ISSN: 2278 – 7798
International Journal of Science, Engineering and Technology Research (IJSETR)
Volume 5, Issue 10, October 2016

The 10Th September 2016 Lake Victoria Earthquake: Insights from Distributions of Strong Ground Motion, Felt Intensity and Induced Damages

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***Abstract*— A 5.9 magnitude earthquake that hit the Lake Victoria region of northern Tanzania on September 10, 2016 caused widespread damages. As many as 840 houses were completely destroyed, thousands of people were left homeless, at least 17 people lost their lives, and more hundreds suffered injuries. We analyzed the strong-motion records (PGA) predicted or reported by global seismic station during the event, the felt intensity data collected by on-line systems from people who felt the event, and correlated them to visual structural damages reported from affected sites. The findings were that the distribution of PGA and instrumental seismic intensity were lower than observable infrastructural damages. These lower values of derived or estimated instrumental and felt intensity values than the earthquake generated infrastructural damages are directly related to the age and type of buildings, as well as building practices at the affected areas. Overall, the large populations in this region are residing in structures that are vulnerable to earthquake shaking, though some few resistant structures exist. The comparisons of the USGS predicted and observed data for the Lake Victoria earthquake to that predicted using local empirical equation, reviled some miss- correlations as well specifically closer to the earthquake epicenter.**

***Index Terms*—Earthquake ShakeMap, Earthquake damages, Seismicity, Earthquake severity.**

I. INTRODUCTION

An earthquake with the magnitude of 5.9 on the Richter scale and at a depth of 40km hit the Lake Victoria region between Tanzania, Uganda and Rwanda on 10th September at 15:27 local time [3]. The epicenter for the earthquake was to the east of the north-western town of Nsunga on the border of Lake Victoria. The earthquake was considered 7.99 on the Modified Mercalli Intensity scale which is between very strong and severe [3], [9].

The earthquake struck around 44 kilometers from Bukoba with generated ground acceleration of about 10 %g and Modified Mercalli intensity (MMI) of about VI [3], [9]. The quake inflicted extensive damage to buildings in Bukoba (Figure 1), resulted into 17 fatalities, injured 252 people and 840 families were left homeless. The town of Bukoba suffered the most damages into its infrastructures such as roads and collapses of most building due to the age and type of building construction practices in the city [9]. A school (or school residence) was damaged with 15 boys injured. The vulnerable nature of the building typologies are one cause of the high number of fatalities through this event, but of course a magnitude 5.9 earthquake would cause major damage even in developed countries. Over half of buildings in the affected area were built of Pole and Mud (often basic columns with rammed earth in between in Adobe style). 41.4% of buildings are built with bricks of mostly baked or sun-dried form [3].

The strong ground motion induced by the Lake Victoria earthquake could be felt in Uganda where four people were killed in Kamuli and seven others were injured in the Rakai District [5]. In Rwanda and Burundi, people were running for fear, as well as in Kenya. In Uganda the nearest places to the event epicenter were Minziro, Bulembe, Ruzinga, Kakira, Buyango, Kakindu, Kyesimbi, Mtukula, Kanyigo, and Itara [5].

Fig. 1: Buildings damages in Bukoba following magnitude 5.9 September 2016 earthquake

According to Fig. 1, Adobe type of houses suffered completely collapse while some few walls were sported remaining standing in the same areas for other type of building construction materials.

Immediately after a large earthquake, emergency managers needed to assess the damaged areas. Tools developed for earthquake damage assessment, such as the ShakeMap tool developed by U.S. Geological Survey Earthquake Hazards Program (USGS-EHP) to provide necessary near-real-time maps of ground motion and shaking intensity were used [8]. During the Lake Victoria Region earthquake of September 10 2016, no nearby Tanzanian seismic station was operational to record the event, but few sensors in the neighbouring countries such as Mbarara, in Uganda (MBAR) and Kilima Mbogo (KMBO) in Kenya, as well as several global seismic stations, did record the event as shown in Figure 2(a). Apart from the instrumental data, several

Manuscript received October 6, 2016.
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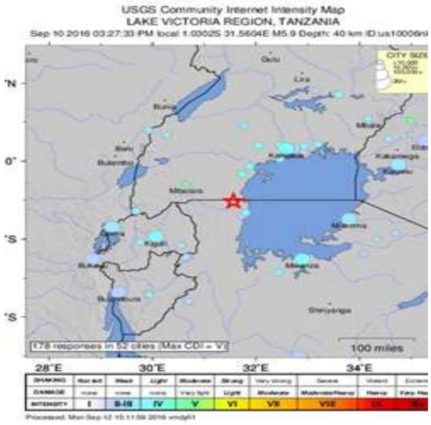
people who felt the earthquake did provide their site response in the USGS on-line system as shown in Figure 2(b).

(a) Stations reporting the event



(b) Responses during the event

Fig.2: Stations operational during Magnitude 5.9 Lake Victoria Earthquake and the position of people providing felt report (Source: USGS)

According to Fig 2, the Magnitude 5.9 earthquake of September 10, 2016 along Lake Victoria was recorded by many global stations, as well as felt by many people in the region who contributed into the felt intensity data.

II. Historical Seismicity

Historically, seismicity in the East African Rift is mainly concentrated along the branches of the rift system, which is at the edges of the Victoria micro-plate, and along the main rift running through Ethiopia in the north, and Malawi and Mozambique in the south [10]. Over the preceding century, a magnitude 4.3 event in Lake Victoria in December 2013 was recorded within 100 km of the September 10, 2016 earthquake. Within 500 km of the September 10, 2016 earthquake, about 22 events with magnitude of about 6 and above have occurred on the Western Branch of the Rift System to the west of today's earthquake within the preceding century[3]. These include a magnitude 6.6 earthquake in March 1966 near Lake Edward on the Uganda-DRC border. Tanzania's largest historic earthquake over this time period was a magnitude 7.2 event in July 1919, near Lake Tanganyika in the west of the country [3]. A magnitude 6.8 earthquake near the center of Lake Tanganyika in December 2005 resulted in half a dozen or more fatalities, other historical earthquakes are shown in Table 1.

Table.1: Earthquakes in the area between 2002 and 2016 with their fatalities (Source: USGS)

Event Date	Longitude	Latitude	Mag	Depth	Fatalities
2002-01-17	29.077	-1.684	4.7	10km	7
2002-05-18	33.733	-2.907	5.5	10km	2
2002-10-24	29.004	-1.884	6.2	10km	2
2008-2-3	28.945	-2.318	5.9	10km	44
2008-2-14	28.876	-2.294	5.4	10km	1
2015-8-7	28.897	-2.141	5.8	11km	1
2016-9-10	31.560	-1.030	5.9	40km	23
2016.9-23	29.107	-2.611	4.8	10km	7

From Table 1, earthquakes have claimed more than 87 live in the region between 2002 and September 2016, with the magnitude 5.9 of 2008 generating more fatalities than other earthquakes. The 2008 Lake Kivu earthquake shook several countries in Africa's Great Lakes region at 07:34:12 (GMT) on February 3 (Fig 3). It measured 5.9 on the moment magnitude scale according to the United States Geological Survey and lasted about 15 seconds. The epicenter was 20 kilometers north of Bukavu at Lake Kivu in the Democratic Republic of Congo.

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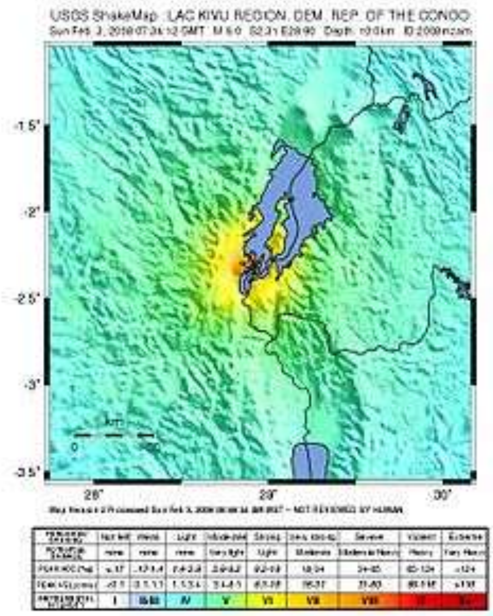


Fig. 3: Magnitude 5.9 Lake Kivu Earthquake of 2008 (Source: USGS)

For this earthquake, at least 25 people were confirmed dead in Rwanda, with a further 200 seriously injured [6]. Ten people were killed when a church collapsed in the Rusizi District of Western Province in Rwanda. In the Democratic Republic of Congo at least 5 were dead and 149 seriously injured. The earthquake was felt in Burundi, causing a break in the electricity supply, and as far as the Kenyan capital Nairobi [6].

III. Observed Strong Ground Motion

The only available data used for analysis of the September 10, 2016 earthquake of Lake Victoria in this study, are those contributed from the nearby Mbarara, Uganda and Kilima Mbogo, Kenya seismic stations, global seismic station around the world, as well as on-line felt reports. From instrumental, felt reports or earthquake ground motion derived data, most of the earthquake damages were identified to be in Bukoba area where the ground acceleration of about 10.5%g has been reported (Fig 4).

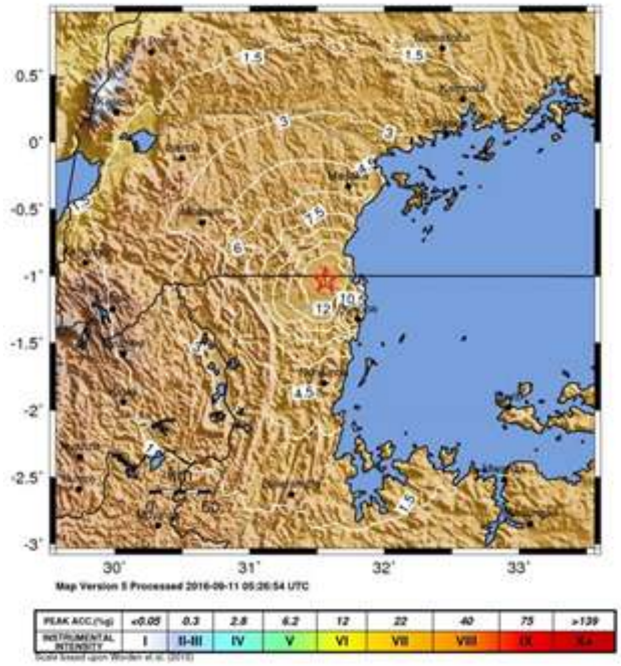
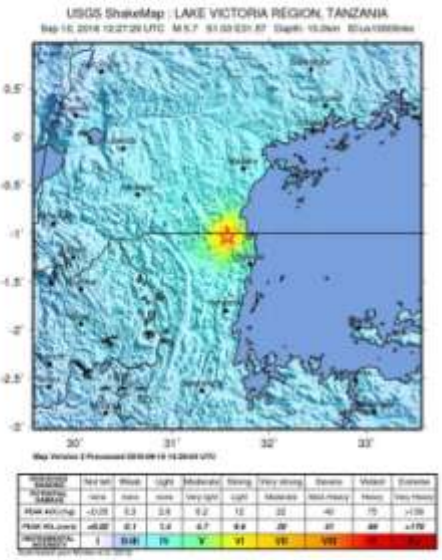


Fig 4: Peak ground acceleration (PGA) during Lake Victoria Earthquake (Source: USGS)

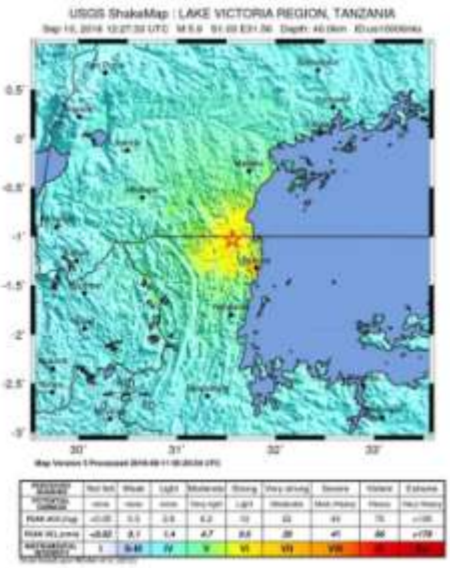
According to Figure 4, PGA higher than 12% g were observed from this earthquake near the epicenter and decreased as the epicentral distances increased, reaching 10.5 % g at an epicentral distance of about 57 km in Bukoba, to about 3%g at a distance of 118 km in Mbarara, and to less than 1%g at about 224 km in Mwanza.

IV. Felt Seismic Intensity and Instrumental Intensity

Less than 10 minutes from the onset of the Lake Victoria Earthquake of September 10, 2016, the USGS DID YOU Feel It (DYFI) online system started receiving the felt report from population within the affected area [3]. Using the on-line collected data as well as some instrumental data, the USGS published the initial ShakeMap Figure 6(a) that were updated to Fig 5(b) two days later.



(a) Initial ShakeMap Report



(b) Revised after 4 days ShakeMap

Fig 5: ShakeMap for Lake Victoria September 2016 Earthquake

From Figure 5, after receiving the damage reports from the affected area, the ShakeMap was revised to reflect the observed situations from the Lake Victoria earthquake of September 10, 2016.

V. . Comparison of Observed and Predicted Ground Motion

Due to limited availability of recorded ground motions during earthquakes in several regions, ground motion estimates for a particular earthquake normally relies on ground motion data from other seismic regions with broad similarity to earthquake region, empirical ground motion prediction models, ground motion simulations or a mixture of these three options. In this study, the USGS derived results for the earthquake, that adopts the mixture of the first two options is compared to ground simulation based results to gain insights for the performances of the two methods in representations of actual ground motion situations during the earthquake as well as its correlation to the reported damages.

In this study, peak ground acceleration (PGA) prediction Equation (1) was adopted [2]. This prediction equation was the extension of the ground prediction model developed by Mavonga (2007) using small earthquake in Kivu region (just few kilometers from the current event). Thus, the selected model suites the region of current application very well, as opposed to other global models adopted by USGS.

$$PGA = 1.42 \exp(1.43M) R^{-1.2} (0.719) \log(\tau) \quad (1)$$

Where M is earthquake magnitude, τ is the arrival time difference between S-wave and P-waves at the site, and R is the epicentral distance of the site.

Fig 6 compares the USGS estimated and this study empirically predicted ground motion for the earthquake at the affected region.

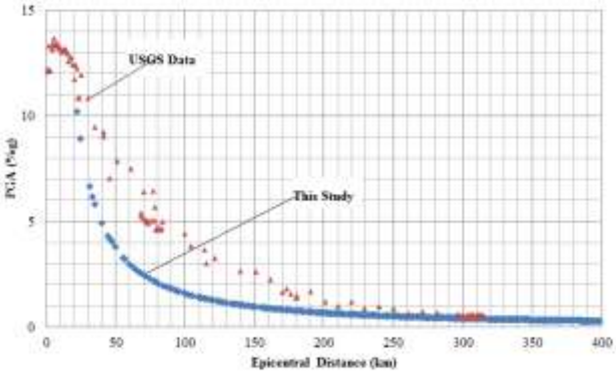


Fig 6: USGS estimated and this study empirically predicted PGA for the Earthquake

According to Figure 6, closer to the earthquake epicenter (less than 20 km), the data from the two methods are very close to each other, at a distance between 20 km and 200km, the USGS estimated PGA data are significantly larger than that predicted from this study, while at a distance above 200 km, both estimates are very close to each other (Table.2).

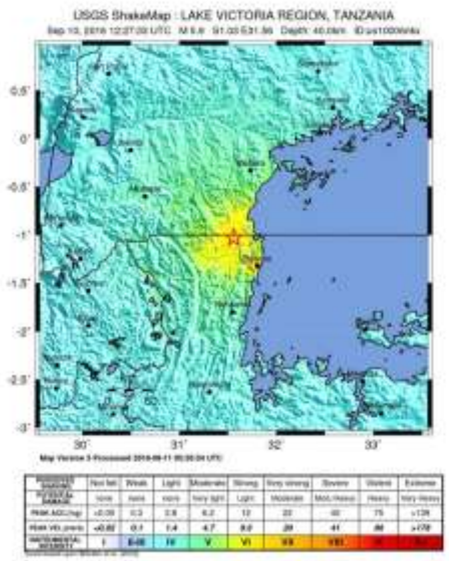
Table 2: Comparisons of PGA at varying epicentral Distances

Distance (km)	USGS (PGA)	This study (PGA)	Difference (%g)
24	10.8	10.3	0.5
57	8.0	3.0	5.0
118	2.8	1.1	1.7
224	0.9	0.8	0.1
300	0.5	0.46	0.04
320	0.4	0.39	0.01

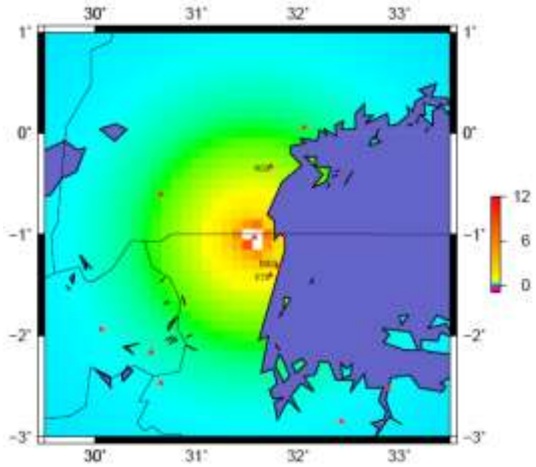
From Table 2, closer to the earthquake epicenter the difference between the two estimates of PGAs is small, in the middle the difference is very large, and at the far distances the estimates are very closer again. This is very common case when there is no local instrumental data recorded during the earthquake in which the USGS utilize global empirical equation to estimate the data at the site. Thus the USGS data and the locally predicted data solution are expected to be different but still very useful for emergency purposes.

VI. Rapid Impact Report

Rapid earthquake impacts report like ShakeMaps are very useful because emergency officers and international aiding agencies can appreciate the level of expected damages due to an earthquake at the very early stage of a disaster. In generating earthquake ShakeMaps, USGS mixes data generated from global ground motion model together with observed instrumental data and seismic intensity information collected form online system [11]. For the Lake Victoria earthquake ShakeMaps, Fig 7 presents the comparisons of the USGS derived ShakeMap with the empirically predicted ShakeMap from this study.



(a) USGS



(b) This study

Fig 7. USGS and Empirically predicted ShakeMap for Magnitude 5.9 Lake Victoria Earthquake of 2016

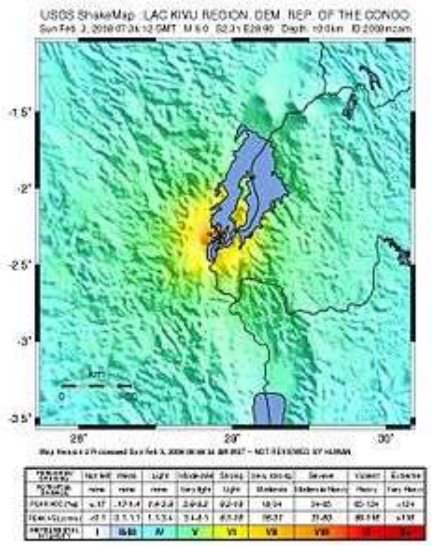
From the Fig 7, the location of expected damaged zones from the earthquake correlates well between the two ShakeMaps generation methods, although that from this study extends further than that of USGS.

Bukoba town is marked under severe damages for both ShakeMaps, Mwanza city is predicted with strong shaking without or with small damages, while parts of Kenya like Kilima Mbogo is predicted with ground motion that can be well felt but with absolutely no damages.

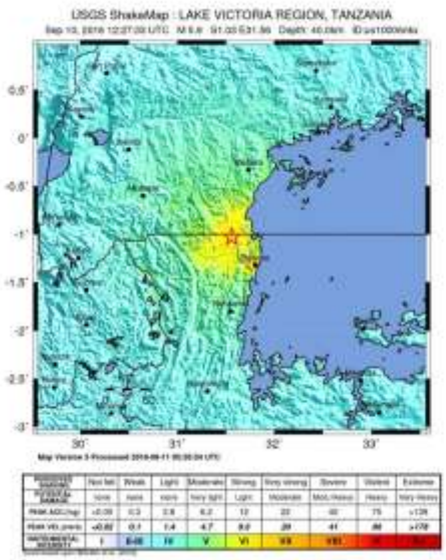
The USGS rapidly generated impact reports (ShakeMaps) must be carefully considered in regions with absence of instrumental data. In order to accept fully the impacts reports generated from felt reports, the difference in building types as well as building practices must be considered in report generations, as well as the seismic damageability knowledge of people contributing the data. Before the damage reports from the affected area, only small areas were predicted to be expecting some damages for this event according to USGS.

VII. Rapid Impact Report comparisons for SIMILAR Magnitude 5.9 September 10, 2016 Lake Victoria and 2008 Lake Kivu Earthquakes

In 2008 magnitude 5.9 earthquake was recorded in the same region with epicenter along Lake Kivu. Using the impacts report from the two earthquakes, Fig 8 presents the resulting USGS damage predictions for this region,



(a) 2008 Lake Kivu



(b) 2016 Lake Victoria

Fig 8: Comparing Magnitude 5.9 Earthquakes in Lake Kivu and Lake Victoria (Source: USGS)

From the Figure, the two earthquakes of comparable magnitudes revile comparable pattern of damages closer to the earthquake epicenters according to USGS data.

Using the local prediction methodology from this study, Fig 9 presents the ShakeMaps comparisons for the two events.

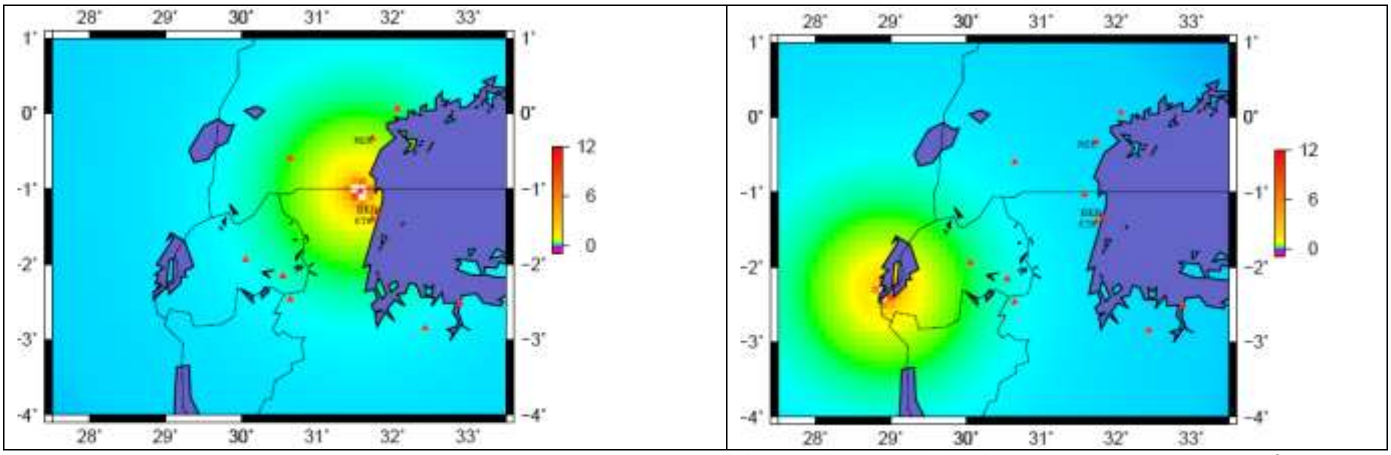


Fig.9. PGA ShakeMaps comparison for two events in the same region

From Fig.9, the comparable earthquakes in terms of magnitude are predicted to induce similar patterns of damages in the region. At the epicenter, the 2016 Lake Victoria earthquake indicates higher damages as compared to 2008 lake Kivu earthquake.

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