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FORECASTING THE HAZARDS OF SEISMIC-INDUCED BUILDING COLLAPSE IN LAGOS-NIGERIA THROUGH QUALITY OF REINFORCING STEEL BARS

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ABSTRACT

Building structures are built to support specific class of loads and the design process starts with the choice of the most appropriate combination of materials for optimal safety, economy, aesthetics and social benefits. Reinforced concrete, comprising of concrete and steel reinforcing bars, is one of the most commonly used materials in the built environment industry worldwide. The expected quality of these materials used to produce reinforced concrete must be such that they guarantee ductile behaviour during the expected lifetime of the built structure. However, this is not usually the case in Nigeria, as cases of building collapse due to poor quality materials has been increasingly reported. Also, recent earth tremors in various parts of Nigeria has brought to the fore the need to consider seismic effects in future building designs in Nigeria, which until these recent events was considered aseismic. This research attempts to predict the risks of seismic-induced building collapse in Lagos-Nigeria from the quality of steel reinforcing bars commonly adopted in Lagos. Adopting a uniform seismic intensity similar to the one measured recently in Nigeria, Monte Carlo simulation method was used, employing MATLAB software, to draw random data of building area, occupancy limits, construction quality and failure probability for the study area. Results obtained show that as the quality of steel reinforcement decreases, the area to be affected by a moderate seismic occurrence increases together with the number of people at risk. The implication of this finding is that measures need to be taken to ensure that quality construction materials are used for construction in Lagos in order to protect lives and minimize damage to properties from possible future earth tremor or earthquake.

Key words: Reinforced-Concrete, Building Collapse, Seismic-Risks, Built Area, Ground Motion, Steel Reinforcing Bars.

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1. INTRODUCTION

Over the ages, as the world continue to experience growth and development, so does the quality of construction material available for construction [1]. The transition from the primitive age to the contemporary information/knowledge worker's age, has seen the changes of construction materials from earth to wood, to stone to concrete, to steel to composites [2]. It is the quality of these materials that determines the type of structure obtained in each epoch of human existence. Reinforced concrete, the second generation of concrete material is a product of continuous material evolution and represents the mostly used construction material in the world [3]. It is a composite material per excellence [4] and is widely used because of the complimentary properties of the leading constituent materials of concrete and steel. Concrete and steel offer balancing supports to each other and complement each other's weaknesses, thereby providing the most common structures everywhere [5]. Steel reinforcement imparts great strength, ductility, toughness to concrete and reduces creep and risk of cracks, [6]. The coefficient of thermal expansion of steel (5.8×10^{-6} to 6.4×10^{-6}) is nearly the same as that of concrete (5×10^{-6} to 7×10^{-6}) guaranteeing that temperature changes will not provoke relative movement between embedded steel bars and concrete [7]. The quality of concrete and steel reinforcement adopted must be such to guarantee a ductile behaviour expected of reinforced concrete structure.

Though reinforced concrete has been greatly developed and successfully applied world over, it remains one of the material combinations greatly abused. The application of reinforced concrete composite comes with various challenges in different parts of the world and in Nigeria, where building collapse has become common. Most of the collapsed buildings in Nigeria were made of reinforced concrete [8, 9, 10]. Several researchers have investigated the causes of building collapse in Nigeria and identified corruption, poor supervision, quackery, non-compliance to building codes, non-conformance of material quality and natural hazards among the leading reasons for collapse [10 – 15]. The costs of building collapse are generally very fatal as they include loss of lives, disabilities, economic losses, increase in number of homeless people, among many others [9, 14]. The overall implication of frequent building collapse is that it impedes national development and is not in alignment with the United Nations' (UN) Sustainable Development Goals [15].

A natural hazard previously not considered as a possible cause of building collapse in Nigeria is earthquake because it was widely believed that Nigeria is an aseismic region. But recent series of tremors in Kaduna State and some that have taken place in the western region of Nigeria poses a great concern. After a moderate magnitude seismicity was experienced in September 2009 in Western region of the Nigeria, the Nigerian National Space Research and Development Agency (NARSDA) stated that Nigeria is vulnerable to the occurrence of an earthquake in the near future [16]. Adepelumi [17] used Weibull probability density model to estimate the probable occurrence of earthquake in the South Western part of Nigeria. From here, the need for the generation and execution of seismic risk analyses becomes very evident. Researchers have predicted some levels of seismic hazard based on ground motion modelling in terms of the peak ground acceleration [18].

The structural characteristics that govern its reaction to seismicity are size, geometry, structural arrangement, quality and type of materials and foundation properties [19 – 23]. Developing nations like Nigeria are highly susceptible to severe harms in case of seismic activity because of high population density, poor quality structures, poverty and poor infrastructure. It is possible to reduce the risk of damage to humans and buildings by designing earthquake resistant infrastructures. But the decline in quality of steel bars used in Nigeria has been noticed in recent times, while the need for adequate preparedness for seismic hazard calls for urgent attention. This declining quality of steel bars in the face of possible seismic risks necessitated that this research be carried out.

This research models risks and losses on the built environment due to seismicity in Nigeria, using Lagos State as a case study. It evaluates building areas and number of victims that will be affected considering moderate ground motion in conjunction with quality of common reinforcing bars used in Nigeria. Models like this evaluate losses and provide governments and other stakeholders with information that are necessary for decision making before and after an earthquake. They help in prioritizing 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 [20].

2. METHODOLOGY

The five administrative divisions in Lagos State served as the data collection points, the divisions include: Ikeja, Lagos, Badagry, Epe, and Ikorodu divisions. In each of the divisions, tensile strength data for high yield steel rebar with different diameters was collated. With the aid of Google Earth application an estimate of the built area in each of the divisions was generated. Due to uncertainties involved, the area was obtained as a range rather than as point estimates. A survey to ascertain the quality and size distribution of steel rebar was carried-out on each division. Steel rebar was categorized into three groups based on diameter of steel: 12 mm diameter, 16 mm diameter, and 20 mm diameter.

Occupancy for each of the divisions was estimated by dividing the population by its built area. Monte-Carlo simulation method was used, employing MATLAB software, to draw random variables of construction quality, built area, probability of failure and occupancy limit. The model determined the area of buildings and then the casualty estimated that would be affected by earthquakes with different ground motions. The model calculated two 3 × 3 matrices. The first matrix contains building area arranged according to steel rebar diameter by construction quality (CQ). A second 3×3 matrix was computed which contained the probability of failure (impending collapse or severe damage) arranged in accordance to steel rebar diameter and construction quality (CQ). The entry-wise or dot product of these matrices gave estimates of affected area either as impending collapse or severely damaged. To calculate the first matrix, the built area per steel rebar diameter per construction quality, steel rebar tensile strength value was allocated to one of three levels of CQ. Values of tensile strength of steel (f_y) < 410 N/mm^2 were assigned poor quality construction (PQ), tensile strength between 410-460 N/mm^2 were assigned average quality of construction (AQ), and tensile strength data > 460 N/mm^2 were assigned high quality construction (HQ).

$$Built\ Area;\ [A] = \begin{array}{cccc} & PQ & AQ & HQ \\ \emptyset 12mm & a_{11} & a_{12} & a_{13} \\ \emptyset 16mm & a_{21} & a_{22} & a_{23} \\ \emptyset 20mm & a_{31} & a_{32} & a_{33} \end{array} \qquad (1)$$

where;

A = Built area

∅ = Steel rebar diameter

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 construction quality.

To obtain results for the second matrix, probability of failure is drawn from the fragility functions. Given different peak ground acceleration (pga) values the probabilities of either impending collapse or severe damage was calculated. The failure probability (P_f) conditioned by ground motion parameter was calculated using the log-normal cumulative distribution function (Eq. 2). The result produced was arranged into a second matrix with values containing probability of impending collapse or severe damage per steel rebar diameter and per construction quality.

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

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. Adapted from [21]

		Lower limit		**Average limit**		**Higher limit**	
		Median (μ)	Log Std (β)	Median (μ)	Log Std (β)	Median (μ)	Log Std (β)
IC	ø12 mm	1.25	0.442	1.01	0.44	0.771	0.439
	ø16 mm	0.679	0.442	0.55	0.45	0.418	0.459
	ø 20 mm	0.549	0.440	0.447	0.448	0.344	0.456
SD	ø12 mm	0.49	0.531	0.414	0.488	0.338	0.445
	ø16 mm	0.32	0.562	0.269	0.522	0.217	0.482
	ø 20 mm	0.275	0.597	0.232	0.518	0.189	0.44

$$Probability\ of\ failure\ (IC);\ [B] = \begin{matrix} & PQ & AQ & HQ \\ \emptyset 12mm & b_{11} & b_{12} & b_{13} \\ \emptyset 16mm & b_{21} & b_{22} & b_{23} \\ \emptyset 20mm & b_{31} & b_{32} & b_{33} \end{matrix} \tag{3}$$

$$Probability\ of\ failure\ (SD);\ [C] = \begin{matrix} & PQ & AQ & HQ \\ \emptyset 12mm & c_{11} & c_{12} & c_{13} \\ \emptyset 16mm & c_{21} & c_{22} & c_{23} \\ \emptyset 20mm & c_{31} & c_{32} & c_{33} \end{matrix} \tag{4}$$

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

$$[A] * [C] = N \quad (6)$$

where;

A = Matrix of Built Area (km^2)

B = Matrix of Probability of impending Collapse

C = Matrix of Probability of severe damage

M = Area impending collapse (km^2)

N = Area severely damaged (km^2)

P = Population

The second matrix contains values for probabilities of impending collapse (Eq. 3) or severe damage (Eq. 4). The dot product or entry-wise product of the two matrixes (Eq. 5) was used to calculate the area under the risk of impending collapse. To obtain the area with tendency for severe damage, the matrix of impending collapse was replaced with the severe damage matrix (equation 6).

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

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

To calculate the number of casualties affected by the earthquake, the area impending collapse was multiplied by the occupancy rate as shown in Eq. (7). Occupancy rate was estimated by dividing the population by the built area. Similarly, the estimate of people affected at severe damage level was obtained by replacing impending collapse area by severe damage area (Eq. 8).

3. RESULTS AND DISCUSSION

Table 2 shows the data collated during field exercise which includes the built area, floor-height group distribution, and occupancy limit. Table 3 contains the distribution of the diameter of steel rebar against construction quality (CQ). It was observed that for ø12 mm steel, 25% were of poor quality, 12% were of average quality and 63% met the high quality requirement. 31% of ø16 mm steel was poor in quality, 15% average quality and 54% reached the high quality benchmark. Comparing the quality of the three steel rebar diameters, it was observed that buildings constructed with ø20 mm steel performed better in terms of construction quality with 69% high quality and only 16% were of poor quality.

Table 2 Estimates of building Area, distribution of floor-heights, and occupancy levels

	Building Area (km^2)		**Steel rebar distribution**			**Occupancy (person/km^2)**	
Division	Min	Max	ø12 mm	ø16 mm	ø20 mm	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 Showing floor-height distribution against Construction Quality (CQ)

	PQ	AQ	HQ
ø12 mm	0.25	0.12	0.63
ø16 mm	0.31	0.15	0.54
ø20 mm	0.16	0.15	0.69

The fragility curves are shown Figures 1 to 3. From the presented curves, it is observed that for both the impending collapse and severe damage performance levels, as the floor height increases, the probability of failure increases. Similarly, as the construction quality increases from PQ to HQ, the probability of failure decreases for both limit states.

The model estimates the built area that will be affected at impending collapse and severe damage performance levels considering a uniform seismic intensity measure for the entire study area. Figure 4 depicts the histograms for estimated area affected considering different ground motion values under the existing construction quality and non-seismic design for both impending collapse and severe damage limit states.

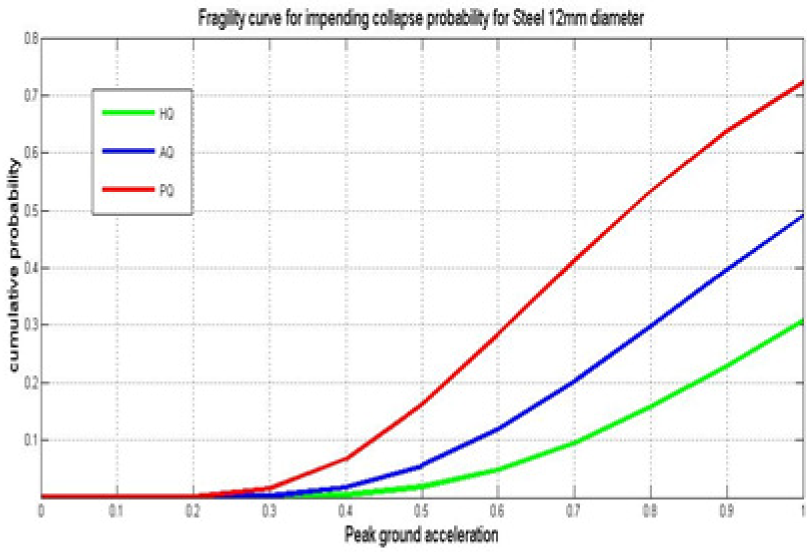

Figure 1 Fragility curve for impending collapse probability for ø12 mm steel

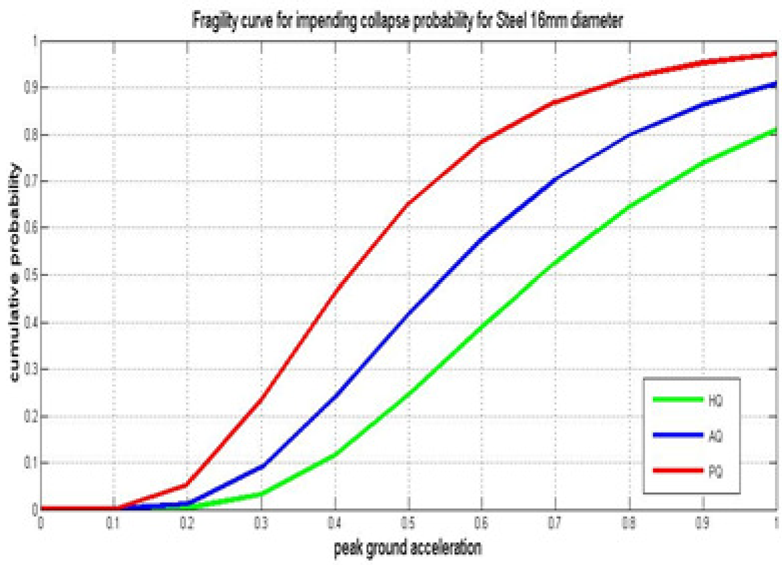

Figure 2 Fragility curve for impending collapse probability for ø16 mm steel

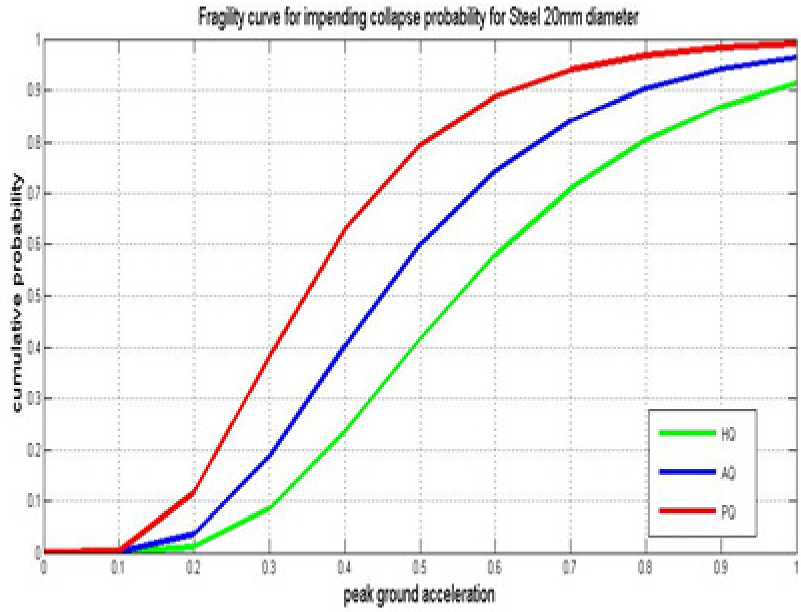

Figure 3 Fragility curves for impending collapse probability for ø20 mm steel

At the impending collapse limit state and a minor uniform seismic intensity measure of 0.2 g between 23.6 – 24.8 km^2 will be susceptible to collapse (Figure 4a). An average ground motion intensity of 0.4g will affect about 224 – 236 km^2 of buildings at the impending collapse state (Figure 4b) and as the intensity increases to 0.6 g the vulnerable area range increases to 730 – 765 km^2. Considering the severe damage performance level, at seismic intensity measure of 0.2 g the model indicates that between 545 – 575 km^2 of built area will be affected. As the peak ground acceleration values increase to moderate and high values of 0.4 g and 0.6 g, the estimated range of affected area increases to between 905 – 945 km^2 and 1230 – 1300 km^2 respectively.

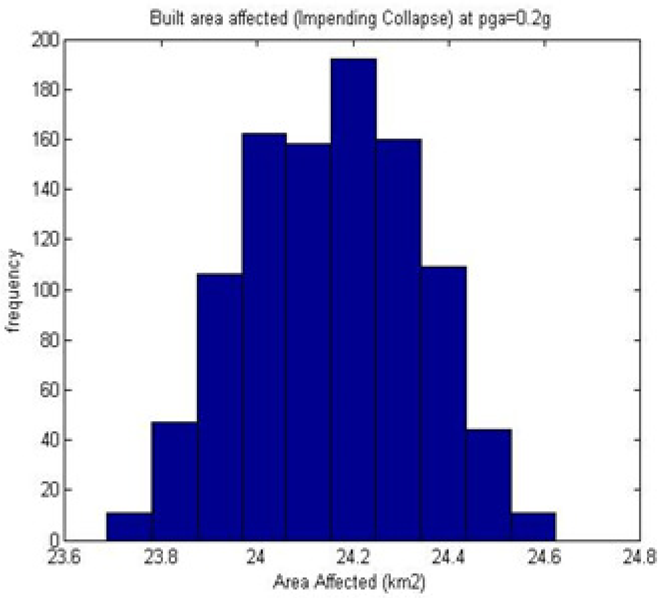

Figure 4a Histogram of area under impending collapse due to pga = 0.2 g

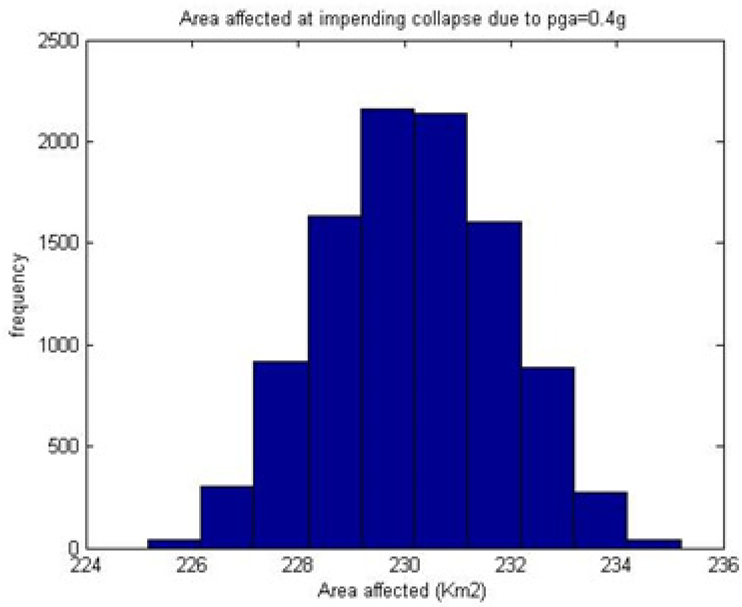

Figure 4b Histogram of area under impending collapse due to pga = 0.4 g

The number of people to be affected is equally modelled and shown in Figures 5a and 5b. From the result generated and assuming a uniform ground motion for the study area, it is observed that at impending collapse limit state with pga = 0.2g about 1.54 $\times 10^5$ – 1.61 $\times 10^5$ persons will be affected (Figure 5a). An average seismic intensity measure of 0.4g will have a casualty figure between 1.46 – 1.54 million (Figure 5b) and as the intensity measure increases to a higher value of 0.6g the casualty range becomes 4.75 – 5.0 million people.

For the severe damage limit state, and assuming a uniform pga value for the entire study area to be 0.2g, between 3.56 – 3.72 million people will be affected. As the ground motion increases to 0.4 g and 0.6g, the estimated casualty range becomes 5.9 – 6.2 million and 8.05 – 8.45 million people respectively.

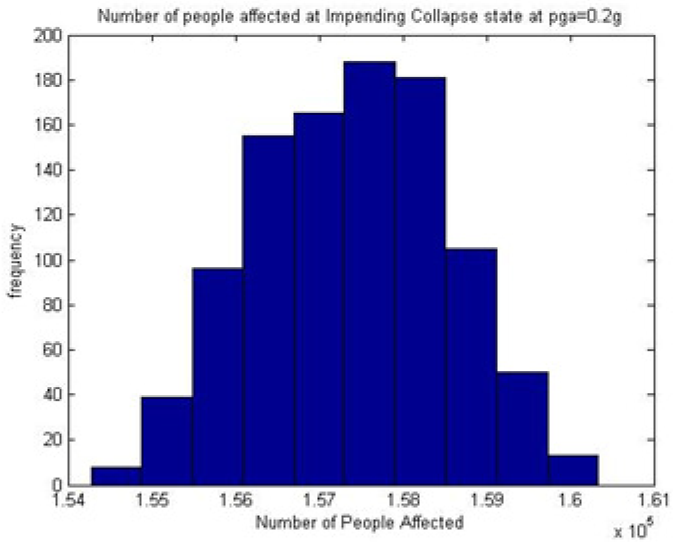

Figure 5(a) Number of people affected at IC due to pga = 0.2 g

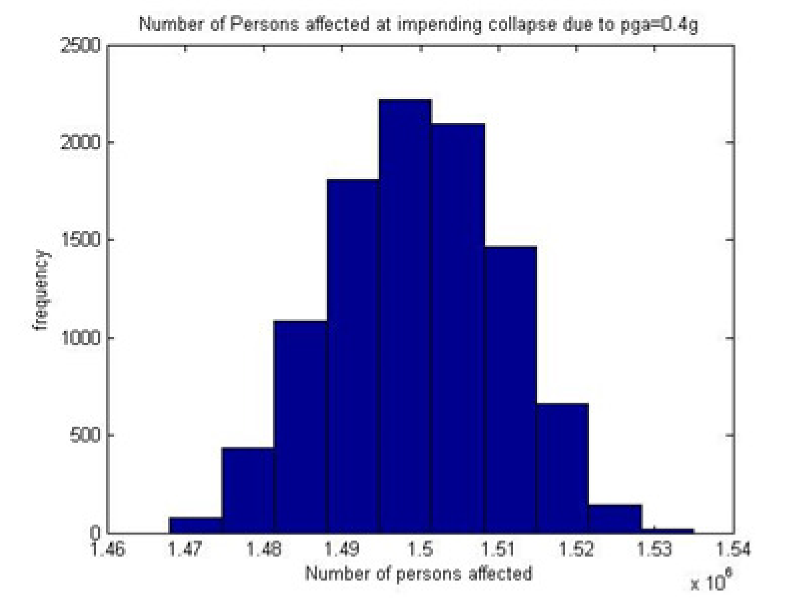

Figure 5(b) Number of people affected at IC due to pga = 0.4 g.

4. CONCLUSIONS

This study clearly shows that an average seismic intensity measure of 0.4g within Lagos State will have a colossal negative impact on its residence based on the current strengths of steel bars adopted for construction in Lagos-Nigeria. The fragility curves show that as the floor height increases, the probability of failure increases. An average ground motion intensity of 0.4g will affect about 224 – 236 km^2 of buildings at the impending collapse state. Losing between 224 – 236 km^2 of a total area of 3600 km^2 and 1.46 – 1.54 million people of a total population of 21 million people for a moderate ground motion intensity of 0.4g will definitely leave a sour and traumatic effect on the government and people of Lagos State. It is therefore necessary for Nigeria to take proactive measures to mitigating the effects of such possible natural hazards. One way to reduce the risk of damage on humans and the built environment will be to drive for improved quality of steel bars adopted for construction and to implement the design of ductile structures capable of withstanding the impact of seismic hazards.

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