Seismic Liquefaction Hazard-Vulnerability Analysis and Mapping of Existing Important Buildings of Mumbai City, India

Analyse de la vulnérabilité des risques de liquéfaction sismique et cartographie des bâtiments importants de Mumbai City, India

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ABSTRACT: The predominantly saturated sandy soils of 2m to 3m thick in Mumbai city of India are likely to be subjected to seismic liquefaction during moderate to high earthquake magnitudes (M_w) of greater than 6.5. In this paper, seismic liquefaction hazard-vulnerability-risk analysis and mapping of existing important buildings of Mumbai city such as schools, hospitals, Government offices, hotels, fire stations, heritage structures, and educational institutions are carried out in ArcGIS platform. The seismic liquefaction of the sandy soils of Mumbai city is estimated in terms of probability (PL) of failure and the vulnerability is assessed as Overall building Vulnerability Index (VIo). One square kilometer grid based estimated PL and VIo are computed for the entire Mumbai city, and are combined for preparing liquefaction risk maps for Mumbai city for different earthquake magnitudes (M_w). The liquefaction risk maps show that some of the areas of Mumbai city lie in moderate to severe liquefaction zones having risk value ranging between 0.5 and 1.0. These risk maps can be helpful to predict the extent of damage caused to the existing important buildings due to liquefaction, to take action against prevention of liquefaction hazard, and for planning rescue and recovery operations during earthquake hazard.

ABSTRAIT : Les sols sableux à saturation prédominante de 2m à 3m d'épaisseur dans la ville de Mumbai en Inde sont susceptibles d'être soumis à une liquéfaction sismique pendant des magnitudes de tremblement de terre de modérée à élevée (M_w) supérieures à 6,5. Dans le présent article, l'analyse des risques liés à la liquéfaction sismique-vulnérabilité-risque et la cartographie des bâtiments importants existants de la ville de Mumbai tels que les écoles, les hôpitaux, les bureaux gouvernementaux, les hôtels, les casernes de pompiers, les structures patrimoniales et les établissements d'enseignement sont réalisés sur la plate-forme ArcGIS. La liquéfaction sismique des sols sablonneux de la ville de Mumbai est estimée en termes de probabilité (PL) d'échec et la vulnérabilité est évaluée comme l'indice global de vulnérabilité des bâtiments (VIo). Un kilomètre carré basé sur la base estimée PL et VIo sont calculés pour l'ensemble de la ville de Mumbai, et sont combinés pour la préparation des cartes de risque de liquéfaction pour Mumbai ville pour différentes grandeurs séisme (M_w). Les cartes de risque de liquéfaction montrent que certaines zones de la ville de Mumbai se situent dans des zones de liquéfaction modérées à sévères dont la valeur de risque se situe entre 0,5 et 1,0. Ces cartes de risque peuvent être utiles pour prévoir l'ampleur des dommages causés aux bâtiments importants existants en raison de la liquéfaction, pour prendre des mesures contre la prévention des risques de liquéfaction et pour planifier les opérations de sauvetage et de récupération pendant tout danger naturel.

KEYWORDS: Seismic vulnerability, liquefaction, risk maps, Mumbai city.

1 INTRODUCTION

The recent Nepal earthquake of 2015 is a proof of poor seismic resistance of the existing constructions leading to a huge damage and loss of life. In this context, the seismic safety of Mumbai city, related to existing important buildings or critical infrastructure such as schools, hospitals, government offices, hotels, fire stations, heritage structures, and educational institutions, is at stake as it is a densely populated coastal city. Secondly, mapping of liquefaction hazard for a city like Mumbai is not done by many.

Vulnerability is generally referred to as the inability of people, organizations, and societies to withstand adverse impacts of multiple stresses to which they are exposed. A vulnerability assessment requires systematic examinations of the population and buildings or structures or facilities to identify its susceptibility to damage from the effects of any natural hazards.

GIS provides an efficient way to identify natural hazard-prone areas and the vulnerable structures, and resources. Huge volumes of data are compiled on various parameters and are presented through maps revealing the hazard-vulnerability-risk of a given area. In this paper, the liquefaction hazard – vulnerability – risk assessment and mapping for the existing important buildings of Mumbai city is carried out on ArcGIS platform.

2 STUDY AREA

The study area comprises of Mumbai city and its suburbs in India. Mumbai, the financial capital and densest populated city of India is a coastal city located in seismic zone III according to the Indian seismic design code IS 1893-Part I (2002). The soil cover in the city is predominantly sandy-silty upto 2m to 3m thick with water table depths ranging from 1.8m to 7m from ground surface. This exposes the city to earthquake hazards such as seismic liquefaction. More basic details about the study area are available in Choudhury and Mhaske (2010) and Mhaske and Choudhury (2011a,b).

In this paper, the vulnerability of the existing important buildings of Mumbai city as shown in the base map of Mumbai city, presented in Figure 1, are assessed against seismic liquefaction hazard.

The spatial data such as location and geometry of the infrastructure along with non-spatial data such as type of structure, age and names are derived from OpenStreetMap (OSM) which is one of the most popularly used geographic databases.

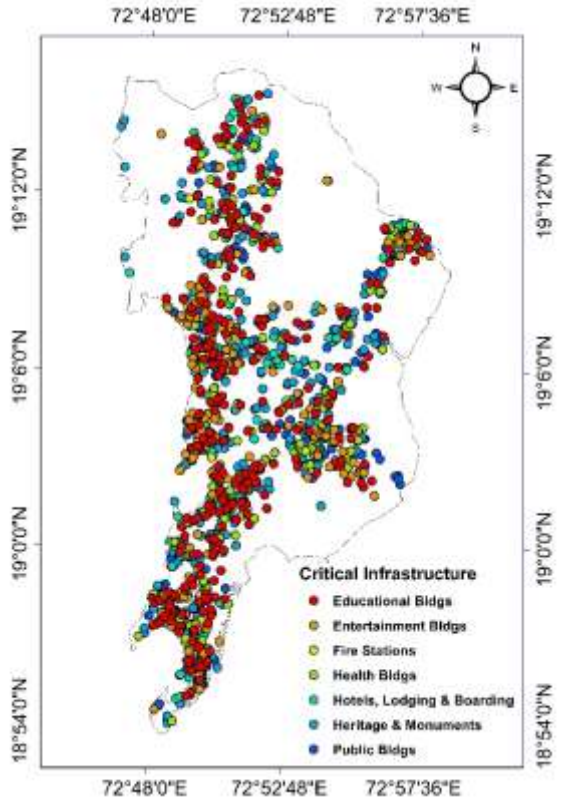

Figure 1. Base map of Mumbai city showing existing important buildings

3 HAZARD – VULNERABILITY – RISK MAPPING

Various researchers such as Brabharan et al. (2000), Piya (2004), Baise et al. (2005), Pearce and Baldwin (2005), Tanaka et al. (2006), Knudsen et al. (2009), Li et al. (2009), Menezes and Galvao (2009), Mostaffa et al. (2010), Karakas and Coruk (2010), Mote and Dismuke (2011), Mhaske and Choudhury (2010), Tosun et al. (2011), Habibullah et al. (2012), Choudhury et al. (2015) and Phule and Choudhury (2015) have prepared liquefaction hazard or risk maps for different areas. In the present study, liquefaction hazard-vulnerability-risk map is prepared for the existing important buildings of Mumbai city.

3.1 *Vulnerability mapping*

The study area of Mumbai city is divided into 550 square grids of 1km size and number of important buildings in each grid is counted by overlaying the grid layer on the base map of Mumbai city. The vulnerability index (VI) of each indicator for each grid is calculated by using the simple and easy vulnerability model proposed by Cutter et al. (2000), Wu et al. (2002), Chakraborty et al. (2005) and Collins et al. (2009).

The VI for each type of building for each grid (V_i) is calculated (see Eq. 1) which is scaled down to the VI of each grid (VI_i) to a value greater than zero and less than or equal to 1 by using maximum vulnerability from all the grids (V_{max}). An Overall Vulnerability Index (VIo) is then calculated for each grid by computing the average of the VI's of all types of existing important buildings as shown in Figure 2.

$$VI_i = V_i / V_{max} \quad (1)$$

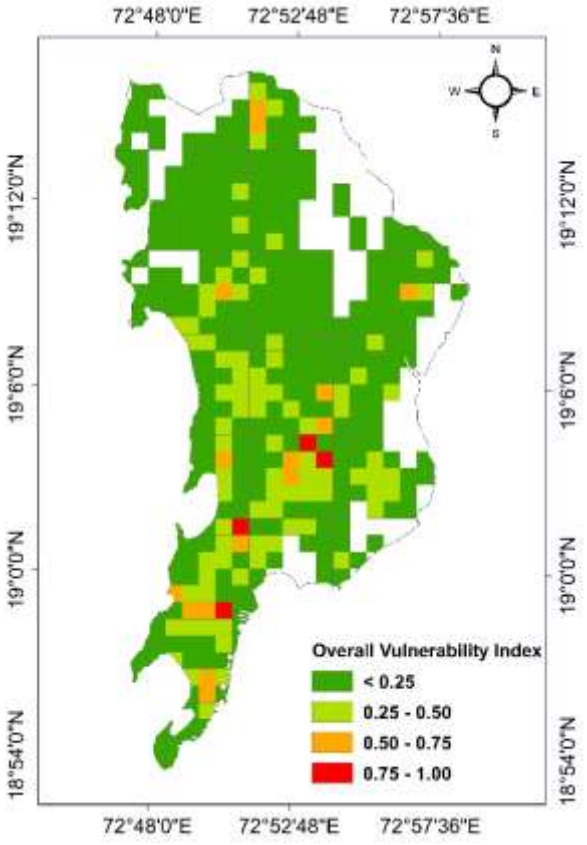

Figure 2. Overall building vulnerability grid map of Mumbai city

The VIo for the existing important buildings is found to be in the range of 0.25 to 1.0. The map signifies some of the important areas of Mumbai city having more of closely located important buildings and hence these areas are expected to be highly vulnerable.

3.2 *Liquefaction hazard mapping*

In the present study, hazard maps of liquefaction for soils of Mumbai city are generated in ArcGIS by first collecting the spatial data of the field test locations and then estimating the probability against liquefaction (PL) and then finally contouring the PL estimates. The estimation of PL is carried out by using the reliability approach based on the simplified procedure of Idriss and Boulanger (2008) (Phule and Choudhury, 2017). The hazard maps are produced for different earthquake magnitudes (M_w)'s of 5.5 to 7.5. The PL is found in the range of 0.3 to 1.0. Figure 3 shows the liquefaction hazard map of Mumbai city for M_w of 7.5. The PL and VIo maps are then combined to produce the liquefaction risk maps for the Mumbai city of India.

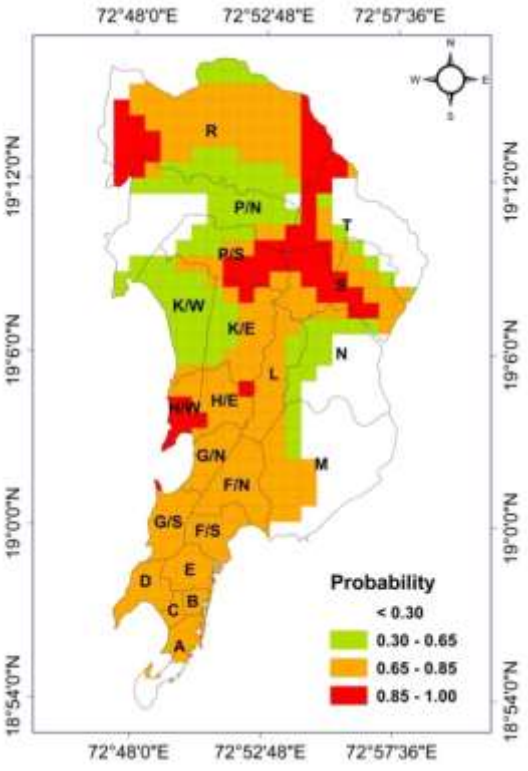

Figure 3. Liquefaction hazard grid map of Mumbai city

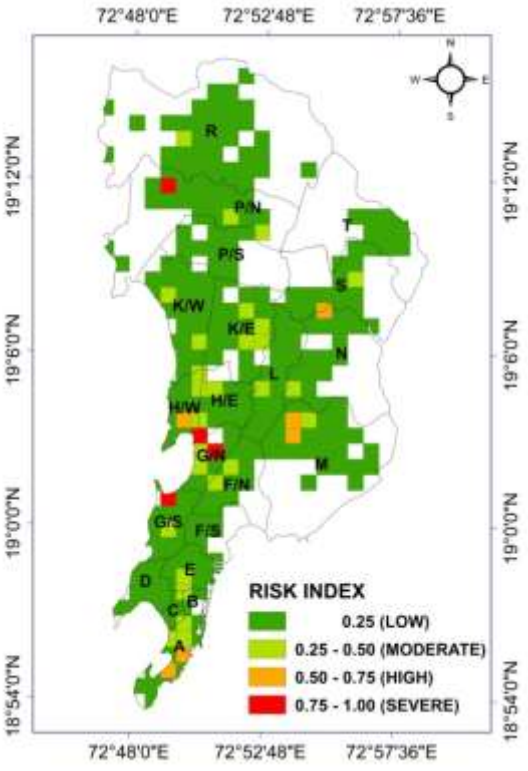

Figure 4. Liquefaction risk map of Mumbai city for M_w - 7.5

3.3 *Liquefaction risk mapping*

The building vulnerability map of Mumbai city is combined with the liquefaction hazard map to generate the liquefaction risk map for different M_w's. Figure 4 shows a risk map for a M_w of 7.5 for Mumbai city. The areas are classified into low, moderate and severe liquefaction zones having liquefaction risk value ranging from 0.25 to 1.0. The liquefaction risk maps indicate that most of the areas of Mumbai city comes under low to severe risk zones for M_w of 7.5. It is observed that the some of the areas have liquefaction risk index of 0.50 to 1.00 indicating moderate to severe liquefaction.

However, it is to be noted that the results of the analysis are based on the available limited field and laboratory soil database for the city.

4 CONCLUSIONS

In this paper, seismic liquefaction hazard-vulnerability-risk assessement and mapping is carried out for Mumbai city in India for the existing important buildings and color coded risk maps showing grid wise risk are produced in ArcGIS. The maps show that few areas of Mumbai city may be prone to 50 to 100% liquefaction risk. These risk maps of the city can be used by the professionals to identify the areas with potentially heavy damage and also to assess the extent of damage and can also be useful to the citizens to create awareness of the vulnerability of an area to earthquake hazard.

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6 REFERENCES

Baise L. G., Higgins R. B., and Brankman C. M. 2005. Liquefaction hazard mapping-statistical and spatial characterization of susceptible units. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(6), 705-715.

Brabhaharan P. 2000. "Earthquake Ground Damage Hazard Studies and their Use in Risk Management in the Wellington Region, New Zealand." 12th World Conf. on Earthquake Eng., Auckland, New Zealand. Paper No.1588.

Chakraborty J., Tobin G. A., and Montz B. E. 2005. Population evacuation: assessing spatial variability in geophysical risk and social vulnerability to natural hazards. *Natural Hazards Review*, 6(1), 23-33.

Choudhury D. and Mhaske S. Y. 2010. Geospatial technology for study of response system – phase of earthquake disaster management of Mumbai city. *Disaster Advances*, 3(4), 23-29.

Choudhury D., Phanikanth V. S., Mhaske S. Y., Phule R. R. and Chatterjee K. 2015. Seismic liquefaction hazard and site response for design of piles in Mumbai city. *Indian Geotechnical Journal*, 45(1), 62-78, doi: 10.1007/s40098-014-0108-4

Collins T. W., Grineski E. S., and Aguilar M. L. 2009. Vulnerability to environmental hazards in the Ciudad Juárez (Mexico)–El Paso (USA) metropolis: A model for spatial risk assessment in transnational context. *Applied Geography*, 29(4), 448-461.

Cutter S. L., Mitchell J. T., and Scott M. S. 2000. Revealing the vulnerability and places: A case study of Georgetown County, South Carolina. *Annals of the Association of American Geographers*, 90(4), 713-737.

ESRI 2014. ArcGIS Desktop: Release 10.2.1. Redlands, CA: Environmental Systems Research Institute.

Habibullah B. M., Pokhrel R. M., Kuwano J., and Tachibana S. 2012. GIS-based soil liquefaction hazard zonation due to earthqauke using geotechnical data. *International Journal of Geomatics*, 2(1), 154-160.

Idriss I. M. and Boulanger R. W. 2008. "Soil Liquefaction during Earthquakes", Earthquake Engineering Research Institute, Oakland, CA

IS 1893: Part 1 2002. "*Criteria for earthquake resistant design of structures – Part 1: General provisions and buildings*" Bureau of Indian Standards, New Delhi.

Karakas A. and Coruk O. 2010. Liquefaction analysis of soils in the western Izmit basin, Turkey. *Environmental and Engineering Geoscience*, 16(4), 411-430.

Knudsen K. L., Bott J. J., Woods M. O., and McGuire T. L. 2009. Development of a Liquefaction Hazard Screening Tool for Caltrans Bridge Sites. 2009 ASCE Technical Council on Lifeline Earthquake (TCLEE) Conference, (pp. 573-584). Oakland.

Li X., Li G., and Li C. 2009. Analysis of Ground Motion Parameters and Ground Liquefaction Prediction Using GIS for Kunming Basin, China. Proc., International Conference on Geo-Spatial Solutions for Emergency Mgmnt., (pp. 78-83). Beijing, China.

Menezes G. B. and Galvao T. B. 2009. Geostatistical Assessment of Liquefaction Models: A GIS-Based Approach. Proc., 10th International Symposium on Environmental, Geotechnical and Sustainable Development. Bochum.

Mhaske S. Y. and Choudhury D. 2010. GIS-based soil liquefaction susceptibility map of Mumbai city for earthquake events. *Journal of Applied Geophysics*, 70(3), 216-225.

Mhaske S. Y. and Choudhury D. 2011a. Geospatial contour mapping of shear wave velocity for Mumbai city. *Natural Hazards*, 59(1), 317-327, doi: 10.1007/s11069-011-9758-z

Mhaske S. Y. and Choudhury D. 2011b. GIS-GPS based map of soil index properties for Mumbai. In Geo-Frontiers 2011: Advances in Geotechnical Engineering, *Geotechnical Special Publication No. 211*, ASCE, Eds. J. Han and D. A. Alzamora (ISBN 978-0-7844-1165-0), Reston, VA, USA, pp. 2366-2375, doi:10.1061/41165(397)242

Mostafa H., Baise, L., Hafez H., and Zahaby K. L. 2010. A GIS-Based Assessment of Liquefaction Potential of the City of New Damietta, Egypt. Gephysical Research Abstracts (GRA), Conference Series for General Assemblies of the European Geosciences Union (EGU) 2010-15630.

Mote T. I., and Dismuke J. N. 2011. Screening-Level Liquefaction Hazard Maps for Australia. Proc., Australian Earthquake Engineering Society 2011 Conference . Barossa Valley, South Australia.

Pearce J. T., and Baldwin J. N. 2005. Final Technical Report on Liquefaction Susceptibility Mapping, St. Louis, Missouri and Illinois. National Earthquake Hazards Reduction Program Award 03HQGR0029, U.S. Geological Survey.

Phule R. R. and Choudhury D. 2015. Seismic liquefaction hazard zonation and contour maps for Mumbai city using open source GIS. *Disaster Advances*, 8(7), 20-33.

Phule R. R. and Choudhury D. 2017. Seismic reliability-based analysis and GIS mapping of cyclic mobility of clayey soils of Mumbai city, India, *Natural Hazards*, 85(1), 139-169, doi: 10.1007/s11069-016-2570-z

Piya B. K. 2004. Generation of a geologic database for the liquefaction hazard assessment in kathmandu valley. M.Sc. Dissertation Report, International Institute for Geoinformation Science and Earth Observation, Enschede, Netherlands.

Tanaka Y., agata, S., Knudsen V., and Kayen R. 2006. Assessment of Ground Defrmation due to Soil Liquefaction in the San Jose, California Area by Using Geotechnical IT. Proc., 8th U.S. National Conference on Earthquake Engineering. San Francisco, California, USA.

Tosun H., Syrek E., Orhan A., Savas H., and Turkoz M. (2011). Soil liquefaction otential in Eskisehir, NW Turkey. *Natural Hazards Earth System Science*, 11(4), 1071-1082.

Wu S. Y., arnal B., and Fisher A. 2002. Vulnerability of coastal communitiesto sea-level rise: a case study of Cape May County, New Jersey, USA. *Climate Research*, 22(3), 255-270.