Risks of seismic activities on built environment in Nigeria

Akpabot I. Akpabot, Anthony N. Ede, Oluwarotimi M. Olofinnade* and Gideon O. Bamigboye

Department of Civil Engineering,
Covenant University,
Km 10, Idiroko Road, P.M.B 1023, Ota, Ogun State, Nigeria
Email: akpabot.akpabot@stu.cu.edu.ng
Email: anthony.ede@covenantuniversity.edu.ng
Email: rotimi.olofinnade@covenantuniversity.edu.ng
Email: gideon.bamigboye@covenantuniversity.edu.ng
*Corresponding author

Abstract: Buildings are designed to be safe to prevent collapse caused by natural or man-made factors. Until recently, Nigeria was believed to be aseismic due to its distance from earthquake zones. However, recent seismic activities have led to the prediction of possible future earthquake occurrence in Nigeria. This study estimates the impact of seismic hazard on the built environment in Nigeria. A model is created to estimates the number of casualties and built areas that would be affected by earthquake of different ground motions. Monte Carlo simulation is used to derive random data of building area, occupancy limits, construction quality (CQ) and failure probability (Pf) for the computational analysis. The results showed that an average seismic intensity measure will affect between 1,000–1,060 km^2 of building area and about 6.5–6.9 million people will be affected. Consequently, these huge losses require urgent mitigating efforts to reduce risks of damages when earthquake occur.

Keywords: reinforced-concrete; building collapse; seismic-risks; built area; ground motion; construction quality; built environment; seismic intensity; Monte Carlo simulation; sustainability.

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Biographical notes: Akpabot I. Akpabot is a Lecturer at the Covenant University, Ota, Ogun State Nigeria. He is currently on his Doctorate degree programme at the Covenant University. His research and teaching interests include, structural analysis, structural health monitoring and construction materials.

Anthony N. Ede is an Associate Professor of Civil Engineering at the Covenant University, Ota, Ogun State, Nigeria. He received his Doctorate degree from the University of Salento. His research interests focus on structural health monitoring, building information modelling and innovative construction materials.

Oluwarotimi M. Olofinnade is a Lecturer/researcher at the Covenant University, Ota, Ogun State, Nigeria. He received his Doctorate degree from the Covenant University. His research interests focus on structural health monitoring, sustainable construction materials, life cycle assessment and sustainability.

Gideon O. Bamigboye is a Lecturer/researcher at the Covenant University, Ota, Ogun State, Nigeria. He received his Doctorate degree from the Covenant University. His research interests focus on innovative construction materials and environmental sustainability.

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1 Introduction

Buildings provide a wide range of accommodation for people in form of schools, offices, residences, etc. Every building is designed to be safe and meet certain needs in order to prevent collapse which usually leads to loss of lives and damage to properties (Ede, 2010a; Ede et al., 2017). Buildings enhance sustainable development; however, in Nigeria, this is yet to produce the required results because of numerous building failures (Windapo and Rotimi, 2012). Buildings that are functional increase the national gross domestic product as they meet present needs and also aid in reducing future deficiencies (Brundtland, 1987). Building collapse is the total loss of bearing capacity that results in sudden falling apart of a building (Oloyede et al., 2010). The consequences of building collapse are usually very fatal; they include loss of lives, disability of collapse victims, loss of properties, economic losses, loss of time and valuable resources, increase in number of homeless people, etc. (Ede, 2010b; Ede et al., 2016a; Ayodeji, 2011; Oluwatobi et al., 2012). The impact of building collapse has the tendency of impeding the development of any nation.

In Nigeria, the conservation of the existing building stock and the future ones to be constructed remains a great challenge (Ede et al., 2016b). The causes of building collapse in Nigeria are numerous; some of these include poor design, poor quality of materials, geology/hydrogeology of an area, insufficient supervision, incompetence, lack of compliance to building codes, etc. (Adeniran, 2013; Ifedolapo, 2015). Furthermore, study by Oloyede et al. (2010) stated that building collapse can be attributed to natural and man-made phenomena. The study went further to explain that a natural phenomenon may consist of earthquakes and typhoons while man-made phenomena consist of disasters which may be borne out of man's negligence.

Models that evaluate losses provide governments and other stakeholders with information that are necessary for decision making before and after an earthquake. These models help in the ranking of activities and program to alleviate the effects of seismic hazard, the development of plans to resist such hazards and in the selection of construction locations and methods (Fernandez, 2014). This study highlights risks and losses on the built environment due to seismic activities in Nigeria using Lagos state as a case study. It estimates the building area and number of casualties that will be affected considering ground motion of different intensities.

Earthquake is a seismic activity that involves a sudden shaking of the ground, causing damages as a result of movement of the earth surface (Shiwua, 2013). Earthquakes are not preventable and even when it is expected; the force with which it attacks is only measurable after its manifestation has left a devastating mark of huge number of human casualties and infrastructural damages. Nigeria is believed to be situated in a seismically inactive area because it is geographically located far from prime earthquake regions. However, despite this believe there has been series of tremors within the country. These tremors occurred along known faults and are being monitored. Osagie (2008) gave a detailed account of the history of earthquakes and tremors in Nigeria and reported that the first tremor occurred in 1923. A moderate magnitude seismic activity was experienced in September, 2009 and its impact was perceived majorly in the western region of the country. After this incidence, the National Space Research and Development Agency (NARSDA) stated that Nigeria is not aseismic and is therefore vulnerable to the occurrence of an earthquake in the near future (Akpan and Yakubu, 2010). Adepelumi (2009) used the earthquake recurrence model using Weibull probability density model to estimate the probable occurrence of earthquake in the south western part of Nigeria. His results predicted the occurrence of a large magnitude earthquake in the near future. This therefore calls for urgent attention and adequate preparedness for this seismic hazard.

Based on the existence of fault zones, the scarcity of seismic information, long term exploration of crude oil and massive disturbance of soil strata due to humongous building activities, there is need for simulation and modelling of earthquakes based on observed crustal/tectonic motion (Adepelumi et al., 2011). Researchers have predicted the seismic hazard for the study area and they expressed it in terms of the peak ground acceleration (pga) to be in a range of 0.16–0.69 g (Adepelumi et al., 2011). The characteristics of buildings that determine how it will react to seismic actions are size, geometry, structural arrangement, building materials and foundation properties (Shiwua, 2013).

Developing nations like Nigeria are more susceptible to severe damage (SDs) due to earthquake occurrence because of high population density, illiteracy, poverty and lack of well-developed infrastructures. However, it is possible to reduce the risk of damage to humans and buildings by designing earthquake resistant infrastructures. Buildings outside the administrative areas are worst-off because most are constructed without adequate quality control.

2 Methodology

In each of the five administrative divisions of Lagos state, concrete compressive strength data with design value of 25 N/mm^2 for different buildings is collated. Google earth application is used to estimate the built area in each of the divisions. Due to uncertainties involved, the area is obtained as a range rather than as single values. A walk-by survey to ascertain the floor-height grouping is carried-out on streets in each division. Building floor-height group is categorised into three, these include: buildings 0–4 floors high, 5–7 floors high and 8 or more floors. Occupancy level for each of the divisions is estimated by dividing the population per division by its built area. A model that uses Monte-Carlo simulation drawing random samples of the obtained parameters is created:

construction quality (CQ), built area, probability of failure and occupancy limit. The model determines the area of buildings and then the casualty estimates that would be affected by earthquakes with different seismic intensity measure. Computational analyses are done using MATLAB.

The model calculates two 3 × 3 matrices. The first matrix contains building area arranged according to building height groups by CQ. A second 3 × 3 matrix is computed which contains the probability of failure [impending collapse (IC) or SD] arranged in accordance to building height groups and CQ. The entry-wise or dot product of these matrices gives estimates of affected area either IC or severely damaged.

To calculate the first matrix, the built area per each floor height group was allocated to one of three levels of CQ. CQ grouping was based on concrete strength. Values of compressive strength of concrete (f_c) < 23 N/mm^2 were assigned poor quality construction (PQ), concrete strength between 23–26 N/mm^2 were assigned average quality of construction (AQ), and concrete strength data > 26 N/mm^2 were assigned high quality construction (HQ).

$$\text{Built Area; } [A] = \begin{array}{l} \\ \leq 4 \text{ FLOORS} \\ 5-7 \text{ FLOORS} \\ \geq 8 \text{ FLOORS} \end{array} \begin{array}{ccc} PQ & AQ & HQ \\ a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{array} \tag{1}$$

where A = built area; PQ = poor quality of construction; AQ = average quality of construction; HQ = high quality of construction.

Equation (1) indicates how the first matrix will be represented, which contains random values of built area distributed by three floor-height groups and by three levels of CQ.

$$P_f = \phi\left[\frac{\ln\left(x/\mu\right)}{\beta}\right] \tag{2}$$

where $\Phi(\cdot)$ = standard normal distribution function; x = peak ground acceleration; μ = median of fragility function; β = log standard deviation of fragility function.

Table 1 Median and logarithmic standard deviation of fragility function for impending collapse (IC) and severe damage (SD) performance levels.

		Lower limit		*Average limit*		*Higher limit*	
		Median (μ)	*Log std (β)*	*Median (μ)*	*Log std (β)*	*Median (μ)*	*Log std (β)*
IC	≤4 floor	1.25	0.442	1.01	0.44	0.771	0.439
	5–7 floor	0.679	0.442	0.55	0.45	0.418	0.459
	≥8 floor	0.549	0.440	0.447	0.448	0.344	0.456
SD	≤4 floor	0.49	0.531	0.414	0.488	0.338	0.445
	5–7 floor	0.32	0.562	0.269	0.522	0.217	0.482
	≥8 floor	0.275	0.597	0.232	0.518	0.189	0.44

Source: Adapted from Celik and Ellingwood (2010)

To obtain results for the second matrix, probability of failure is drawn from the fragility functions. Given different pga values the probabilities of either IC or SD is calculated. The failure probability (Pf) conditioned by ground motion parameter is calculated using the lognormal cumulative distribution function [equation (2)]. The result produced is arranged into a second matrix with values containing probability of IC or SD per floor height and per CQ.

Table 1 contains values of median and standard deviation of fragility function for both IC and SD performance levels. It was produced using the probabilistic finite element method of analysis for concrete. It was adapted because it took cognisance of both aleatoric and epistemic uncertainties and most buildings in Tennessee and Lagos are designed for gravity and wind loads but not to resist earthquakes.

$$\text{Probability of failure (IC); } [B] = \begin{array}{cccc} & PQ & AQ & HQ \\ \leq 4 \text{ FLOORS} & b_{11} & b_{12} & b_{13} \\ 5-7 \text{ FLOORS} & b_{21} & b_{22} & b_{23} \\ \geq 8 \text{ FLOORS} & b_{31} & b_{32} & b_{33} \end{array} \tag{3}$$

$$\text{Probability of failure (SD); } [C] = \begin{array}{cccc} & PQ & AQ & HQ \\ \leq 4 \text{ FLOORS} & c_{11} & c_{12} & c_{13} \\ 5-7 \text{ FLOORS} & c_{21} & c_{22} & c_{23} \\ \geq 8 \text{ FLOORS} & c_{31} & c_{32} & c_{33} \end{array} \tag{4}$$

$$[A]^*[B] = M \tag{5}$$

$$[A]^*[C] = N \tag{6}$$

where ·* = dot product; A = matrix of built area (km^2); B = matrix of probability of IC; C = matrix of probability of severe damage; M = area IC (km^2); N = area severely damaged (km^2); P = population

The second matrix contains values for probabilities of IC [equation (3)] or SD [equation (4)]. The dot product or entry-wise product of the two matrixes [equation (5)] calculates the area under the risk of IC. To obtain area with tendency for SD, the matrix of IC is replaced with the SD matrix [equation (6)].

$$\text{Number of casualties (IC)} = \frac{P}{A} \times \Sigma M \tag{7}$$

$$\text{Number of casualties (SD)} = \frac{P}{A} \times \Sigma N \tag{8}$$

To calculate the number of casualties affected by the earthquake, the area IC is multiplied by the occupancy rate [equation (7)]. Occupancy rate is estimated by dividing the population by the built area. Similarly, the estimate of people affected at SD level is obtained by replacing IC area by SD area [equation (8)].

3 Results

Table 2 shows the data collated during field exercise which includes the built area, floor-height group distribution, and occupancy limit. The built area was obtained as a range rather than as point estimates because of the uncertainties involved with the use of Google earth application. Table 3 contains the distribution of the floor-height groups against CQ. It is observed that half of the buildings ≤ 4 floors were of poor quality and only 10% met the high quality requirement. 60% of buildings 5–7 floors were of average quality and the remaining 40% of buildings shared equally between poor quality and high quality constructions. Comparing the quality of the three floor height groups, it is observed that buildings ≥ 8 floors fared better in terms of CQ with 30% high quality and only 10% poor quality of buildings.

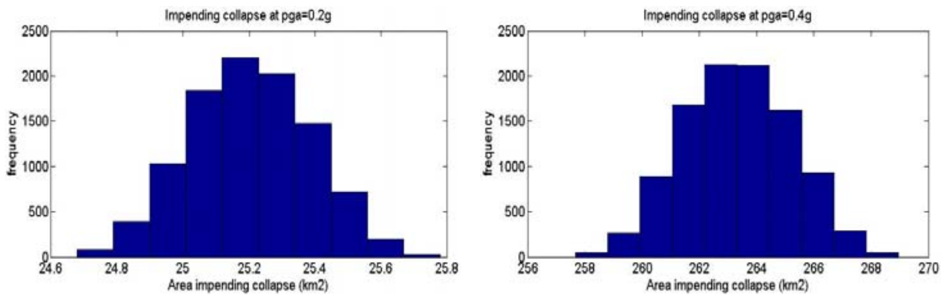
Table 2 Estimates of building area, distribution of floor-heights, and occupancy levels in each division

	Building area (km^2)		*Floor-height group distribution*			*Occupancy (person/km^2)*	
Division	*Min*	*Max*	*≤4 floors*	*5–7 floors*	*≥8 floors*	*Min*	*Max*
Ikeja	380	395	0.5	0.3	0.2	11,736	12,537
Lagos	110	120	0.3	0.5	0.2	9,670	9,981
Badagry	440	450	0.6	0.3	0.1	5,587	5,707
Ikorodu	170	180	0.4	0.5	0.1	2,653	2,995
Epe	400	425	0.4	0.5	0.1	1,214	1,355

Table 3 Floor-height distribution against construction quality (CQ)

	PQ	*AQ*	*HQ*
≤4 floor	0.5	0.4	0.1
5–7 floor	0.2	0.6	0.2
≥8 floor	0.1	0.6	0.3

Figure 1 Histogram of area under impending collapse due to, (a) pga = 0.2 g and (b) pga = 0.4 g (see online version for colours)

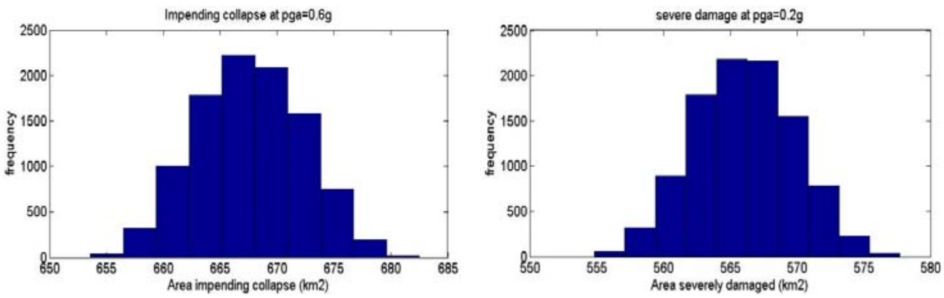


(a) (b)

High rise buildings fared better in terms of concrete strength of data. It was also noted that most of these buildings are owned by government agencies, multinationals or other well to do Nigerians who will see to it that quality is ensured to enhance the durability of the structure. The high values of concrete strength may not be unconnected with the fact that most of the high rise buildings are handled by professionals and foreign contractors. It is also worthy to note that most collapse occurs in buildings that are less than four floors high due to the prevalent rate of quacks in the construction industry. A typical Nigerian in a bid to reduce cost would rather patronise an unqualified charlatan rather than a qualified practitioner to undertake his construction works. The result is the increase in the number of below quality buildings as well as the eventual collapse of such structures.

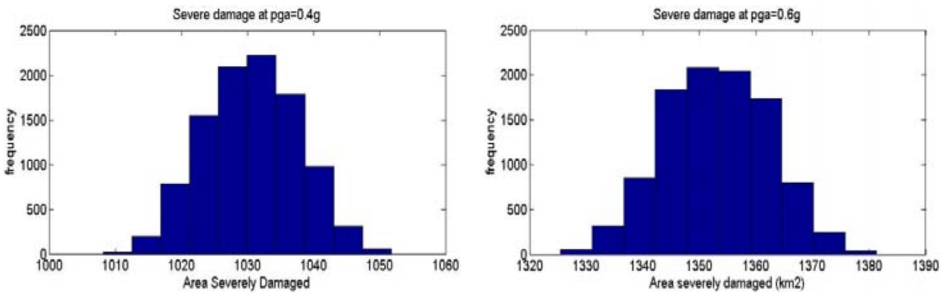
The model estimates the built area that will be affected at IC and SD performance levels considering a uniform seismic intensity measure for the entire study area. Below are histograms for estimated area affected considering different ground motion values under the existing CQ and non-seismic design for both IC and SD limit states.

Figure 2 Area of impending collapse due to, (a) pga = 0.6 g and (b) area affected under severe damage due to pga = 0.2 g (see online version for colours)



(a) (b)

Figure 3 Histograms of area exposed to severe damage due to, (a) pga = 0.4 g (a) and (b) pga = 0.6 g (see online version for colours)



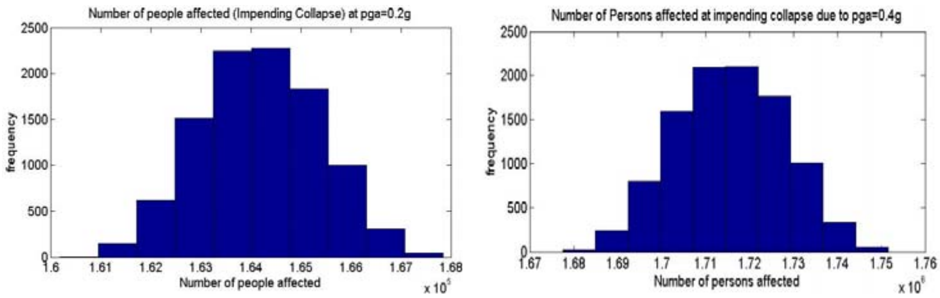
(a) (b)

At the IC limit state and a minor uniform seismic intensity measure of 0.2 g between 24–26 km^2 will be susceptible to collapse [Figure 1(a)]. An average ground motion intensity of 0.4 g will affect about 256–270 km^2 of buildings at the IC state [Figure 1(b)] and as the intensity increases to 0.6 g the vulnerable area range increases to 650–685 km^2 [Figure 2(a)].

Considering the SD performance level, at seismic intensity measure of 0.2 g the model indicates that between 555–580 km^2 of built area will be affected [Figure 2(b)]. As the pga values increase to moderate and high values of 0.4 g and 0.6 g, the estimated range of affected area increases to between 1,000–1,060 km^2 and 1,320–1,390 km^2 respectively [Figures 3(a) and 3(b)].

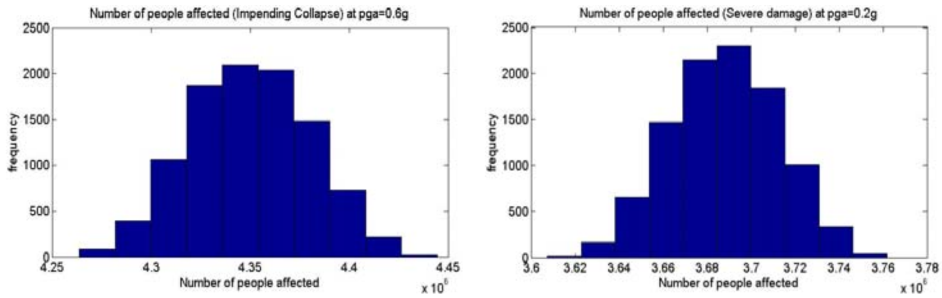
From the histograms, it can be seen that for both the IC and severe damaged states, the built area affected increases as ground motion increases. Comparing the values of both limit states shows that more square kilometres will be severely damaged in the events of minimal and higher ground motions. The impact of losing large building areas will not only negatively impact on Lagos state but also on the entire country since the state serves as the commercial headquarters of Nigeria. Number of casualties is also estimated for different ground motions and the results are shown in Figures 4(a) and 4(b), 5(a) and 5(b) and 6(a) and 6(b) respectively.

Figure 4 Number of people affected at IC due to, (a) pga = 0.2 g and (b) pga = 0.4 g (see online version for colours)



(a) (b)

Figure 5 Number of people affected at IC due to, (a) pga =0.6 g and (b) at SD pga =0.2 g (see online version for colours)



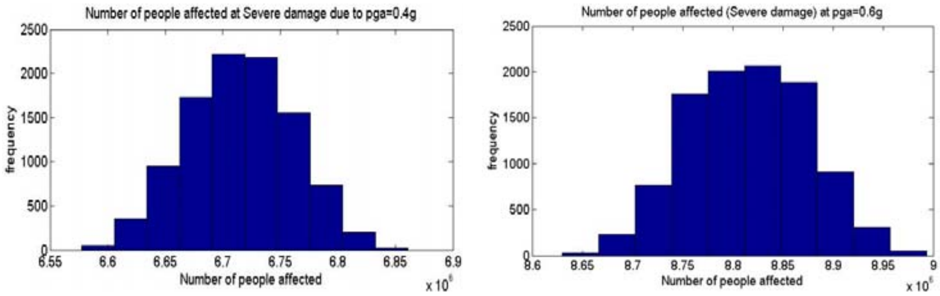
(a) (b)

From the result generated and assuming a uniform ground motion for the study area, it is observed that at IC with pga = 0.2g about 1.6×10^5–1.68×10^5 persons will be affected [Figure 4(a)]. An average seismic intensity measure of 0.4g will have a casualty figure between 1.67–1.76 million [Figure 4(b)] and as the intensity measure increases to a higher value of 0.6g the casualty range becomes 4.25–4.45 million people [Figure 5(a)].

For the SD limit state, and assuming a uniform pga value for the entire study area to be 0.2g, between 3.6–3.78 million people will be affected [Figure 5(b)]. As the ground motion increases to 0.4g and 0.6g, the estimated casualty range becomes 6.55–6.9 million and 8.6–9.0 million people respectively [Figure 6(a) and 6(b)].

Apparently, as the ground motion increases the number of people affected also increases for both the IC and SD performance levels. Based on these statistics, and considering that the estimated population of Lagos state is 21 million (Lagos State Government, 2017), the impact of even a minor intensity seismic activity in this region will be very devastating. The magnitude of these losses on humans, buildings and destruction of the environment are a consequence of the existing quality of buildings. Such negative impact could be drastically reduced if there is adherence to quality standards especially of construction materials by all stakeholders in the building industry. Definitely, good CQ alone is not sufficient to resist earthquakes, and in cases of high earthquakes would not help if the buildings failed to consider seismic load during the design stage. However, good CQ will significantly reduce the losses on both humans and the environment in the event of a small or medium earthquake activity.

Figure 6 Number of people affected at SD due to, (a) pga = 0.4 g and (b) pga = 0.6 g (see online version for colours)



(a) (b)

4 Conclusions

This study shows that an average seismic intensity measure of 0.4g within the built up environment of Lagos state will have a colossal negative impact on its residence. Losing between 1,000–1,060 km^2 of a total area of 3,600 km^2 and 6.5–6.9 million people of a total population of 21 million people will definitely leave a sour and traumatic effect on the government and people of Lagos state. It is therefore necessary to make efforts towards mitigating the effects of such natural hazard. One way to fortify the area and reduce the losses is by designing and building seismic resistant buildings. Design and construction of earthquake resistant buildings will reduce the risk of damage on humans and the built environment by withstanding the impact of such hazards.

Therefore, government must seek for ways of collaborating with relevant stakeholders to produce seismic maps that are necessary for the design of seismic resistant structures. Existing important buildings should also be retrofitted to resist earthquakes. Finally, efforts must be made to ensure that buildings comply with standards as regards to quality of building materials, as this will further strengthen buildings in the study area in the event of seismic activities. Failure to ensure compliance to quality standards will increase the vulnerability of structures and increase the risks of damage, collapse and deaths during earthquake.

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