensity X or greater (for events lacking magnitude). The database was compiled from over 280 scientific and scholarly sources, regional and worldwide catalogs, and individual event reports. A subset of 26 earthquakes from the database for the years 1990-2001 were used in this study. Sixteen of the sources used to compile the entire database were used to compile the information for these 26 events. All of the epicentral information (latitude, longitude, depth, and magnitude) for the subset was obtained from [20]. The loss figures for the subset were obtained from six different sources, but losses for 20 of the events were obtained from the EM-DAT database [21]. Although 20 of the events were from one source, the EM-DAT [21] database was also compiled from many sources such as U.S. Government agencies, United Nations offices, reinsurance companies, etc. [21]. The Modified Mercalli Intensities listed in the database were assigned from observed effects of the earthquakes collected from several sources [3].

5. Methods

5.1. PROCESSING METHODS

The methodology developed by Chan *et al*. [4] was used to produce the earthquake loss estimation map for India. All of the data processing was done on a Windows NT machine using ESRI's ArcInfo 8 and ArcView 3.2, Microsoft Excel 2000, and the Thompson AWK version 2.03 programming language. There are four main steps required to produce the map. The steps are 1) Determine the regression equations using a subset of the NGDC Significant Earthquake Database, the GDP data for each country, and the Landscan 2000 30-arc-second population grid; 2) Convert the GSHAP peak ground acceleration data to Modified Mercalli Intensities (Appendix); 3) Create the GDP per unit area grid for India using the GDP for India and the LandScan 2000 30-arc-second grid; and 4) Create the earthquake loss map using the 30-arc-second grids for each Modified Mercalli Intensity level based on the regression equations developed in Step 1 and the grids created in Steps 2 and 3.

5.2. ESTIMATED ECONOMIC LOSS

Chan *et al*. [4] found that estimated economic loss for a given area is determined from the following relationship:

$$L = \sum P(I) \times F(I, \mathrm{GDP}) \times \mathrm{GPD}$$

where L is the economic loss, $P(I)$ is the probability of an earthquake of intensity I, and $F(I,\mathrm{GDP})$ is a measure of the area's vulnerability to earthquake damage for the given GDP value and the earthquake of intensity I. The GDP is used as a macroeconomic indicator to represent the total exposure of an area in the earthquake loss estimation. In this study , the $P(I)$ is determined from the GSHAP data, the computed GDP of an area is determined from GDP and population density, and $F(I,\mathrm{GDP})$ is determined from the relationship between reported losses from earthquakes to the computed GDP of the affected zone.

5.2.1. *GDP per Unit Area*

Since GDP is usually provided for a country, it must be apportioned over the nation or province. Chan *et al*. [4] found a strong correlation between GDP and population density for the States in the United States and the Provinces in China. The GDP of an individual unit is determined according to the following relationship:

$$\text{GDP per unit area} = (\text{GDP of region}) \times \frac{(\text{population in unit area})}{(\text{regional population})}$$

Chan *et al*. [4] used the Center for International Earth Science Information Network (CIESIN) 5-minute gridded population database in their GDP calculation. In this study, the GDP of an individual unit area was calculated from the 30-arc-second Landscan 2000 population data and the GDP from the World Bank WDI [12].

5.2.2. *Relationship between GDP and Known Seismic Loss*

The next step in the loss estimate is to determine the relationship between GDP and known seismic loss. Chan *et al*. [4] found a strong correlation between GDP and known seismic loss for 29 earthquakes from high, middle, and low-income nations from 1981-1995. Since India is a low-income nation, to determine the relationship between GDP and known seismic loss for India, 26 earthquakes from 1990-2001 (Table 3) were extracted from the NGDC Significant Earthquake Database according to the following criteria:

- the events were from low-income countries,
- some type of dollar damage was reported,
- a MMI or MSK intensity value was assigned,
- the GDP for the year 2000 for the country was listed in the World Bank WDI [12], and
- the epicenter was on land.

Since most of the damage in major earthquakes occurs within 30 km of the epicenter, the zone of maximum earthquake loss was defined to be within 30 km of the epicenter. Using the ESRI ArcView geographic information system (GIS), the population data within 30 km of the epicenter for each earthquake was extracted from LandScan 2000. These data were combined with the GDP of the country to determine the GDP of the epicentral zones according to Equation 2 in Section 5.2.1.

The reported losses from the NGDC Significant Earthquake Database were then plotted against the computed GDPs of the epicentral zones for events with Modified Mercalli Intensities > VI (Figure 5). There is a wide scatter in the data, but this is not surprising considering that the data are from developing countries where population and economic data are not as reliable as in more developed countries. The earthquake loss data from the NGDC Significant Earthquake Database also introduce errors. The reported losses are from different sources that may have used different criteria for reporting losses (Section 4.4). For example, the loss may refer to one major city or town that experienced damage, or it may refer to an entire area. In addition, depending on when the loss estimates are reported, right after an event or several months later, the values can vary by a factor of 10 to 100.

The reported losses vs. GDPs for intensities IX-X correlate well, resulting in a trendline with a coefficient of determination of 0.77. Three intensity VIII events from India (1991, 1993 and 1999) correlated well with the intensities IX-X and were included in that grouping. Either large aftershocks or major landslides were associated with these events, so it was not unreasonable that they would fit into this group. The Log(Loss)-to-Log(GDP) ratio for these events range from 1.209 to 5.694 (Table 3). It was expected that the intensity VIIIs and perhaps VIIs and VIs would result in separate trend lines. Unfortunately, all of the intensity VIIIs resulted in similar Loss/GDP relationships, ranging from 0.591 to 1.056 (Table 3), and were all grouped in one area on the graph. As a result, the intensities VI-VIII were grouped together to create a second trendline with a coefficient of determination of 0.75. For the two intensity ranges, the empirical constants and coefficients of determination for the two intensity ranges are shown in Table 4.

TABLE 3. Earthquake Events used in the formulation of the Loss-GDP relation from the National Geophysical Data Center's Significant Earthquake Database and the World Bank's World Development Indicators

Date			**Lat.**	**Long.**	**Depth (km)**	**Country**	**Mag.**	**MMI**	**Deaths**	**Loss***	**Log(Loss)/ Log(GDP)**
1990	05	30	45.8	26.7	89	Romania	7.1	VI	14	23.700	0.854
1990	06	20	37.0	49.4	19	Iran	7.7	X	40,000	8,000.000	1.711
1990	07	16	15.7	121.2	25	Philippines	7.7	VII	2,412	369.600	0.917
1991	04	22	9.7	-83.1	10	Costa Rica	7.6	X	77	510.000	1.250
1991	10	19	30.8	78.8	10	India	7.0	VIII	2,000	60.000	1.952
1992	05	15	41.0	72.4	50	Kyrgyzstan	6.2	VII	3	31.000	0.633
1992	08	19	42.1	73.6	27	Kyrgyzstan	7.5	IX	54	130.000	5.694
1993	09	29	18.1	76.5	7	India	6.3	VIII	9,782	1,300.000	1.364
1995	05	27	52.6	142.8	11	Russia	7.5	IX	1,989	300.000	2.545
1995	07	30	-23.3	-70.3	46	Chile	7.5	VII	3	1.660	0.134
1995	10	01	38.1	30.1	33	Turkey	6.2	VIII	101	205.000	0.865
1996	02	03	27.3	100.3	11	China	6.5	IX	322	483.000	1.775
1996	05	03	40.8	109.7	26	China	6.0	VIII	18	97.000	0.685
1997	02	04	37.7	57.3	10	Iran	6.8	VIII	100	30.000	0.591
1997	02	28	38.1	48.1	10	Iran	6.1	VII	965	76.000	0.882
1997	05	10	33.8	59.8	10	Iran	7.3	X	1,572	500.000	1.715
1997	05	21	23.1	80.0	36	India	5.6	VIII	56	143.000	0.745
1997	07	09	10.6	-63.5	20	Venezuela	6.8	VIII	81	81.000	0.632
1998	01	10	41.1	114.5	30	China	5.7	VIII	49	285.500	1.056
1999	03	28	30.5	79.4	15	India	6.6	VIII	100	70.000	1.863
1999	08	17	40.7	29.9	17	Turkey	7.8	X	15,637	8,500.000	1.209
1999	11	12	40.8	31.2	10	Turkey	7.5	IX	834	10,000.000	1.410
1999	12	22	35.3	-1.3	10	Algeria	5.5	VII	24	60.929	0.675
2000	08	04	48.8	142.2	10	Russia	7.1	VI	0	0.920	-0.065
2001	01	26	23.4	70.2	16	India	8.0	X	18,000	4,600.000	1.877
2001	02	13	13.7	-88.9	10	El Salvador	6.5	VI	315	1,500.000	0.894

*Reported in US $million at the time of the earthquake, rate of inflation is not accounted for

5.3 GSHAP PEAK GROUND ACCELERATION

The Global Seismic Hazard Assessment Program (GSHAP) peak ground accelerations were retrieved, April 27, 2001, from the World Wide Web: http://seismo.ethz.ch/GSHAP/global/. The acceleration data for India were extracted for inclusion as the seismic hazard assessment layer in this study. Since the loss estimation model required Modified Mercalli Intensity information, the peak ground accelerations were converted into intensities (see Appendix).

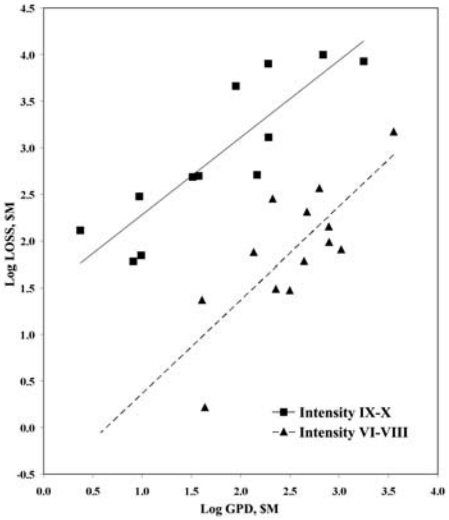

Figure 5. Economic loss (millions $US) plotted against GDP (millions $US) for Modified Mercalli Intensities VI-VIII and IX-X.

TABLE 4. Relationship between GDP and Economic Loss

Intensity	Regression Equation	R^2
VI-VIII	L = -0.638 + 1.002G	0.75
IX-X	L = 1.452 + 0.829G	0.77

L = log of Loss
G = log of GDP
R^2 = coefficient of determination

5.4. CREATION OF INDIA EARTHQUAKE LOSS MAP

The final step was to create the earthquake loss map for India by combining the Indian GDP unit areas (Section 5.2.1) and the GSHAP maximum intensity data (see Appendix), according to the regression equations in Table 4.

6. Results and Discussion

6.1. OVERVIEW OF RESULTS

The results of the analysis show expected earthquake losses for India during the next 50 years at 10% probability of exceedance (Figure 6). The expected losses are high for the northern states of Uttar Pradesh, Haryana, Bihar, West Bengal, and Assam. Significant earthquake losses are also expected in parts of Gujarat, Maharashtra, Rajasthan, Andhra Pradesh, and Kerala. Although the losses are lower than in some of the northern areas, this analysis indicates that all of the states of India are expected to experience some level of earthquake loss. It is also interesting to note that several areas that have a high seismic hazard according to the GSHAP map, such as the northern areas of Jammu, Kashmir, Himachal Pradesh, and Punjab are not expected to experience high earthquake losses due to the low level of exposure (GDP). These areas are also located in high seismic zones (Zones IV and V) in the BIS seismic zoning map (Figure 1). These comparisons show how earthquake loss estimates based on macroeconomic indicators could be useful in determining areas where earthquake mitigation efforts should be concentrated, such as where earthquake building codes need to be developed or enforced.

6.2. COMPARISON OF THE EARTHQUAKE LOSS MAP AND THE VULNERABILITY ATLAS OF INDIA

Since the GSHAP and BIS maps are only concerned with the seismic hazard analysis and not the vulnerability analysis, the earthquake loss map for India from this study was compared with the *Vulnerability Atlas of India* prepared by the Ministry of Urban Development [9]. The Atlas contains earthquake hazard maps for each state, with vulnerability levels indicated at the district level. For example, the state of Andhra Pradesh located on the southeast coast of India, has 23 districts. Andhra Pradesh is an interesting state to analyze, since most of the area that is now in that state was located in Zone 0 in the first GSI and BIS seismic hazard maps. The expected losses for Andhra Pradesh from the earthquake loss map for Andhra Pradesh are shown in Figure 7 and the Earthquake Hazard Map of Andhra Pradesh from the Atlas is shown in Figure 8. The difference in the level of detail in the two maps is immediately apparent. The map from the Atlas is very simplified showing only three levels of risk: Very Low Damage Risk Zone, Low Damage Risk Zone, and Moderate Damage Risk Zone. The map produced using the macroeconomic indicator shows expected earthquake losses ranging from \$0 to \$650 (US \$million) for the next 50 years. The Moderate Damage Risk Zone in the Atlas covers a large area of the state, but the map from this study indicates that a much smaller area of the state is expected to experience earthquake losses.

To better understand the resulting earthquake loss map for Andhra Pradesh based on macroeconomic indicators, the expected Modified Mercalli Intensities calculated from the GSHAP map are shown in Figure 9 and the population density map from LandScan 2000 is shown in Figure 10. It can be seen that there are very high levels of seismic risk expected in the same areas that are designated Moderate to Low Damage

Risk Zones in the Earthquake Hazard Map for Andhra Pradesh from the Atlas. The difference is found in the low population densities in the same areas, which results in a low level of exposure and low expected earthquake losses.

The ultimate test of the accuracy of any earthquake loss estimation methodology is the occurrence of a damaging earthquake in the future. But knowing areas of high levels of exposure could help in decision-making and reducing losses from earthquakes.

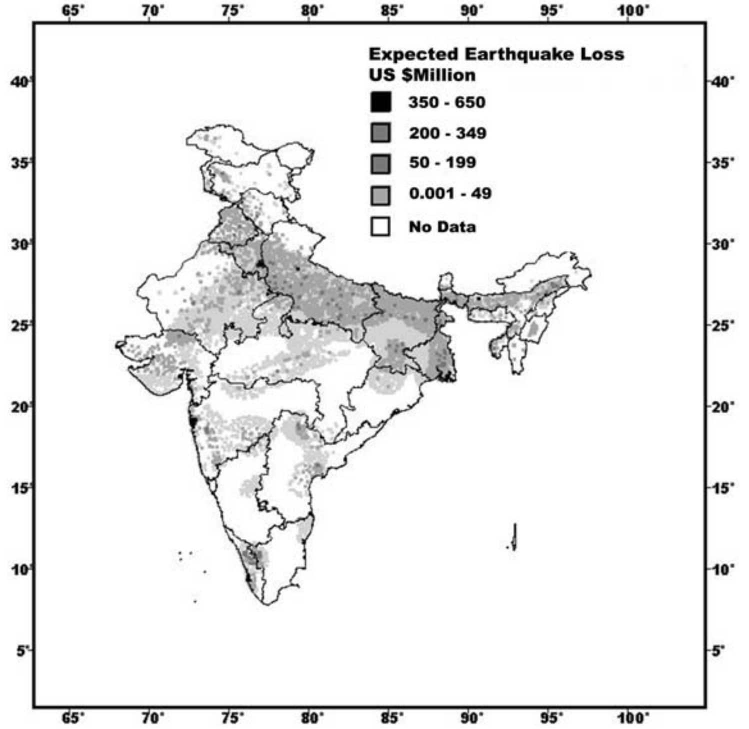

Figure 6. Expected earthquake loss map for India during the next 50 years at 10% probability of exceedance.

7. Summary, Conclusion, Further Work, Acknowledgments, and Disclaimer

7.1. SUMMARY

This study used population data from LandScan 2000 and GDP from the World Bank as macroscopic indicators of the total exposure in low-income countries to losses from earthquakes. These data were combined with NGDC Significant Earthquake loss data to determine the relationship between GDP and known seismic loss. It was found that there is a good correlation between GDP and known seismic loss, resulting in coefficients of determination of 0.77 for intensities IX-X and 0.75 for intensities VI-VIII. The resulting regression equations were applied to GSHAP acceleration data (converted to Modified Mercalli Intensities) to produce an earthquake loss estimation map for India.

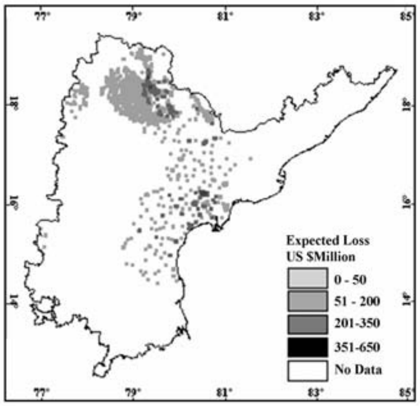

Figure 7. Expected earthquake loss map for Andhra Pradesh, India, during the next 50 years at 10% probability of exceedance.

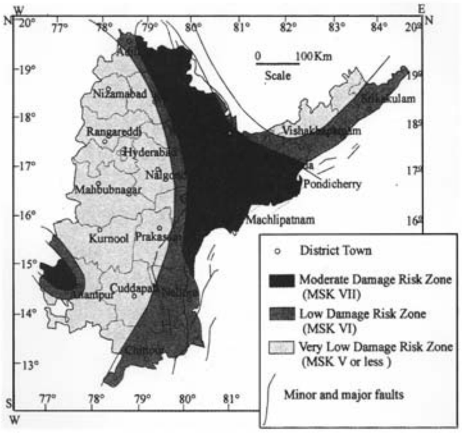

Figure 8. Earthquake hazard map of Andhra Pradesh, India, Vulnerability Atlas of India.

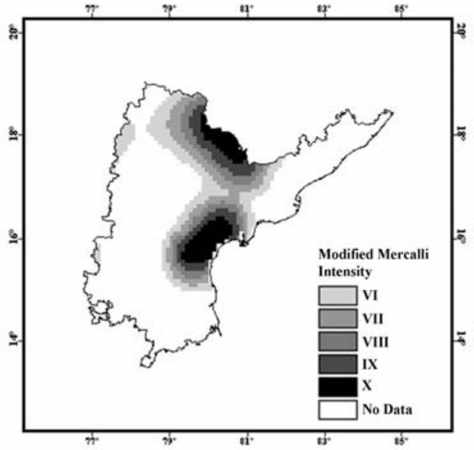

Figure 9. Expected Modified Mercalli Intensity for Andhra Pradesh, India, calculated from GSHAP peak ground acceleration.

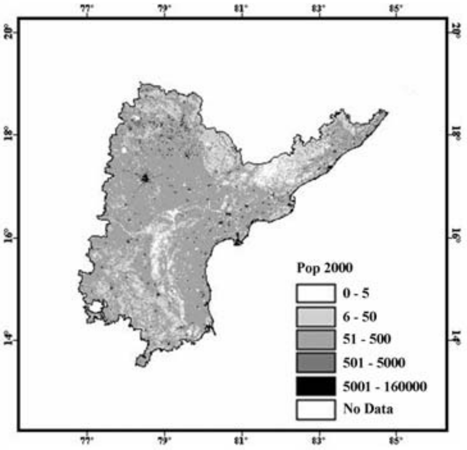

Figure 10. Population density map of Andhra Pradesh, India, Landscan Global Population Database 2000.

7.2. CONCLUSION

The earthquake loss estimation map produced in this study was compared with the *Vulnerability Atlas of India* for the state of Andhra Pradesh. The loss estimation map produced using macroeconomic indicators results in a much more detailed map, since the Landscan 2000 population data are at 30-arc-second resolution and the GSHAP data are at 6-minute resolution. This suggests that the earthquake loss estimation map produced using macroeconomic indicators is a better representation of the economic vulnerability.

The results of any analysis are only as good as the input data. As discussed in Section 4.4, there are several possible sources of errors in the NGDC Significant Earthquake Database. The accuracy and spatial resolution of the population and economic data also affect the quality of the analysis. In spite of these problems, these results are particularly important for developing countries that often do not have the resources to collect detailed inventories of buildings and other facilities that are at risk from earthquakes. This methodology provides an inexpensive and quick way to determine a region’s vulnerability to earthquakes.

7.3. FURTHER WORK

The methodology described here could be used to determine the relationship between known seismic loss and GDP for middle- and high-income countries. These results could then be used to develop a high-resolution (30-arc-second grid cell) earthquake loss estimation map for the globe.

7.4. ACKNOWLEDGMENTS

The authors would like to thank Dr. Lowell S. Whiteside for providing data, input, and guidance on this project.

7.5. DISCLAIMER

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either express or implied, of the U.S. Government.

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Appendix:
Conversion of GSHAP Peak Ground Acceleration to Modified Mercalli Intensity

To convert the peak ground acceleration data to intensity, the relationships between acceleration, magnitude, and intensity must be determined. Since Bhatia *et al*. [7] used the Joyner and Boore [22] attenuation relationship to develop the probabilistic seismic hazard map of India, the same attenuation relationship was used in this study to convert the GSHAP peak ground acceleration to Modified Mercalli Intensities. Joyner and Boore [22] define the relationship between acceleration and magnitude as:

$$\log A = -1.02 + 0.249 M_w - \log r - 0.00255 r + 0.25 P$$

$$r = (d^2 + 7.3^2)^{1/2} \qquad 5.0 < M_w < 7.7.$$

Where A is peak horizontal acceleration in g, M_w is the moment magnitude, d is the closest distance to the surface projection of the fault rupture in km, P is 0 for 50 percentile values and 1 for 84 percentile values. For simplicity in this study, the distance d and P are assumed to be 0, and hence, we obtain from the previous equations

$$\log A = -1.902 + 0.249 M_w.$$

Due to errors and non-uniformity resulting from a multi-step conversion of magnitudes, Zhang *et al*. [18] assumed that for most earthquakes $M_w \cong M_s$. Therefore, M_s magnitude values were used in the GSHAP earthquake catalog for Asia. From the definition of M_s [18], the relationship between maximum intensity (I_o) and peak ground acceleration can be determined:

$$M_s = M_w = 0.605 I_o + 1.376$$

$$\log A = -1.902 + 0.249\,(0.605 I_o + 1.376)$$

$$\log A = -1.56 + 0.15 I_o$$

The GSHAP peak ground accelerations (log A) were then converted to maximum intensities using the relationship shown in Table 5.

TABLE 5. Relationship between Modified Mercalli Intensity and Peak Ground Acceleration (PGA)

Modified Mercalli Intensity	**Peak Ground Acceleration**
VI	0.219g - 0.308g
VII	0.309g - 0.436g
VIII	0.437g - 0.616g
IX	0.617g – 0.870g
X	> 0.871g