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Short-term Probabilistic Prediction of Earthquake Occurrence in Southwestern Nigeria.

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Abstract
Prediction of the time interval when the next strong earthquake or tremor would occur in a seismic source region is a difficult and ill-posed problem. In this study, a priori information on past records of earthquake occurrences, distribution of observed interval times between earthquake events and the elapsed time since the last earthquake occurred are the information needed for the prediction of a new seismic event. A well-tested, time-dependent statistical model was employed to predict the probabilistic occurrences of earthquakes. The Earthquake Recurrence Model uses two predictors based on concepts of fracture and earthquake recurrence rate. This probability model takes the mean recurrence intervals and standard deviation of historic earthquake events in the study area in order to determine the probability of earthquake occurrence for the predicted years. The earthquake records used showed that at least twelve minor earthquakes/tremors of magnitude (M_S) varying between 1 and 5.4 had occurred in the region since 1914. A time-window of Year 2008-2029 was considered for the modelling exercise taking into consideration the Ijebu-Ode region, south-western Nigeria. It is thus assumed that the sequence of events recorded in this region represents a set of an unknown number of consecutive phases, and that the observations follow the Poisson distribution process. The results of the model showed that the probability of earthquake occurrence in the study area between the Year 2009 and 2028 increased from 2.8% to 91.1%. The result also showed that the probability of 2 events occurring has the highest likelihood within the predicted years. It was also observed that the Weibull probability density model predicts a damaging earthquake ($M \geq 5$) before Year 2020. However, there is inherent danger in using purely empirical predictors like the one employed in this study; therefore the result should be treated as preliminary.

Keywords: *Earthquakes, Probability, Recurrence Model, Seismics, Statistical Model, Nigeria.*

Introduction
Natural hazards are assuming ever greater economic importance, not only on a regional scale but also on a global scale. The growth of major cities in hazard-prone areas, and the public anxiety associated with earthquake risks such as destruction of buildings, fire outbreak and loss of lives have focused attention on the problems of insurance against natural hazards, disaster mitigation, and disaster prevention (David, 1995).

In the last three decades, there has been considerable optimism among scientists concerning the future of earthquake prediction. Many observational studies showed that the occurrence of major earthquakes was preceded, at least on some occasions, by anomalous behaviour of animals and variations in measurable phenomena such as changes in groundwater level, fluctuations of magnetic and electric fields, and small changes in the topography near the causative earthquake fault (David, 1995).

Probabilistic forecasting of earthquakes both on short and long term bases is well established (Kagan and Jackson, 1994; Ogata, 1988; Kagan and Knopoff, 1987). The need for an integrated and Africa-wide early warning system is now imperative to warn coastal population of impending hazards from flooding, earthquakes and other associated coastal hazards. Such an early warning system will also complement and ensure preparedness programmes to alleviate poverty and enhance national socio-economic developmental programmes.

Some scientists have proposed statistical distributions for the conditional probabilistic determination of future earthquakes on a specific fault which include the Double Exponential (Utsu, 1972), Gaussian (Rikitake, 1974), Weibull (Hagiwara, 1974), Log-normal (Nishenko and Buland, 1987), Gamma (Utsu, 1984; Ferráes, 1967) distributions. But according to Aki (1989), prediction of earthquake should be based objectively on precursory phenomenon. 2002, Console *et al.* (2002) gave a detailed account of the relevance of statistical method in predicting the year, n, when the next large earthquake will occur in a Japanese prefecture; while Ferráes (2003a, 2003b) used the Weibull method for predicting the time interval in which the next large earthquake of magnitude ≥ 7 will occur in Mexico. Also, Pievatolo and Rotondi (2008) successfully identified seismicity phases using statistical method.

Furthermore, Wright (1976) identified two major fracture zones along with other important shear zones that are possibly important segments of longer fracture systems in Nigeria (Fig. 1). Tectonic movements along these fracture zones are suspected to be the source of the tremors and/or earthquakes that have been experienced in the study area.

The ultimate aim of this study is to provide information about future earthquake occurrences in south-western Nigeria so as to assist in hazard reduction. The probabilistic forecasting is defined as estimating the probability of occurrence of an earthquake within a specified time, place and magnitude window. In this study, the Empirical Recurrence Earthquake Model is used to predict the probabilistic occurrence of earthquake in Ijebu-Ode and environs between year 2009 and year 2028. This project is borne out of the fact that earthquake events occur in cycles. That is, once an event takes place in a particular region, definitely another event would occur again, although the events are not periodic. The main objective therefore is to predict the reoccurrence of earthquake events in the next twenty years, based on plausible mathematical method. The prediction will assist in taking pragmatic measures (planning and evacuation) to reduce the risks that are associated with the earthquake events.

The study area

Ijebu Ode is located in Ogun State, Nigeria about 65 km north-east of Lagos, and 70 km south of Ibadan. Fig. 1 shows the location of the study area within the south-western part of Nigeria. Ijebu Ode and its environs lie between Latitudes 6°40’N and 6°55’N and Longitude 3°45’E and 4°10’E having an area extent of about 1600 km^2.

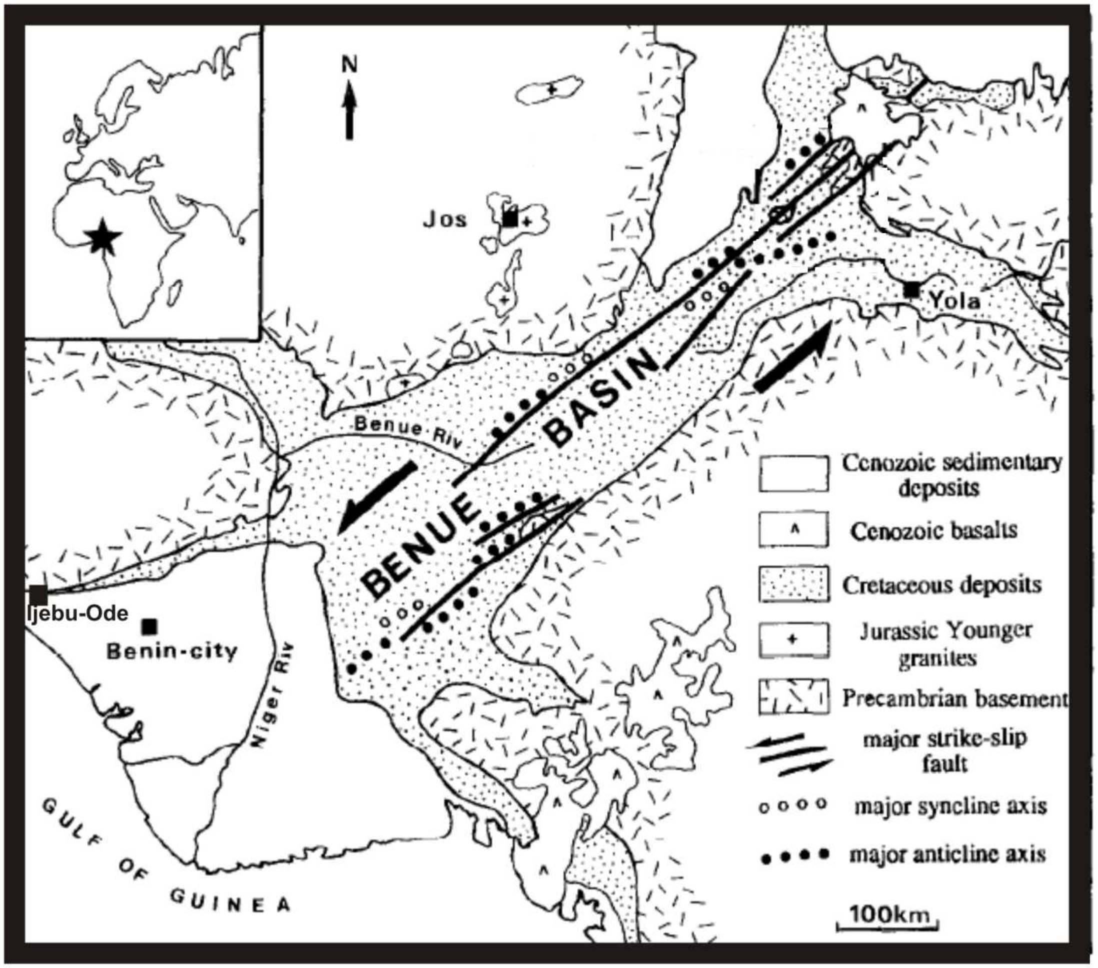

Fig. 1: Generalised geological of map of Nigeria (After Michel Guiraud and Plaziat, 1993)

Ijebu Ode is situated in one of the sedimentary basins of Nigeria named the Dahomey Basin. The basin is also known as the Benin Basin, Dahomey Embayment or West Nigerian Basin in older literature. It extends from south-eastern Ghana in the west, through southern Togo and southern Benin Republic to south-western Nigeria. The axis of the basin and thickest sediments occur slightly west of the border between Nigeria and the Benin Republic. The evolution of structural and tectonic setting within the Dahomey Basin has been accounted for by many authors. The Basin was initiated during the Mesozoic in response to the separation of the African-South American land masses and the subsequent opening of the Atlantic Ocean.

Deposition was initiated in fault-controlled depressions on the crystalline basement complex. The depressions were formed as a result of rift-generated basement subsidence during the Early Cretaceous (Neocomian). The subsidence gave rise to the deposition of a very thick sequence of continental grits and pebbly sands over the entire basin. Over 1400 meter of these sediments is preserved in coastal areas in Nigeria and offshore Benin Republic (Omatsola and Adegoke, 1981; Billman, 1992). During the Late Cretaceous (Santonian), there was another episode of major tectonic activity, probably associated with the closure and subsequent folding of the Benue Basin. The basement rocks as well as the sediments in the basin were tilted and block-faulted, forming a series of horsts and grabens (Omatsola and Adegoke, 1981). Considerable erosional activity accompanied the uplifting and block-faultings, and the extensive Lower Cretaceous sediments were almost completely eroded from the horsts.

During the Maastrichtian, the basin became quiescent and has experienced only gentle subsidence since. The basin is bounded on the west by faults and other accompanying tectonic structures like horsts and grabens. The Benin Hinge Line, a major fault structure marking the western limit of the Niger Delta basin, marks its eastern limit. To the west of the Benin Hinge Line is the Okitipupa Ridge (Adegoke, 1969). All these tectonically faulted structures mentioned above are seismologically favourable for the occurrence of earth tremors any time the faulted blocks move along each other in the course of their readjustment. The stratigraphic sequences within the Dahomey Basin are the Ise (oldest), Afowo, Araromi, Ewekoro, Imo, Oshosun, Ameki, Ogwashi-Asaba and the Benin Formations (youngest).

Methodology: Empirical earthquake recurrence Model

In order to predict the occurrence of an earthquake in a particular region, a probability model for an earthquake occurrence is required. This probability model describes how earthquakes are distributed over time, given a set of assumed conditions. It uses the rupture source mean occurrence rate as primary input. A suite of probability models that take into account various amounts of physics going on in the block-faulted system; various views on the relative importance of certain observables, e.g. date of the last rupture and recent seismicity rates. Statistical probability models are useful tools in characterizing seismic hazard, because earthquakes are, for all practical purposes, random phenomena.

Earthquake hazard assessment and seismicity studies are relatively new areas of research in Nigeria. Owing to rarity of earthquakes in this part of Africa, the database for this study is almost nonexistent. However, awareness of seismic hazards has been on the increase since the occurrence of a major earthquake in northwest Gulf of Guinea on September 30, 1971 with a magnitude of 6.0, and in Guinea on December 22, 1983 with magnitude of 6.4. The latter was followed shortly by some widely felt tremors in Ijebu-Ode area of southwestern Nigeria in July and August, 1984.

The sources of the seismic events records used are the USGS, Orfeus (Netherlands) and LAMTO Seismic Observatory, Ivory Coast. The sources determined the epicenter of the July 28, 1984 earth tremor to be at Ijebu-Ode. The years of the previous earthquake occurrences in the Ijebu-Ode region were recorded by other seismic observatories around the world. Given an interval of t years since the occurrence of the previous event, it is important to determine the probability of failure before time $t+\Delta t$. Then the conditional probability $P(t<T\leq t+\Delta t|T>t)$, which is the probability that an earthquake occurs during the next Δt interval is given by Ferráes (1967):

$$P(\Delta t/t) = \frac{P(t < T \leq t + \Delta t)}{P(T \geq t)} \quad (1)$$

In terms of probability density of T, say f, we have

$$P(t < T \leq t + \Delta t) = \int_t^{t+\Delta t} f(s)ds \quad (2)$$

and

$$P(T \geq t) = \int_t^{\infty} f(s)ds \quad (3)$$

By substituting Equations (2) and (3) in Equation (1)

$$P(\Delta t/t) = \frac{\int_t^{t+\Delta t} f(s)ds}{\int_t^{\infty} f(s)ds} \quad (4)$$

Wesnousky (1984) pointed out that Equation (4) provides a reasonable tool for estimating seismic hazard on a fault or faulted segment and made assumption that the underlying probability distribution of earthquake recurrence time intervals is normal. If earthquakes behave in a purely periodic fashion, the conditional probability P(*Δt/t*) would always be unity. However, in nature, stochastic fluctuations occur. Therefore, the forecasting can be obtained by maximizing the conditional probability P(*Δt/t*) at

$$\frac{\partial}{\partial t} p(\Delta t/t) = 0 \quad (5)$$

In general, P(*Δt/t*) is a real-valued function of two real variables (*Δt*, *t*). *t*, the elapsed time since the last earthquake, can be measured. Thus, our fundamental problem is to predict the time interval, *Δt*, for the occurrence of the next event, given an observed *t* since the last earthquake.

Empirical earthquake recurrence model can be used to predict a probabilistic occurrence of an earthquake event within a given range of magnitude, in a particular area over a time interval *Δt*. The prediction is done based on the records of the years of events that had taken place in the area with respect to the year of prediction and the predicted year of event to occur.

If X_1, X_2, X_3, X_4, …………………X_n are the recorded years of earthquake events, the approaches to using recurrence model is as follows:

Determination of the mean recurrence interval, μ, of years of earthquake events:

$$\mu = \frac{X_1 - X_n}{n-1} \quad (6)$$

Determination of recurrence times between each successive pair of earthquake events:

X_1-X_2, X_2-X_3, X_3-X_4, ………… X_{n-1}-X_n (7)

Determination of standard deviation, σ, of the number of recurrence intervals with the number of earthquake events recorded:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \mu)^2}{n-1}} \quad (8)$$

Determination of the elapsed years, Et, since occurrence of the last event, X_l, with respect to the year of prediction, Yp:

$$Et = Yp - X_1 \quad (9)$$

Determination of the number of year the elapsed years shy of, Ys or past, Yp the mean recurrence interval:

$$Ys = \mu - Et \quad (\mu \geq Et) \quad (10a)$$

$$Yp = Et - \mu \quad (\mu \leq Et) \quad (10b)$$

How many standard deviation shy of σ_s, or past of σ_p, the mean recurrence interval would be?

$$\sigma_s = \frac{Y_s}{\sigma} \quad (11a)$$

$$\sigma_p = \frac{Y_p}{\sigma} \quad (11b)$$

A normal distribution of recurrence intervals is distributed about the mean recurrence interval, where a curve is plotted using the expression below:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (12)$$

Equation (12) is later converted to the standard Normal Probability Density Function which is a bell-shaped curve, of a function $\phi(z)$ plotted against predicted years

$$\phi(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2} \quad (13)$$

where $z = \frac{x-\mu}{\sigma}$ and $x = Et$

The probability of an earthquake occurrence in a certain year with respect to present year is calculated by dividing area under the curve from year of prediction to the predicted year by area under the curve from the year of prediction to infinity.

Results and Discussion

Earthquake recurrence estimation

The available set of recorded years in which earthquakes of intensity ranging from IV–VI, on the basis of their macroseismic effects, had occurred in Ijebu-Ode and its environs are: 2007, 2002, 1993, 1984, 1969 and 1960. Using the earthquake recurrence model to predict the probabilistic occurrences of earthquakes for 2009 – 2028 in Ijebu-Ode and its environs based on the above set of years of earthquake occurrences, the following data are determined:

The mean recurrence interval from Equation (6), $\mu \approx 8 years$;

Recurrence time interval between successive pair of earthquake events from Equation (7) are respectively 5, 1, 8, 9, 15, 9;

The standard deviation of the six recurrence time intervals from Equation (8), $\sigma \approx 5 years$;

The elapsed year since the occurrence of the event of 2007 with respect to 2008 from Equation (9), $Et = 1 year$;

Using Equation (10a), the elapsed year is 7 years shy away from the mean recurrence interval;

The standard deviation shy of the mean recurrence interval from Equation (11a), $\sigma_s = 1.4$;

Equation 13 is then used to generate a standard normal probability density function curve for $1 \le x \le 26$ and a graph of $\phi(z)$ plotted against predicted years (Fig. 2).

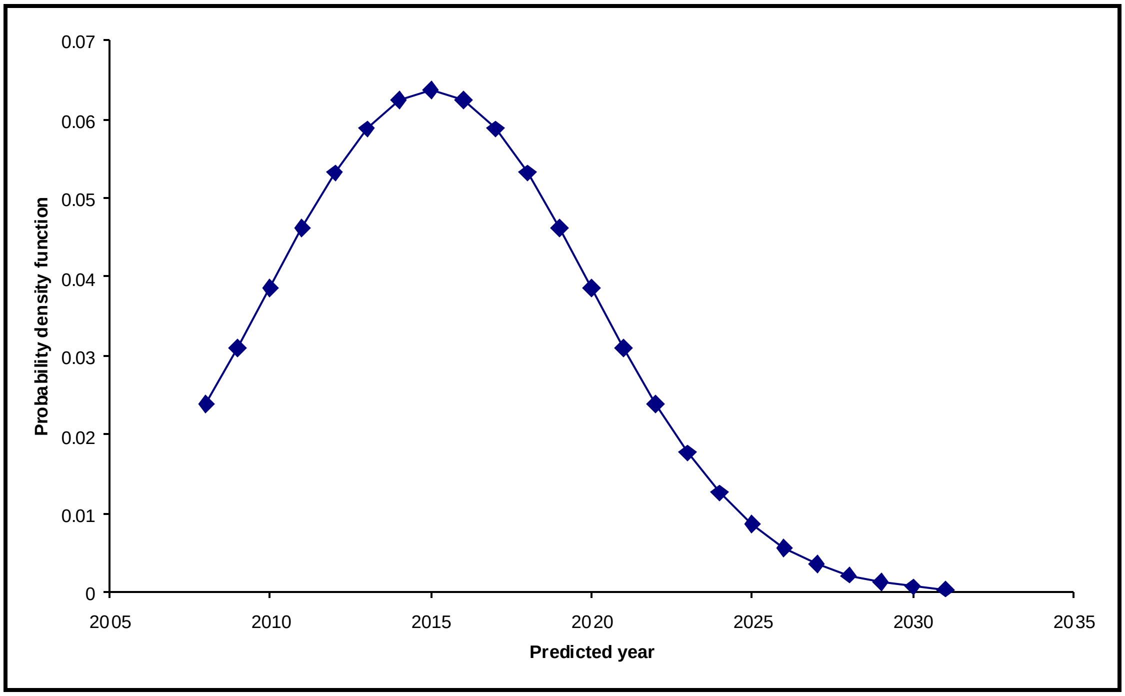

Fig. 2: Normal Probability density function curve for empirical earthquake recurrence model

Probability of earthquake occurrence in 2009 (P_{2009})

The probability of earthquake occurrence in 2009 is the area under the curve from 2008 to 2009 divided by the area from 2008 to infinity. In year 2009, the elapsed time (Et) is 6 years shy of the mean recurrence interval. Equation (11) gives

$$\sigma_s = \frac{6}{5} = 1.2$$

From Fig. 2, the area under the probability density curve from the mean to 1.4 standard deviation shy of the Mean is 0.306443. The area under the probability density curve from the Mean to 1.2 standard deviation shy of the Mean is 0.022494. The area under the probability density curve from 1.4 standard deviation shy of the Mean to infinity is 0.5 + 0.306443. Therefore,

$$P_{2009} = (0.306443 - 0.283949) / (0.5 + 0.306443)$$
$$= 0.028$$
$$= 2.8\%$$

By using the same principle, the probability of earthquake occurrence between 2010 and 2028 was determined and the results are as shown in Table 1. If the earthquakes are considered to be distributed randomly (i.e. they are characterised by Poisson distribution), then the probability of an earthquake occurring does not depend on how much time has elapsed since the last earthquake. The probability of 'x' number of earthquakes occurring in a given interval of time t is given by:

$$P(x) = \frac{(vt)^x e^{-vt}}{x!} \qquad (14)$$

where v is the average rate of occurrence (1/µ)

Table 1: Summary of probability of earthquake occurrence

Predicted Year	Standard Deviation Shy of or Past Mean	Probability Density Function	Area under Probability Density Curve	Probability of Earthquake Occurrence	Percentage Probability (%)
2009	-1.2	0.030988	0.283949	0.027893	2.7893
2010	-1	0.038613	0.255687	0.062938	6.2938
2011	-0.8	0.046228	0.21978	0.107463	10.7463
2012	-0.6	0.053175	0.175255	0.162674	16.2674
2013	-0.4	0.058767	0.122429	0.228179	22.8179
2014	-0.2	0.062401	0.063032	0.301833	30.1833
2015	0	0.063662	0	0.379993	37.9993
2016	0.2	0.062401	0.063032	0.458154	45.8154
2017	0.4	0.058767	0.122429	0.531807	53.1807
2018	0.6	0.053175	0.175255	0.597312	59.7312
2019	0.8	0.046228	0.21978	0.652524	65.2524
2020	1	0.038613	0.255687	0.697049	69.7049
2021	1.2	0.030988	0.283949	0.732094	73.2094
2022	1.4	0.023893	0.306443	0.759986	75.9986
2023	1.6	0.0177	0.32545	0.783555	78.3555
2024	1.8	0.012599	0.343173	0.805532	80.5532
2025	2	0.008616	0.361389	0.82812	82.812
2026	2.2	0.005661	0.381276	0.852781	85.2781
2027	2.4	0.003574	0.403414	0.880232	88.0232
2028	2.6	0.002168	0.427892	0.910585	91.0585

X	$(X-\mu)^2$	Z	Z^2	$Z^2/2$	Ø(z)
5	9	-0.6	0.36	0.18	0.33
1	49	-1.4	1.96	0.98	0.15
8	0	0	0	0	0.40
9	1	0.2	0.04	0.02	0.39
15	49	1.4	1.96	0.98	0.15
9	1	0.2	0.04	0.02	0.39
	Σ = 109				

The probability of getting 0, 1, 2, 3 and 4 earthquakes from Equation (14) are respectively 8%, 20%, 25%, 21%, and 13%.

As shown in Table 1, the probabilities of earthquake occurrence increase from 2.8% to 91.1% between 2009 and 2028; this forecast result passes the 95% confidence limit. Furthermore, as the predicted years of earthquake occurrence tend to infinity, the probability of earthquake occurrence would tend to rise to 100%. Also, the divergence of the curve in Fig. 3 gives unity, i.e. diverges to 100%, confirming that earthquake will most likely occur in this region within the predicted frame of years. The implication of the increment in these probabilities directly with the increment in the years is that as the years go by, more stress is built up within the plane of the block-faulted system in the sub-surface of Ijebu-Ode area. According to the steps that are involved in earthquake cycle, since earthquakes of low magnitudes had occurred in Ijebu-Ode, this area has been in stages of quiescence and precursory activity which involve stress build-up within the plane of the block-faulted system. Presently, the stress is acting on the fault plane, and an event will take place in this region when the fault plane can no longer withstand the stress acting on it. The high probability values towards the end of the predicted years show that there is the likelihood of earthquake occurrence between 2017 and 2028 where the probability of earthquake occurrence ranges from 6.0% to 91.1%.

It should be noted, however, that the predictions of probabilities of earthquake occurrence as shown in Table 1 do not guarantee that earthquake events will keep occurring throughout all the times of the years, especially where probabilities of occurrence are high, but they will occur at random out of the years predicted. The probabilities of getting 0, 1, 2, 3, 4, and 5 events within the 20 predicted years of earthquake according to Equation (13) are 8%, 20%, 25%, 21%, 13% and 6% respectively. This shows that the probability of 2 events occurring within the 20 predicted years is the highest.

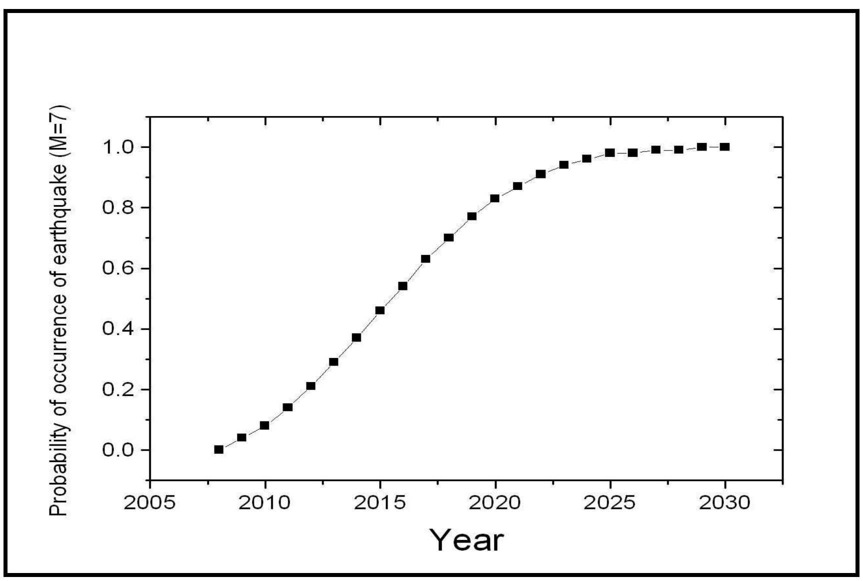

Fig. 3: Probability of reoccurrence of earthquake in Ijebu-Ode and its environs

Conclusions

The time interval for the occurrence of the next large earthquake in Ijebu-Ode area of south-western Nigeria using the maximum of the conditional probability $P(\Delta t / t)$ of earthquake occurrence was determined using the Weibull probability density model. The model was statistically tested and the results obtained provide useful information regarding earthquake potential and seismicity of the study area. From the study, it was estimated that a large earthquake of magnitude M≥ 5 may possibly occur within the next time interval, $\Delta t = 30$ years, counting from 2008 or before 2038. The event occurrence tends to be very high in the next 15 to 20 years in this seismic region. Having established that Ijebu-Ode and its environs are seismic windows that are still building up stress in the sub-surface block-faulted systems, seismic hazards and attendant effects are the dangers ahead of the study area within the next few years, if earthquake of appreciable magnitude should occur in Ijebu-Ode and its environs. It is worthy of note that while the earthquake probability model obtained is not exhaustive, other statistical probability models can be carried out in the region in order to determine the probable date and time these predicted events will take place. However this model, as developed from this study, could serve as a source for seismic hazard and risk estimations for the purpose of planning long term earthquake strategies.

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