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Simulated PGA Shaking Maps for the Magnitude 6.8 Lake Tanganyika earthquake of December 5, 2005 and the observed damages across South Western Tanzania

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Abstract- The South Western Tanzania (SWTZ) is found within the Western branch of the East African Rift Valley (EAR) system, one of the most seismically active regions in African continent (Mavonga, 2010, 2007). The SWTZ area was strongly shaken by the magnitude 6.8 earthquakes that occurred on December 5, 2005, along Lake Tanganyika, living communities dwelling close to the earthquake epicenter in fears (USGS, 2005). No seismic sensors were close enough to provide instrumental recordings of the event, but few citizens who experienced the strong ground shaking provided eyewitness report via online questionnaire system (Did You feel it?) operated by the US Geological Survey (USGS) for global earthquake predictive shaking maps. The USGS predictive ground shaking maps can take minutes to days to generate depending on the availability of internet in the earthquake affected areas. The main objective of this study is to demonstrate how simulated earthquake peak ground acceleration (PGA)shaking maps can be used to rapidly assess the impact of the earthquake for faster deployment of emergency responses when earthquake magnitude and epicenter location are available. We simulate the magnitude 6.8 earthquake of December 5, 2005 and measure the initial P-wave information for estimation of earthquake source parameters (event location and magnitude). Then, we apply the estimated earthquake magnitude and epicenter location to the SWTZ PGA ground attenuation relationship in order to predict the eminent S-wave PGA values expected from the earthquake across the region and map them as PGA shaking maps. The simulated shaking maps of the magnitude 6.8 earthquake and the damage levels reported at different locations were comparable. Proving that simulated PGA shaking maps can be used for early warning and rapid earthquake impact assessments.

Index Terms- empirically estimated PGA, predictive shaking maps, simulated earthquake PGA maps; Scenario earthquake.

I. Introduction

Scenario earthquake ground shaking maps describes the ground motion generated by a large earthquake at each grid point across the affected areas , giving a quick indication of the extent and nature of shaking effects used as a proxy for earthquake expected damage assessment and as tool for fast emergency responses (Allen et al., 2004; Wald et al., 1999). That is, in case of the occurrence of large earthquakes, rapid estimation of areas expected to experience strong ground shaking can be an advantageous for deployment of emergency teams and provision of early warnings to public.

Where denser seismic networks are available, Shaking maps are produced directly from instrumentally recorded data. When only sparse networks are operational, algorithms are implemented to allow faster local characterization of event location and magnitude from data recorded by few closer to epicenter stations and from which predictions of strong ground motion mapped as shaking maps are performed via region empirical attenuation relationships. Where no instruments are available, macroseismic systems that collect reports from actual people who experience the event, generate ground shaking maps from eyewitness reports.

Wald et al., (1999) developed systems called USGS ShakeMaps that generate earthquake ground shaking maps by combining instrumental peak ground measurements and the data predicted in sparsely covered areas from ground attenuation equations with considerations for local geological conditions. Allen et al., (2004) developed shaking maps generation methodology that utilizes initial information from earthquake preliminary motions (P-waves) observed by few closer to the event epicenter stations for estimation of event source information (location and magnitude) and predictions of up-coming earthquake final motion (S-wave) at target site. The two methodologies provide accurate results when denser seismic networks are available, with accompanying knowledge of geological conditions across the region (Allen et al., 2004; Wald et al., 1999). Deployment of denser seismic networks is closetful as well as accurate characterization of geological conditions across the seismically active region.

The USGS DID YOU FEEL IT? (DYFI) system, collects macroseismic seismic intensity data as eyewitness report from internet users who experience ground shaking as well as any damage reports to generate earthquake intensity maps immediately as they are reported (Wald et al., (2011). These ground shaking maps are called Community Internet Intensity Maps (CIIM) and they contribute greatly in quick assessment of the scope of the earthquake for emergency especially when instruments are not available to record data ((Wald et al., 2011, 1999). Provided that internet will remain functioning as well as power systems even during strong ground shaking, CIIM can provide direct first assessment of earthquake hazard if people can take the filling of the online questionnaire as the first priority to their safety (Wald et al., 2011).

Matsuoka and Yamamoto, (2012), developed QuakeMap which is earthquake ground shaking maps generation system triggered automatically by the publications of seismic waveform records from Japanese seismic network portal site. Here, pre-established ground amplification factors at each station, are required to first convert recorded data to base rock level , as well as some interpolation technique to estimate spatial distribution of ground motion parameters at the base rock level for the whole region (Matsuoka and Yamamoto, 2012). The methodology must wait for the stations to report the final seismic data that wastes some valuable warning times.

In this study, we introduce the earthquake peak ground acceleration (PGA) simulation procedure that uses simple C-program for predicting earthquake expected PGA at each grid point and Generic Mapping Tool (GMT) based C-shell script for map generation. In the prediction of grid point PGA values, rapidly estimated earthquake source parameters earthquake preliminary motion (P-waves) and region P-wave based PGA attenuation relationship are the only parameters required. The study aim at demonstrating that, it is possible to rapidly predict the damage pattern of the earthquake by simulating the expected PGA values from rapidly estimated earthquake source parameters. To evaluate the methodology, we apply the numerical simulation techniques to the magnitude 6.8 earthquakes of 2005 along Lake Tanganyika to produce the preliminary P-wave information and predict the peak ground shaking and damage distribution. We compare the simulated PGA shaking maps to the values generated by USGS system for the same earthquake using observed peak ground motions (S-wave) and eyewitness reports.

II. THE DECEMBER 5, 2005 LAKE TANGANYIKA EARTHQUAKE

The magnitude 6.8 earthquake of December 5, 2005 along Lake Tanganyika was strongly felt across the SWTZ and surrounding countries and as far as Nairobi, Kenya (see Figure 1).

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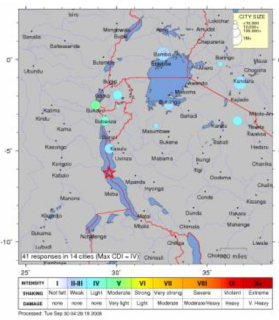

Figure 1 The USGS Internet Intensity Map for magnitude 6.8 earthquake of Dec 5, 2005 in Lake Tanganyika (USGS, 2013*)*

Several damages as well as fears for strong ground shaking were reported by eyewitnesses near the epicenter areas and at several distances from the epicenter (see Table 1).

Table 1: Reported earthquake effects at particular distance

s/n	Repoters distance (km)	Reported Situation
	55	dozen house collapsed, roofs falling buried childrens
	70	Two deaths, dozen of houses collapses in Kalemie, steel roof falling
	845	felt in Arusha,
	315	In Bunjumbura, three story building sway in two waves of the quake.
	417	Bukavu, felt
	794	Kampala, felt
	475	Kigali, felt
	147	In Kigoma (150km) set panicked people running from buildings.
	797	Felt in Kireka,
	405	Kirundo, Caused people running in Angola searching shelter.
	973	felt in Lilongwe, Mombasa , and Ruanda
	646	Lubumbashi, felt
	969	Felt in Nairobi, Nairobi- people scared running down tall buildings
Source: USGS(2013)		

Using these macroseismic (eyewitness report) data, the USGS DYFI system, generated and published the earthquake shaking intensity distribution shown in Figure 2.

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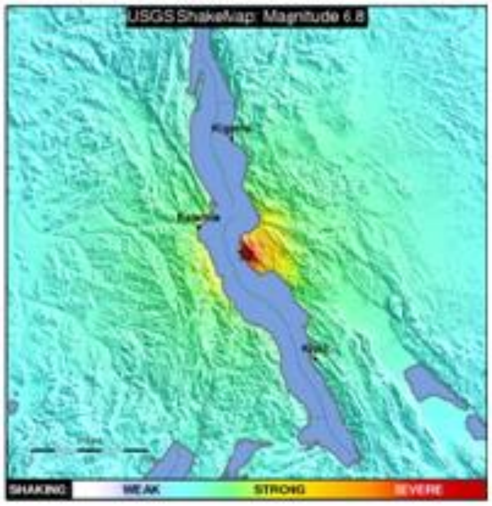


Figure 2 Community Internet Intensity Map for Magnitude 6.8 earthquake of December 5, along Lake Tanganyika.

From Figure 2, most damages were observed near the epicenter, but the earthquake was strongly felt along most part of SWTZ region.

III. Methodology

The goal is to produce PGA predictions and its spatial distribution paying special attention to maximum values that will indicate the potential damaged zones. Our predictions are based on the event magnitude and epicenter location information released rapidly following the observation of earthquake initial P-wave motions.

A. Determining PGA at Grid Points

In Knowing earthquake magnitude and its epicenter location, first uniformly spaced grid of phantom stations are created across the affected region with spacing for each grid point kept constant at 0.1º by 0.1 º. Utilizing the estimated event geographical location, the epicentral distance between each grid point and event location are estimated using Equation (1).

$$R = 111.19\sqrt{\cos(LatG) * (LonG - LonE)^2 + (LatG - LatE)^2}$$
(1)

Where R is distance between grid point and event epicenter in kilometer, LatG and LonG are latitude and longitude coordinate of grid point, and LatE and LonE are latitude and longitude coordinate of event.

Then, the peak ground acceleration (PGA) values at each grid point are predicted using an empirical attenuation relation based on base rock shown in Equation (2).

$$PGA = 1.42 \exp (1.43M) R\text{-}1.2 (0.719 \ln (\tau)) \quad (2)$$

Where M is the earthquake estimated magnitude, R is the distance from the event epicenter to the grid point center and τ is the P-wave observation time window selected as 4 seconds. The reason for the selection of time window of 4 seconds is due to several researches in EEW systems that suggests the use of at least three seconds of P- wave data for arriving at reasonable estimations of earthquake parameters (Lawrence et al., 2011; Satriano et al., 2011; Cochran et al., 2009; Lawrence et al., 2009; Wald et al., 2006; Allen, 2004).

B. Earthquake PGA Data Mapping

After completing the PGA assessment for all the grid points, the computed earthquake PGA values are used as input to the C-shell mapping script containing ordered Generic Mapping Tool (GMT) commands. This is the C-shell script that inputs PGA values into various GMT mapping commands to transform the gridded PGA datasets into PGA AlertMaps visual display that is colour coded according to hazard level of predicted PGA value at each grid cell. The PGA AlertMaps can be useful for determining which sub-regions to notify of incoming significant ground motion.

For easy visualization of predicted PGA values at various grid points, color code is used according to the following categorization: red- yellow represented severe shaking, green represented strong shaking and light blue to blue represented the decreasing weak shaking. The red – to orange represents the severe ground shaking region with ground shaking level that are above 0.5g. This will be the area that is predicted to have severe ground shaking, and most damages are expected here. Green region will be the areas predicted with ground shaking levels below 0.5g but above 0.1g. Strong ground shaking is expected in this region, but not necessarily with damages. The blue region will be with ground shaking levels below 0.1g, representing a weak ground shaking region and no damage is expected here. By looking on colour coded PGA AlertMaps, areas requiring immediate emergency response were expected to be easily identified by colours for faster rescue operation planning.

IV. Results and Discussions

A. PGA Shaking Maps for Magnitude 6.8 of December 5, 2005, Lake Tanganyika earthquake

The simulated PGA values were mapped as shaking maps, for easy identification of severe, strong and weak shaking areas by map colours (see Figure 3).

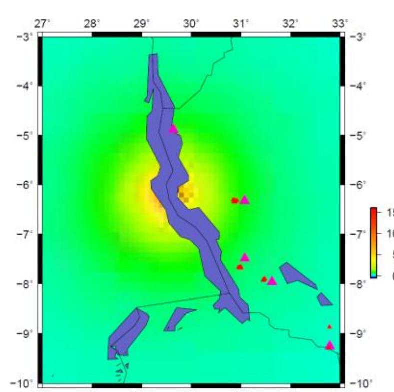


Figure 3 PGA Ground Shaking Map using P-wave method

From Figure 3, severe shaking is indicated by red- yellow colour, which is mostly in epicentral region. Strong ground shaking is green coloured and weak ground shaking is coloured bluish.

B. Comparisons for PGA Ground shaking maps for Magnitude 6.8 of December 5, 2005, Lake Tanganyika earthquake

The PGA shaking maps simulated in this study and the published ground shaking maps generated from eyewitness reports by USGS DYFI system are compared as shown in Figure 4.

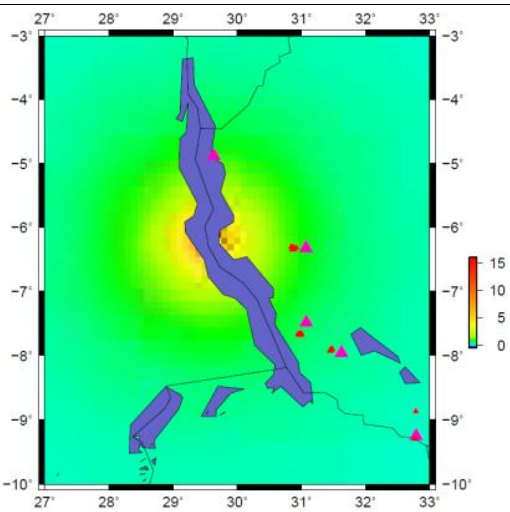
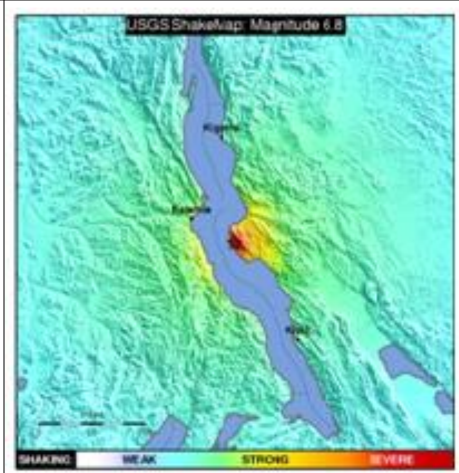
This study PGA Map	USGS ShakeMaps
	

Figure 4: Comparisons of Earthquake Shaking Maps generated from this study data and USGS reports

According to Figure 4, P-wave PGA shaking maps form this study, show large areas experiencing severe and strong ground shaking, while the USGS published ShakeMaps show only areas very close to the epicenter as experiencing severe and strong shaking. For the weak ground shaking, the USGS ShakeMaps categorizes most part of SWTZ and Tanzania under weak shaking ground due to the earthquake, while the this study PGA shaking maps only categorizes areas at some distance under weak ground shaking.

B. Relating simulated P-wave PGA values to the eyewitness reports

There is correlation between PGA values to the experienced damages, but not always absolute agreement since experiences and damage can be affected by many other factors, including the quality of earthquake engineering, type soil cover, as well as construction practices. Generally speaking, PGA values of 0.001 g to 0.01 m/s² are perceptible by people, 0.02 g to 0.2 m/s² people lose their balance, and above 0.50 g very high; well-designed buildings can survive if the duration is short. Table 2 compares the eyewitness reports and simulated PGA values.

Table 2. Comparisons of Simulated PGA and Eyewitness reports

s/n	Repoters distance (km)	Reported Situation	Simulated PGA	Warning type
	55	dozen house collapsed, roofs falling buried childrens	1.91	Severe
	70	Two deaths, dozen of houses collapses in Kalemie, steel roof falling	1.44	Severe
	845	felt in Arusha,	0.07	Weak
	315	In Bunjumbura, three story building sway in two waves of the quake.	0.23	Strong
	417	Bukavu, felt	0.17	Weak
	794	Kampala, felt	0.08	Weak
	475	Kigali, felt	0.14	Weak
	147	In Kigoma (150km) set panicked people running from	0.59	Severe

		buildings.		
	797	Felt in Kireka,	0.07	Weak
	405	Kirundo, Caused people running in Angola searching shelter.	0.23	Strong
	973	felt in Lilongwe, Mombasa , and Ruanda	0.05	Weak
	646	Lubumbashi, felt	0.11	Weak
	969	Felt in Nairobi, Nairobi- people scared running down tall buildings	0.05	Weak

From Table 2, area located below 150 km from the earthquake epicenter, like Kigoma and Kalemie were simulated within the region of severe ground shaking with possible damages, categorization which agrees with eyewitness reports. Areas at a distance of more than 150 km but within the range of 400 km, are simulated with strong ground shaking, in agreement with eyewitness reports. Areas above 400 km and within 900 km, are simulated in weak ground shaking, and are also in agreement with eyewitness report. Generally, the eyewitness collaborates well with predicted level of PGA values.

V. CONCLUSION

The SWTZ is seismically active and citizens dwelling in the region need to be warned for any large earthquake approaching them. Because earthquake source parameters can be out-sourced from real-time system's web-based publications, simulation of earthquake impacts through simulation is demonstrated in this study for rapid emergency responses and early warning application.

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