LETTER

Spatio-temporal dynamics in seismic exposure of Asian megacities: past, present and future

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Abstract

The estimation of urban growth in megacities is a critical and intricate task for researchers and decision-makers owing to the complexity of these urban systems. Currently, the majority of megacities are located in Asia which is one of the most disaster-prone regions in the world. The high concentrations of people, infrastructure and assets in megacities create high loss potentials for natural hazards; therefore, the forecasting of exposure metrics such as built-up area is crucial for disaster risk assessment. This study aims to identify and project the dynamics of built-up area at risk using a spatio-temporal approach considering seismic hazard in three Asian megacities, namely Jakarta, Metro Manila and Istanbul. First, Landsat Thematic Mapper images were processed to obtain the built-up areas of 1995 and 2016 for Metro Manila, and of 1995 and 2018 for Jakarta and Istanbul. The SLEUTH urban growth model, a cellular automaton (CA)-based spatial model that simulates urban growth using historical geospatial data, was then employed to predict the urban growth of these megacities by 2030. Finally, seismic hazard maps obtained for 10% and 2% probabilities of exceedance were overlaid with built-up area maps. For a seismic hazard of 10% probability of exceedance in 50 years, the total urban area subjected to Modified Mercalli intensities (MMI) VIII and IX has increased nearly 65% over 35 years in Metro Manila. For Jakarta and Istanbul, the total urban area at the MMI VIII level has increased nearly 79% and 54% over 35 years, respectively. For a seismic hazard of 2% probability of exceedance in 50 years, the total urban area subjected to MMI IX has increased nearly 75%, 65% and 49% over 35 years in Jakarta, Metro Manila and Istanbul, respectively. The results show that urban growth modelling can be utilized to assess the built-up area exposed to high risk as well as to plan urban growth considering natural hazards in megacities.

1. Introduction

The 2018 Revision of World Urbanization Prospects by the United Nations reported that 55% of the world’s population lives in urban areas today, whereas this number is projected to reach 68% by 2050 with 90% of the increase occurring in Asia and Africa [1]. According to the same report, around one in eight of the world’s urban dwellers lives in one of the 33 megacities, i.e., cities with more than 10 million inhabitants. As the megacities continue to urbanize at a rapid pace, it becomes more essential to track the urban growth of these complex systems not just for their past and current states but also for the future.

As a result of rapid and sometimes unplanned urbanization, the high concentration of people and physical assets coupled with high hazard levels increases the degree of disaster impact for the megacities located in hazard-prone areas. Exposure is a term to describe the people and assets at risk that may suffer damage and loss due to hazards [2]. This term includes several dynamic and complex dimensions...
such as the built-up environment and population as well as the economy. The effect of exposure on disaster losses has been strong, and it has been established with much more confidence when compared to the effects of other elements of risk, namely vulnerability and hazard [3]. Among these three elements of risk, modelling of exposure and vulnerability plays a crucial role in earthquake risk management due to a unique feature of seismic risk in which making predictions about the hazard is relatively harder for earthquakes when compared with weather- and climate-related hazards. The characteristics of earthquakes highlight the importance of decreasing exposure to mitigate possible losses. One of the important measures for this purpose can be employing exposure-informed policies such as controlling the expansion into higher hazard zones by urban planning.

In this study, ‘built-up area at risk’ is investigated as a metric of seismic exposure. Within the context of our study, built-up area (also referred to as urban area) technically represents impervious surfaces, which are mainly man-made structures. Hence, the built-up environment corresponds to the areas where there are people, infrastructure and physical assets as well as economic activities. These areas have high economic and human loss potential when they are located in earthquake-prone regions; therefore, they can be utilized by further studies on possible losses by estimating the population, GDP or wealth/asset value at seismic risk in these areas [4–6]. The built-up area information has also been regarded as a useful indicator for sustainable development strategies; thus, it can be utilized in the scheme of the 2030 Agenda Sustainable Development Goals [7].

The dynamics of exposure trends have been investigated by different studies considering various types of natural hazards and at different scales from global to local. One of the recent global studies on population and built-up land exposure, Atlas of the Human Planet 2017: Global Exposure to Natural Hazards, was conducted by European Commission for various natural hazards such as earthquakes, volcanoes, floods and tropical cyclones [2]. They monitored the change of exposure using four epochs, namely 1975, 1990, 2000 and 2015, at continent and country levels. On the other hand, statistics at the local or regional level have also been generated by different studies to assess population and built-up land exposure, Atlas of the Human Planet 2017: Global Exposure to Natural Hazards, was conducted by European Commission for various natural hazards such as earthquakes, volcanoes, floods and tropical cyclones [2]. They monitored the change of exposure using four epochs, namely 1975, 1990, 2000 and 2015, at continent and country levels. On the other hand, statistics at the local or regional level have also been generated by different studies to assess population and built-up land exposure to natural hazards with higher resolutions [8–11]. Although the past and current exposure trends have been assessed often, there is a lack of future exposure estimations, especially for built-up areas at risk, since it is not easy to make projections for large areas such as cities. Furthermore, statistical projections fail to present realistic growth as they just focus on the temporal aspect but do not consider the spatial dimension. As opposed to that, exposure studies can move a step further by utilizing urban growth models which can generate spatio-temporal future predictions for city-level analysis.

Numerous recent studies have worked on global urban growth modeling [6, 12, 13], yet the spatial resolutions used by these studies are lower than 30 arcseconds which can be considered coarse for city-level analysis. Cellular automaton (CA)-based models have been regarded as one of the most useful and reliable models to draw information on the spatio-temporal dynamics of complex systems like cities [14, 15]. Therefore, the SLEUTH urban growth model [16], a CA-based model which simulates urban growth using historical geospatial data, was employed in this study to predict the urban growth of selected Asian megacities by 2030. Although urban growth predictions have been used by several studies on other types of natural hazards such as flooding [17–20], there is only one application known to us which investigates the relationship between spatio-temporal urban growth and future disaster risk triggered by earthquakes [21]. However, our study focuses more on exposure assessment rather than implementation of land-use allocation regulations and risk mitigation policies as scrutinized in [21].

The main objectives of this study are:

• to model the historical urban growth of the Jakarta, Metro Manila and Istanbul megacities spatio-temporally,
• to simulate future urban growth of these megacities using the SLEUTH model,
• to assess the spatio-temporal change in the built-up area exposed to seismic hazard over time (from 1995 to 2030).

In section 2, the methodology for mapping past and present built-up area for selected years is explained. Then, the CA-based urban growth model is introduced along with the required inputs and calibration steps. The background information for probabilistic seismic hazard maps is presented for 10% and 2% probabilities of exceedance in 50 years. In section 3, the results of the urban growth projection are given, seismic hazard maps are shown, and the change in built-up area at seismic risk is discussed in detail.

2. Seismic exposure assessment and urban dynamics

2.1. Study area

Being located on top of or near seismic faults, Asian megacities are often exposed to extreme seismic events [22]. In fact, Asia has been the region with the highest built-up area exposed to earthquakes for 1975, 1990, 2000 and 2015 with the total area tripling from 1975 to 2015 [2]. In this study, three earthquake-prone megacities from developing countries in Asia, namely Jakarta, Metro Manila and
Istanbul, were selected for case studies due to their rapid urbanization and population growth. Jakarta and Metro Manila are located on the so-called Pacific Ring of Fire, the region around the Pacific Ocean with high volcanic and seismic activity. Having been exposed to several destructive earthquakes in its history, the Southeast Asia region had two recent major destructive earthquakes in 2018. In addition to thousands of severely injured people and damaged houses, Lombok (Mw 7.0) and Palu (Mw 7.4) earthquakes resulted in 564 and 2081 total casualties, respectively [23]. Istanbul, situated along both sides of the Bosphorus Strait, has been exposed to high levels of earthquake ground motion dating back to the 1500s due to its location within active seismogenic areas [24]. It has been the focus of recent risk studies especially after the devastating Kocaeli (Mw 7.6) and Duzce (Mw 7.2) earthquakes in 1999. Erdik et al stated that there was an increased risk in Istanbul due to the unprecedented increase in the probability of occurrence of a large earthquake [25].

The Jakarta megacity is located in the Greater Jakarta metropolitan region which is the world’s second-largest urban agglomeration. It has a total area of 651 km² and its population was 9.6 million in 2010 [26]. Jakarta’s population growth was the highest in the urban areas of East Asia excluding China between 2000 and 2010 [27]. Its urbanization was so fast that nearly one-quarter of the non-urban land was converted to urban land for industry, commerce and housing purposes from 1980 to 2002 [26]. Metro Manila (Metropolitan Manila or Manila) is officially known as the National Capital Region (NCR) in the Philippines. Consisting of 16 cities, it covers an area of 636 km² [28] with a population of around 13 million in 2015 [29]. The Metro Manila region has shown a clear densification process with a drastic increase in the proportions of high-density areas between 1990 and 2014 [30]. Istanbul, one of the world’s most populous cities, had a population of around 15 million [31] and an immense area of 5461 km² by 2018 [32]. Its population increased from nearly 3 million to 12 million between 1975 and 2007 due to expansion of the city limits, income growth and migration [33].

2.2. Methodology

2.2.1. Mapping urban areas and prediction of urban growth

Landsat Thematic Mapper (TM) images (available at https://earthexplorer.usgs.gov/) were processed by a semi-automatic classification plugin on Quantum Geographic Information System (QGIS) [34] to extract the past and current built-up land information (the details about the Landsat TM images are given in the Supplementary Materials (available online at https://stacks.iop.org/ERL/15/094092/mmedia)). During training of built-up cells, false colour composite displays were used to select pixels that include man-made structures through visual interpretation. Local knowledge, actual land-use maps (where available) and high-resolution Google Earth images were also utilized as references in this process. For all selected megacities, 1995 was used to represent the past. To represent the present, the built-up areas in 2018 were selected for Jakarta and Istanbul, while those in 2016 were selected for Metro Manila. The changes in built-up area from past to present are represented in figures 1(a)–(c) along with other intermediate years which were used as inputs for the urban growth model. The specific years were selected due to the availability of the Landsat TM images with less cloud cover. The overall accuracy values of the semi-automatic built-up area classification range between 0.8 and 0.9 for the selected cities, which are around the suggested accuracy limit of 0.85 [35].

Urban growth dynamics is nonlinear, and its prediction is highly complex. The combination of geographic information systems (GIS) and remote sensing with urban growth models has been regarded as a useful approach and gained popularity in recent years for modelling and prediction of future urban growth [36]. The SLEUTH model has been widely used for many regions throughout the world since it is freely available online and able to capture the complex emergence of urban patterns. In addition to its robust routine for historical calibration, it has relatively simple simulation rules that are based on the spatial autocorrelation and principles of neighbourhood effects. Moreover, since the outputs are in GIF format, they are suitable for GIS analysis and effective for the visualization of urban growth scenarios [18, 37–40].

SLEUTH is the acronym for the six types of inputs that the model requires: slope, land use, excluded, urban, transportation and hillshade. In this study, land-use inputs are not needed as the focus is only on urban/nonurban classification. For each region, at least four urban inputs and two transportation inputs corresponding to different time periods are needed for calibration purpose. Therefore, raw data sets which include a set of Landsat TM images of four different years, digital elevation models (DEM), OpenStreetMap (OSM) data (available at www.openstreetmap.org), land-use maps and local historical road network maps were collected for input processing of Jakarta, Metro Manila and Istanbul. For Jakarta and Metro Manila, three sets of inputs with different cell sizes (120 m, 60 m and 30 m) were used at different stages (coarse, fine, final) of calibration. However, only 90 m cell size was used for all calibration steps of Istanbul due to its larger area. Figure 1 shows the built-up area (urban) inputs, and the rest of the inputs are given in the Supplementary Materials.
For each model, five growth coefficients (dispersion, breed, spread, slope and road gravity) are calibrated to obtain the set of best-fit coefficients (given in the Supplementary Materials) which are then used in the prediction mode to simulate future urban growth. During the calibration process, the Lee–Sallee metric, a shape index for the measurement of spatial match, was used for the selection of best-fit coefficients. The metric is defined as the ratio of the intersection to the union of the actual (reference) built-up area ($A$) and the simulated built-up area ($B$) \[ \text{Lee–Sallee index} = \frac{(A \cap B)}{(A \cup B)} \] as shown below:

Therefore, Lee–Sallee values close to 1 suggest a better match. In our study, the Lee–Sallee values are around 0.78 for Jakarta, 0.81 for Metro Manila and 0.75 for Istanbul. After obtaining the probability of urbanization for each cell as the SLEUTH outputs, using the best-fit coefficients, cells with probabilities of urbanization higher than the 50% threshold were treated as cells with built-up area in 2030.

For validation of the urban growth model performance in each megacity, a quantitative...
Figure 2. SLEUTH urban growth predictions with different probabilities of urbanization for 2030 in: (a) Jakarta, (b) Metro Manila, and (c) Istanbul.

measurement called the receiver operating characteristic (ROC) was used [44]. The details of obtaining ROC curves are given in the Supplementary Materials. The area under the curve (AUC) values are calculated as 0.72, 0.70 and 0.91 for Jakarta, Metro Manila and Istanbul, respectively. An AUC value higher than 0.5 represents a model which is better than random. Since all of our values are higher than 70%, the model performances are considered reliable.

2.2.2. Probabilistic seismic hazard assessment
Peak ground acceleration (PGA) values were estimated for Jakarta, Metro Manila and Istanbul with 10% and 2% probabilities of exceedance in 50 years using classical probabilistic seismic hazard analysis (PSHA) on the OpenQuake Engine (available at www.globalquakemodel.org), the software for seismic hazard and risk assessments developed by the Global Earthquake Model (GEM) Foundation
Table 1. Total and built-up areas along with annual growth rates for Period I and Period II.

| Megacity     | Total Area, km² | 1995       | 2016       | 2018       | 2030       | Increased Built-up Area, km² (Annual Growth Rate) |
|--------------|----------------|------------|------------|------------|------------|--------------------------------------------------|
| Jakarta      | 651            | 344 (52.8%)| -          | 517 (79.4%)| 622 (95.5%)| 173 (1.8%)                                      |
| Metro Manila | 636            | 304 (47.8%)| 427 (67.1%)| -          | 500 (78.6%)| 123 (1.6%)                                      |
| Istanbul     | 5461           | 760 (13.9%)| -          | 1195 (21.9%)| 1340 (24.5%)| 435 (2.0%)                                      |

\[ \text{Period I}^b \text{ and Period II}^c \]

\[ \Delta \text{Annual Growth Rate} = \left( \frac{A_1}{A_0} \right)^{1/\Delta t} - 1 \quad (2) \]

where \( A_1 \) is the built-up area in the initial year of Periods I and II, \( A_0 \) is the built-up area at ending year of Periods I and II, and \( \Delta t \) is the duration of each period.

By using the 50% probability of urbanization threshold for newly urbanized cells, trends of urban growth were obtained for each megacity as shown in figures 3(a)–(c). In table 1, the built-up areas for 1995, 2016/2018 and 2030 are given for the three megacities which show the urban expansion for the selected years. For ease of subsequent discussions, Period I and Period II refer to 1995–2016 and 2016–2030, respectively, for Metro Manila. For Jakarta and Istanbul, Period I and Period II refer to 1995–2018 and 2018–2030, respectively. Table 1 also shows the annual growth rate of built-up area in each megacity for Period I and Period II, which is defined as:

3. Results and discussion

3.1. Urban growth projection

Prediction mode in the SLEUTH model was run considering the business-as-usual scenario. Starting from the latest year of the urban inputs, the model was set to predict built-up area change on a yearly basis till 2030. Visual representations of the projections for different probabilities of urbanization corresponding to each cell were obtained as GIF images as shown in figures 2(a)–(c). In these images, yellow cells represent urban land in the start year (2016 for Metro Manila, and 2018 for Jakarta and Istanbul), red cells represent the cells with nearly the entire administrative regions of these cities are predicted to become urbanized by 2030. In contrast, Istanbul has more land in the north, away from the southern coast, for future urbanization. As a result, future urbanization of Istanbul is predicted to occur primarily northwards due to the new infrastructure developments in the northern region as well as around the edge of its city centre, as opposed to the more homogeneous spreading of urbanized areas in Jakarta and Metro Manila.

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\[ \Delta \text{Annual Growth Rate} = \left( \frac{A_1}{A_0} \right)^{1/\Delta t} - 1 \quad (2) \]

where \( A_1 \) is the built-up area in the initial year of Periods I and II, \( A_0 \) is the built-up area at ending year of Periods I and II, and \( \Delta t \) is the duration of each period.

The urban growth modelling results show a drastic increase from past to present (i.e. in Period I) for all three megacities, and a similar trend is predicted for the future (i.e. in Period II). The administrative areas of Jakarta, Metro Manila and Istanbul are 651 km², 636 km² and 5461 km², respectively, as shown in table 1. It can be observed that over the 35-year study period between 1995 and 2030, the increase in built-up area in ascending order is: 196 km² for Metro Manila, 278 km² for Jakarta, and 580 km² for Istanbul. In other words, Istanbul is predicted to grow by a built-up area larger than today’s Jakarta or Metro Manila over the 35-year study period.

For Jakarta, it was observed that the urban area had increased from 344 km² (52.8%) to 517 km²

[45]. The Earthquake Model of Continental Southeast Asia (2018) [46], developed by the Earth Observatory of Singapore at Nanyang Technological University in Singapore, was utilized for Jakarta and Metro Manila, while the Earthquake Model of the Middle East (EMME14) [47] by European Facilities for Earthquake Hazard and Risk (EFEHR) was used for Istanbul. The site amplification effect has been incorporated for the PGA estimates using the slope-based Vs30 data (at 30 arcseconds resolution) from the U.S. Geological Survey Database [48]. Vs30 is the time-averaged shear-wave velocity of surface soils down to 30 m, and it has been regarded as a key index to account for seismic site conditions [49]. The spatial resolution of the PGA maps is also 30 arcseconds (approximately 1 km at the equator), and they were resampled to match the spatial resolution of built-up area cells (90 m for Istanbul, and 30 m for Jakarta and Metro Manila) before the overlaying process.
(79.4%) in Period I with a prediction of 622 km$^2$ (95.5%) by the end of Period II when the entire city is almost completely urbanized. The increase in Metro Manila is also prominent, since the built-up area increased from 304 km$^2$ (47.8%) to 427 km$^2$ (67.1%) in Period I and is predicted to reach 500 km$^2$ (78.6%) in Period II. For Istanbul, there was an increase from 760 km$^2$ (13.9%) to 1195 km$^2$ (21.9%) in Period I. Moreover, this number is predicted to reach 1340 km$^2$ (24.5%) in Period II, when its built-up area will have almost doubled from 1995 with urbanization towards the northern part corresponding to new infrastructure developments in the northern region. Table 1 also indicates that the annual growth rate of Period
I (ranging from 1.6% to 2.0%) is higher than that of Period II (ranging from 1.0% to 1.6%) for the three megacities. For Period I, the highest annual growth rate belongs to Istanbul (2.0%) while Jakarta’s annual growth rate (1.6%) ranks top for Period II. When the difference between two annual growth rates corresponding to two periods is considered, the highest decrease is observed in Istanbul from 2.0% to 1.0%.

Figure 4. Seismic hazard maps for: (a) 10% probability of exceedance in 50 years in Jakarta, (b) 2% probability of exceedance in 50 years in Jakarta, (c) 10% probability of exceedance in 50 years in Metro Manila, (d) 2% probability of exceedance in 50 years in Metro Manila, (e) 10% probability of exceedance in 50 years in Istanbul, and (f) 2% probability of exceedance in 50 years in Istanbul.
4 along with (GMICE) of the ground motion intensity conversion equations, fied Mercalli intensity (MMI) scale. The PGA values of ground motions expressed in terms of the Modified Mercalli intensity give a good measure of seismic damage potential of buildings with respect to the ground motions. However, it is more convenient to correlate the higher-resolution spatial variations of ground motions. 

Metro Manila has only a very high intensity level IX (0.65–1.24 g), while levels VIII (0.34–0.65 g) and IX (0.65–1.24 g) were observed in both Jakarta and Istanbul. Ang for 2% probability of exceedance in 50 years, the PGA values are comparatively higher, ranging between 0.55–0.71 g and 0.94–1.16 g for 10% and 2% probabilities of exceedance in 50 years, respectively. This is largely due to the Valley Fault located in the eastern part of Metro Manila (the red zone in figure 4(d)). In particular, for the hazard map of 2% probability of exceedance in 50 years, the impact of the Valley Fault is significant and shows an extremely high hazard along this fault. The PGA range is wider for Istanbul, when compared to the other two megacities, with 0.19–0.56 g and 0.36–0.95 g for 10% and 2% probabilities of exceedance in 50 years, respectively. 

The PGA values shown in figures 4(a)–(f) reflect the higher-resolution spatial variations of ground motions. However, it is more convenient to correlate seismic damage potential of buildings with ground motions expressed in terms of the Modified Mercalli intensity (MMI) scale. The PGA values were thus converted to the MMI scale using the ground motion intensity conversion equations (GMICE) of [50], in order to overlay them with the built-up areas for the selected years. Therefore, the PGA values for 10% probability of exceedance in 50 years fall into intensity levels VII (0.18–0.34 g) and VIII (0.34–0.65 g) for both Jakarta and Istanbul, and VIII (0.34–0.65 g) and IX (0.65–1.24 g) for Metro Manila. For 2% probability of exceedance in 50 years, Jakarta and Istanbul have higher intensity levels VIII (0.34–0.65 g) and IX (0.65–1.24 g), while Metro Manila has only a very high intensity level IX (0.65–1.24 g).

### Table 2. Built-up area along with annual growth rates for different MMI levels at 10% and 2% probabilities of exceedance in 50 years.

| MMI    | 1995 | 2016 | 2018 | 2030 | Period I<sup>b</sup> | Period II<sup>c</sup> |
|--------|------|------|------|------|----------------------|----------------------|
| Jakarta |      |      |      |      |                      |                      |
| VII    | 2    | –    | 8    | 11   | 509                  | 611                  |
| VIII   | 342  | –    | 509  | 611  | 167                  | 102                  |
| IX     | 241  | 345  | –    | 406  | 104                  | 61                  |
| Istanbul |     |      |      |      |                      |                      |
| VII    | 99   | –    | 273  | 320  | 174                  | 47                  |
| VIII   | 661  | –    | 922  | 1020 | 261                  | 98                  |
| IX     | 14   | –    | 35   | 46   | 21                   | 11                  |
| Jakarta |     |      |      |      |                      |                      |
| VII    | 330  | –    | 482  | 576  | 152                  | 94                  |
| VIII   | 304  | 427  | –    | 500  | 123                  | 73                  |
| IX     | 195  | –    | 431  | 500  | 236                  | 69                  |
| Istanbul |   |      |      |      |                      |                      |
| VII    | 565  | –    | 764  | 840  | 199                  | 76                  |
| VIII   | 330  | –    | 482  | 576  | 152                  | 94                  |
| IX     | 304  | 427  | –    | 500  | 123                  | 73                  |
| Built-up Area, km<sup>2</sup> | 10% prob. of exc. in 50 years | 2% prob. of exc. in 50 years |
| Increased Area, km<sup>2</sup> |                  |                      |
| Annual Growth Rate, % |                      |                      |

<sup>a</sup> Annual Growth Rate = \((\frac{A}{A_0})^{1/M} - 1\)

<sup>b</sup> Period I refers to 1995–2016 for Metro Manila, and 1995–2018 for Jakarta and Istanbul.

<sup>c</sup> Period II refers to 2016–2030 for Metro Manila, and 2018–2030 for Jakarta and Istanbul.

### 3.2. Seismic hazard maps

The seismic hazard maps for 10% and 2% probabilities of exceedance in 50 years are shown in figures 4(a)–(f) for the three megacities. It was observed from the seismic hazard maps that the PGA values for Jakarta range between 0.34–0.44 g and 0.64–0.76 g for 10% and 2% probabilities of exceedance in 50 years, respectively. For Metro Manila, the PGA values are comparatively higher, ranging between 0.55–0.71 g and 0.94–1.16 g for 10% and 2% probabilities of exceedance in 50 years, respectively. This is largely due to the Valley Fault located in the eastern part of Metro Manila (the red zone in figure 4(d)). In particular, for the hazard map of 2% probability of exceedance in 50 years, the impact of the Valley Fault is significant and shows an extremely high hazard along this fault. The PGA range is wider for Istanbul, when compared to the other two megacities, with 0.19–0.56 g and 0.36–0.95 g for 10% and 2% probabilities of exceedance in 50 years, respectively.

The PGA values shown in figures 4(a)–(f) reflect the higher-resolution spatial variations of ground motions. However, it is more convenient to correlate seismic damage potential of buildings with ground motions expressed in terms of the Modified Mercalli intensity (MMI) scale. The PGA values were thus converted to the MMI scale using the ground motion intensity conversion equations (GMICE) of [50], in order to overlay them with the built-up areas for the selected years. Therefore, the PGA values for 10% probability of exceedance in 50 years fall into intensity levels VII (0.18–0.34 g) and VIII (0.34–0.65 g) for both Jakarta and Istanbul, and VIII (0.34–0.65 g) and IX (0.65–1.24 g) for Metro Manila. For 2% probability of exceedance in 50 years, Jakarta and Istanbul have higher intensity levels VIII (0.34–0.65 g) and IX (0.65–1.24 g), while Metro Manila has only a very high intensity level IX (0.65–1.24 g).

### 3.3. Dynamics in seismic exposure

After all built-up area maps were obtained, they were overlaid with seismic hazard maps in terms of the MMI intensity scale to obtain the built-up area exposed to varying degrees of seismic risk. The results for the three megacities in terms of the built-up areas at seismic risk and their ratios out of the total built-up area are shown by bar charts in figures 5(a)–(c) for 10% and 2% probabilities of exceedance in 50 years. The results are also summarized in table 2 along with the details on increased area and annual growth rates. As a result of the slower urbanization rates in Period II, it was observed that the annual growth rates are lower for all MMI levels in Period II when compared with Period I.

For 10% probability of exceedance in 50 years, almost the entire built-up area of Jakarta belongs to MMI VIII, as shown in figure 5(a). The built-up area corresponding to MMI VIII increased from 342 km<sup>2</sup> by 167 km<sup>2</sup> (i.e. 48.8%) to 509 km<sup>2</sup> in Period I and will increase by a further 102 km<sup>2</sup> (i.e. 20.0%) to 611 km<sup>2</sup> in Period II. In short, for Jakarta, the urban area subject to high hazard level MMI VIII has increased nearly 79% over 35 years. For Metro Manila, the majority of the built-up area is in MMI VIII. A drastic increase was observed over the built-up areas for both MMI VIII and MMI IX in Period I and Period II, as shown in figure 5(b). The results show that the built-up area for MMI VIII has increased from 241 km<sup>2</sup> by 104 km<sup>2</sup> (i.e. 43.2%) to 345 km<sup>2</sup> in Period I and by a further 61 km<sup>2</sup> (i.e. 17.7%) to reach 406 km<sup>2</sup> in Period II. Moreover, the built-up area corresponding to MMI IX has increased from 63 km<sup>2</sup> by 19 km<sup>2</sup> (i.e. 30.2%) to 82 km<sup>2</sup> in Period I and by a further 22 km<sup>2</sup> (i.e. 14.6%) to 94 km<sup>2</sup> in Period II. In summary, for Metro Manila, the total urban area subjected to high and very high hazard levels MMI VIII and IX has increased nearly 65% over 35 years. Istanbul has a substantial built-up area in both MMI VII and MMI VIII, as shown in figure 5(c). While the built-up
area of MMI VII increased from 99 km$^2$ by 174 km$^2$ (i.e. 1.8 times) to 273 km$^2$ in Period I and by a further 47 km$^2$ (i.e. 17.2%) to 320 km$^2$ in Period II, the built-up area for MMI VIII increased from 661 km$^2$ by 261 km$^2$ (i.e. 39.5%) to 922 km$^2$ in Period I and by a further 98 km$^2$ (i.e. 10.6%) to 1020 km$^2$ in Period II. Thus, the total urban area subjected to high hazard level MMI VIII has increased nearly 54% over 35 years in Istanbul.

For 2% probability of exceedance in 50 years, the majority of the built-up area of Jakarta belongs to MMI IX, as shown in figure 5(a). The built-up area at seismic risk corresponding to MMI VIII has grown 2.5 times from 14 km$^2$ to 35 km$^2$ in Period I and

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**Figure 5.** Built-up area at seismic risk (km$^2$) for 10% and 2% probabilities of exceedance in 50 years: (a) Jakarta, (b) Metro Manila, and (c) Istanbul.
further increased to 46 km\(^2\) in Period II. For MMI IX, it has increased from 330 km\(^2\) to 482 km\(^2\) in Period I, and further increased to reach 576 km\(^2\) in Period II. In summary, for Jakarta, the urban area subjected to very high hazard level MMI IX has increased nearly 75% over 35 years. In Metro Manila, the entire urban area has a very high hazard level MMI IX for 2% probability of exceedance, as shown in figure 5(b). Therefore, the total urban area subjected to very high hazard level MMI IX has increased nearly 65% over 35 years. For Istanbul, the built-up land corresponding to MMI IX has increased from 565 km\(^2\) to 764 km\(^2\) in Period I and further increased to reach 840 km\(^2\) in Period II, as shown in figure 5(c). For MMI VIII, the urban land has increased from 195 km\(^2\) to 431 km\(^2\) in Period I, with a prediction to reach 500 km\(^2\) in Period II. Thus, the total urban area subjected to very high hazard level IX has increased nearly 49% over 35 years in Istanbul.

4. Conclusion

Exposure is an important element in determining seismic risk that is strongly affected by rapid urbanization. This study focuses on seismic risk exposure, demonstrating the spatio-temporal dynamics of built-up area at seismic risk from 1995 to 2030 utilizing the urban growth prediction of three Asian megacities: Jakarta, Metro Manila and Istanbul. The results show that although each megacity is unique with different dynamics, all three megacities have shown a drastic increase in built-up area and the built-up area at seismic risk in Period I, from 1995 to 2016 or 2018. Furthermore, urban growth models have indicated that urban areas will continue to grow rapidly to 2030 (Period II) in seismically hazardous regions, increasing the exposure and thus risk.

The highest increase in total built-up area was observed in Istanbul with 435 km\(^2\) for Period I. Similarly, based on the results of urban growth models, Istanbul is predicted to show the highest increase with 145 km\(^2\) for Period II. This is expected since Istanbul has a larger urban land area when compared with the other two megacities. The annual growth rates show that the increase in built-up area has slowed down for all three megacities from Period I to Period II. For Period I, the highest annual growth rate belongs to Istanbul while Jakarta ranks top for Period II. Overall, Istanbul is predicted to grow by a built-up area larger than today’s Jakarta or Metro Manila over the 35-year study period.

For seismic hazard of 10% probability of exceedance in 50 years, the highest MMI level observed is IX in Metro Manila among the three megacities. The total urban area subjected to MMI VIII and IX has increased nearly 65% over 35 years in Metro Manila. For Jakarta and Istanbul, the total urban area at MMI VIII level has increased nearly 79% and 54% over 35 years, respectively. For seismic hazard of 2% probability of exceedance in 50 years, the entire urban area of Metro Manila has a very high hazard level MMI IX. The highest increase in the built-up area at this level is observed in Istanbul for Period I and in Jakarta for Period II. The total urban area subjected to MMI IX has increased nearly 75%, 65% and 49% over 35 years in Jakarta, Metro Manila and Istanbul, respectively. Therefore, Jakarta has shown the highest increase in terms of percentage followed by Metro Manila and Istanbul for the specified MMI levels and both probabilities. However, in terms of total built-up area, Istanbul has the highest increase.

In summary, we introduced an approach in this study to reveal the interaction of seismic hazard and built-up area in terms of past, present and future urbanization patterns. It can be used to address and reformulate a risk-sensitive development to mitigate seismic risk. The growing risk trend of Asian megacities can be controlled by adopting risk management processes in urban planning. The results of the case studies suggest incorporating exposure-informed disaster risk considerations in megacities by policymakers. Currently, risk reduction and urban resilience frameworks developed by collaborations with different stakeholders such as the World Bank have been put in place by the governments of Indonesia [51], the Philippines [52] and Turkey [53] for Jakarta, Metro Manila and Istanbul, respectively. These frameworks are proactively seeking effective seismic risk management and mitigation strategies and take spatial planning into account as well as resilience of infrastructure, post-disaster recovery, and sustainable and efficient financing mechanisms. In view of those measures and planned actions, our study can provide additional insights into the relevant risk and exposure, and therefore aid risk-informed disaster risk considerations in megacities. These frameworks are proactively seeking effective seismic risk management and mitigation strategies and take spatial planning into account as well as resilience of infrastructure, post-disaster recovery, and sustainable and efficient financing mechanisms. In view of those measures and planned actions, our study can provide additional insights into the relevant risk and exposure, and therefore aid risk-informed disaster risk considerations in megacities.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://10.6084/m9.figshare.12495608. Data will be available from 19 December 2020.
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