

Rapid Post-Event Catastrophe Modelling and Visualization¹

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Abstract—Catastrophe models capable of rapid data ingestion, loss estimation and visualization are required for post-event analysis of catastrophic events such as earthquakes. This paper describes the design and development of the Automated Post-Event Earthquake Loss Estimation and Visualization (APE-ELEV) system for real-time estimation and visualization of losses incurred due to earthquakes. A model for estimating expected losses due to earthquakes in near real-time is described and implemented. Since immediately post-event data is often available from multiple disparate sources, a geo-browser is described that helps users to visualize and integrate hazard, exposure and loss data.

Keywords-post-event earthquake analysis; catastrophe modelling; loss estimation; loss visualization

I. INTRODUCTION

Over the last twenty years, Catastrophe Modelling Systems [1][2], which seek to quantify expected losses due to catastrophic events, have become a mature technology widely used in the insurance and reinsurance settings. These systems typically focus on **pre-event** analysis. For example, given a collection of 1M building in Japan what is the expected maximum probable loss due to earthquake activity over a one year period? Pre-event catastrophe models are built using a stochastic event catalog to represent a sample of possible future events and a set of three sub-models:

- A *Hazard Model* which determines the degree of the hazard (i.e. ground shaking),
- A *Vulnerability Model* which determines the degree of damage to buildings given the hazard, and
- A *Loss Model* which estimates the level of financial losses.

More recently, with the expansion of sensor networks and development of communication technologies hazard models have been developed that can produce timely evaluation of hazard in near real-time [3], [4], [5], [6], [7], [8]. In this paper, we explore how real-time hazard models can be married to techniques developed for pre-event catastrophe modelling of vulnerability and loss to generate complete **post-event** analysis in the hours, days and weeks immediately following major events.

Two of the first systems to provide real-time earthquake hazard analysis were CUBE (Caltech-USGS Broadcast of Earthquakes) [3] and REDI (Rapid Earthquake Data Integration) [4]. Both these models provided reliable real-time hazard analysis, however, did not focus on loss estimation and were not a general notification system. In late 1990s the ShakeMap system was introduced to automatically generate maps which captured ground motions [5][6]. Building on ShakeMap's hazard model, a number of catastrophe models have been developed. For example, QLARM (Earthquake Loss Assessment for Response and Mitigation) [7], INLET (Internet-based Loss Estimation Tool) [8], ELER (Earthquake Loss Estimation Routine) [9] and PAGER (Prompt Assessment of Global Earthquakes for Response) [10].

Post-event analysis is different from pre-event analysis in a number of important ways:

- the focus is on a single catastrophic event which has occurred rather than a catalog of possible future events,
- there is an evolving view of the event as it unfolds, and therefore the sensor data related to the event changes hours, days and weeks after the event,
- there is a need for rapid estimation of losses to guide early responses [11], and
- since post-event data is available from multiple sources, there is a need to visualize and integrate hazard, exposure and loss data from these multiple sources.

The 2011 Tohoku earthquake that struck off the Pacific coast of Japan at 05:46 UTC on Friday, 11 March 2011 is a recent example that illustrates the importance of post-event analysis. Figure 1 presents the timeline of the earthquake. Fifteen alerts $A_1 - A_{15}$ were issued by PAGER/ShakeMap in time periods ranging from within an hour to six months after the earthquake. The first alert twenty three minutes after the event reported a magnitude 7.9 earthquake and provided initial Peak Ground Velocity and Peak Ground Acceleration maps of the ground shake. Further, over the course of the first day alone four additional alerts were issued each updating the data available. Not only did the earthquake event unfold over time but the data describing the event and our knowledge of the event evolved. The earthquake data alone was not sufficient to produce reliable loss estimates because between 06:15 UTC and 07:52 UTC a tsunami struck the coastal towns. Additional data sources are required for complete loss estimation.

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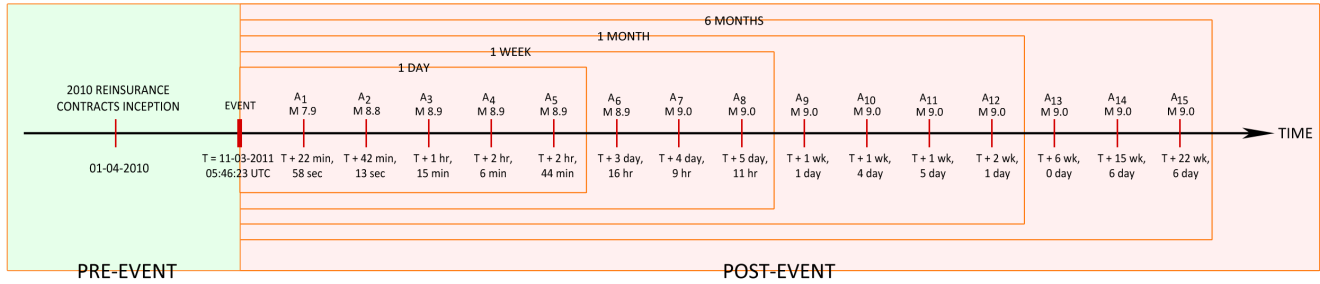


Figure 1: Timeline of the 2011 Tohoku Earthquake

Therefore, for a post-event catastrophe modelling system to be useful in days and weeks after the event, it needs to support (a) rapid data ingestion, (b) rapid loss estimation, (c) rapid visualization and integration of hazard, exposure, and loss data from multiple sources, and (d) rapid visualization of hazard, exposure and vulnerability loss data at multiple geographic levels.

The research reported in this paper explores how techniques developed for pre-event catastrophe modelling can be married to real-time hazard models to produce useful post-event catastrophe models that can provide loss analysis in hours, days and weeks following an event. To achieve this, the Automated Post-Event Earthquake Loss Estimation and Visualization (APE-ELEV) system is proposed, which comprises three primary modules, namely the Earthquake Loss Estimator (ELE), the Earthquake Visualizer (EV) and the ELEV Database (ELEV-DB). The ELE module is built on PAGER/Shakemap for accessing real-time earthquake data and estimating losses at different geographic levels. The ELE module computes financial losses. Visualization of the losses is facilitated by the EV module. The ELEV-DB module aids the functioning of the ELE and EV module.

The remainder of this paper is organized as follows. Section II considers the architecture of APE-ELEV. Section III presents the loss model incorporated in APE-ELEV, while section IV presents the graphical visualizer in APE-ELEV. Section V demonstrates an experimental test case. Section VI concludes the paper and considers future work.

II. APE-ELEV ARCHITECTURE

The Automated Post-Event Earthquake Loss Estimator and Visualizer (APE-ELEV) is a system that allows decision makers to determine expected losses due to the occurrence of an earthquake (on building that are exposed to the earthquake, otherwise called exposure) and graphically display these losses. The system determines two types of losses. Firstly, the Ground Up Loss, referred to as GUL which is the entire amount of an insurance loss, including deductibles, before applying any retention or reinsurance. Secondly, the Net of Facultative Loss, referred to as NFL which is the entire amount of an insurance loss, including

deductibles, primary retention and any reinsurance. The determined losses can be visualized at four geographic levels, namely country, state, county and city, on a geo-browser. The country, state and county levels are sometimes referred to as regions, while the city level is referred to as both point and population centre. A set of indices that allow analysis of the earthquake in a region, otherwise called indicators, facilitate visualization. The indicators can be either event-specific (for example, losses at regions) or geography-specific (for example, population at cities or regions).

APE-ELEV is composed of three primary modules, namely the Earthquake Loss Estimator and Visualizer Database (ELEV-DB), the Earthquake Loss Estimator (ELE) and the Earthquake Visualizer (EV). Figure 2 shows the architecture of APE-ELEV. The ELEV-DB module is a collection of tables related to an event and geographic data. The ELE model (see Figure 2 (top)) as the name suggests estimates the losses incurred when an earthquake occurs. The EV model (see Figure 2 (bottom)) again as the name suggests facilitates the visualization of the loss estimates generated by the ELE model.

The ELEV-DB module comprises seven tables which contribute to the working of the ELE and the EV modules. The tables are (i) T_1 , which consists of industrial data for Ground Up Exposure, (ii) T_2 , which consists of industrial data for Net of Facultative Exposure, (iii) T_3 , which consists of event data, (iv) T_4 , which consists of a set of indicators, (v) T_5 , which consists of geographic information that is used to map lower geographic levels onto higher geographic levels (for example, mapping of cities onto counties or counties onto state), (vi) T_6 , which consists of data that is generated from the Jaiswal and Wald Mean Damage Ratio (MDR) model [13], and (vii) T_7 , which comprises loss data populated by the ELE module.

The ELE module, as shown in Figure 2 (top), comprises three sub-modules, namely the Hazard, Vulnerability and Loss modules. The Hazard module receives two inputs, firstly, the data on cities (i.e. population centres of greater than 1000 people) affected by the earthquake, and secondly, geographic information required for mapping lower geographic levels onto higher geographic levels. The Hazard

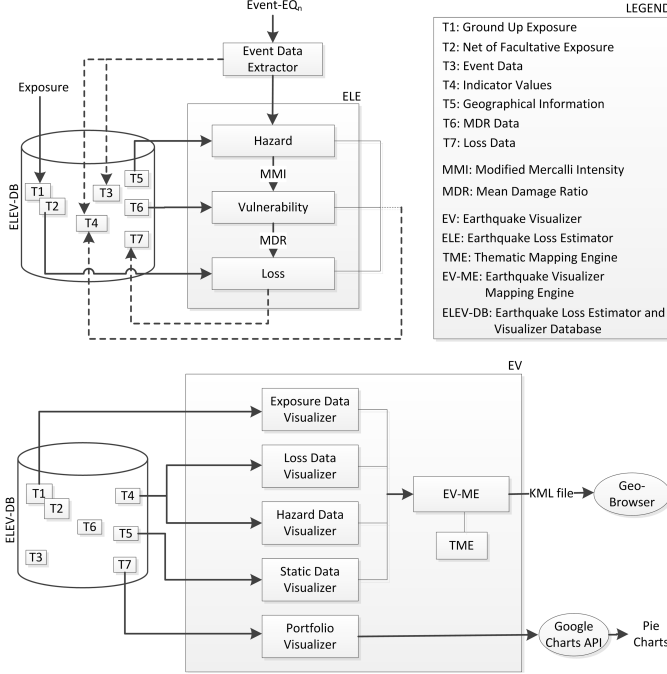


Figure 2: The APE-ELEV architecture comprising the ELE (top), EV (bottom) and ELEV-DB modules

module produces the measure of severity of an earthquake, otherwise referred to as the Modified Mercalli Intensity (MMI), in a city and region. The MMI values along with data from T_6 are used by the Vulnerability module to produce MDR values. This data is employed by the Loss module along with two types of exposure data, namely Ground Up Exposure and Net of Facultative Exposure to generate both the GUL and NFL losses. The Event Data Extractor receives the notification of the event and initiates the ELE.

The EV module, as shown in Figure 2 (bottom), comprises five sub-modules, namely the Exposure Data Visualizer, Loss Data Visualizer, Hazard Data Visualizer, Static Data Visualizer and the Portfolio Visualizer. The visualizer modules employ a geo-browser for graphical display. The Exposure Data Visualizer presents the exposure for different geographic levels. The Loss Data Visualizer presents the GUL and NFL for different geographic levels. The Hazard Data Visualizer presents the MMI and MDR for different geographic levels. Static Data Visualizer is employed for presenting geography-specific indicators, and as the name implies these indicator values do not change from one event to another. The Portfolio Visualizer presents a comparison of losses and exposures. The Earthquake Visualizer Mapping Engine (EV-ME) module facilitates visualization of data on a geo-browser.

Having presented the architecture of APE-ELEV, it is also necessary to consider how the ELE, EV and ELEV-DB modules and their sub-modules glue together for coherent

functioning. The data required to kick-start APE-ELEV is obtained before the occurrence of an earthquake or in a pre-event phase. An Accumulation Model is used to generate the Ground Up and Net of Facultative exposure at the region level. The region level exposure is then disaggregated into cities (i.e. population centres that fall within the region) based on the percentage of population. The city level exposure is further used by the ELE module in the post-event phase.

III. THE ELE MODULE

For an earthquake event, EQ_n , that has just occurred or is unfolding we firstly need to be notified of the event. An automated system for notifying earthquakes is ShakeCast Lite [14]. The ELE module employs ShakeCast Lite for notification alerts which are received by the Event Data Extractor. When the notification alert is received the ELE module is instantiated. Further, we require real-time data of the earthquake. The Prompt Assessment of Global Earthquakes for Response (PAGER) is an automated system that can provide such real-time data. The ELE module employs the real-time data from PAGER/Shakemap that is acquired as an .xml file. The .xml file is then parsed to extract event related information that is stored in T_3 of ELEV-DB. Information such as an affected city, represented as L_4 (L_1 represents country, L_2 represents states, and L_3 represents counties and L_4 represents cities), population of the city, represented as $P(L_4)$ and MMI of the city, represented as $MMI(L_4)$ is provided to the hazard module.

The hazard module computes the MMI at higher geographic levels using the MMI of affected cities. If the geographic level is represented as L_n , where $n = 1, 2$ and 3 , the population at the geographic level L_n is represented as $P(L_n)$ and the MMI at the geographic level L_n is represented as $MMI(L_n)$, then

$$MMI(L_{(n)_i}) = \frac{\sum_{j=1}^q MMI(L_{(n+1)_j}) * P(L_{(n+1)_j})}{\sum_{j=1}^q P(L_{(n+1)_j})} \quad (1)$$

where $i = 1, 2, \dots, p$ (p is the total no of affected regions), and $j = 1, 2, \dots, q$ (q is the number of affected cities in a region i). The geographic data to evaluate whether an affected city lies within a given region is provided through T_5 .

The $MMI(L_n)$, where $n = 1, 2, 3$ and 4 is then utilized by the Vulnerability module to compute $MDR(L_n)$. Unlike the Hazard module, the city level is considered in the Vulnerability module, and therefore n ranges from 1 to 4. It is worthwhile to note that MMI values range from 1 to 12. T_6 which was originally generated by the Jaiswal and Wald MDR model provides the MDR value corresponding to an integer MMI value. Should a floating point MMI value

be obtained during computations from the hazard module, then the MDR values are computed by linear interpolation in the Vulnerability module. For example, if MMI is obtained as 7.5 from the Hazard module, then the MDR values corresponding to MMI-7 and MMI-8 are interpolated in the Vulnerability module to obtain the MDR value for MMI-7.5.

The MDR value of a city is provided to the Loss module, along with the Ground Up and the Net of Facultative exposure data from T_1 and T_2 . The GUL and NFL of a city are computed by multiplying the MDR values for a city with the exposure of the city. The city losses are then aggregated onto higher geographic levels using T_5 to compute the losses on the county, state and country levels. The total loss corresponding to an event is provided to T_3 , while the regional losses corresponding to an event is provided to T_4 and losses related to a specific line of business in T_7 .

The ELEV-DB module plays an important role in providing data to and receiving data from the ELE module. During the period from the notification of an event until completion of computing losses, tables T_3 , T_4 and T_7 are modified. Tables T_1 , T_2 , T_5 and T_6 provide input to the ELE module.

IV. THE EV MODULE

The five sub-modules of EV, namely the Exposure Data Visualizer, the Loss Data Visualizer, the Hazard Data Visualizer, the Static Data Visualizer and the Portfolio Visualizer operate in parallel. This is unlike the ELE sub-modules that operate in sequence. The functioning of the sub-modules of EV are nevertheless presented sequentially in this section for the sake of convenience.

The Exposure Data Visualizer utilizes T_1 and T_2 for displaying two types of exposures, the Ground Up Exposure and the Net of Facultative Exposure. The latitude, longitude and geography related indicators of all regions are extracted from T_5 and provided to the Earthquake Visualizer Mapping Engine (EV-ME). The EV-ME module generates a .kml (Keyhole Markup Language) file that contains place marks which highlight the exposure of the regions. The .kml format is compatible for visualization on Geo-browsers [15], and in this research Google Earth is employed. The Thematic Mapping Engine (TME) is the underlying building block of EV-ME [16]. A number of visualization techniques such as bar, prism, choropleth, collada and push pins are made available for facilitating analysis of the data.

The Loss Data Visualizer utilizes T_4 from which regional loss data is extracted for displaying the Ground Up and Net of Facultative losses. Similar to the Exposure Data Visualizer, the EV-ME module generates a .kml file that is viewable on Google Earth.

The Hazard Data Visualizer utilizes T_4 and T_5 from which regional and point hazard data are extracted respectively for displaying MMI and MDR at all geographic levels. Similar to the above modules a .kml file is generated by the EV-ME module.

The Static Data Visualizer again utilizes T_4 and T_5 from which cities affected by the event and static-data related to the affected cities are extracted respectively. A .kml file is generated by the EV-ME module and the extracted data is visualized.

The Portfolio Visualizer that is incorporated within the EV module compares losses and exposure (of areas affected by the event) by line of business. Data related to the distribution of total losses by line of business such as industrial, personal and commercial is extracted from T_7 . Since visualizations are provided on pie-charts, the EV-ME module is not employed.

V. EXPERIMENTAL TEST CASE

Preliminary studies were pursued to confirm the feasibility of APE-ELEV. To this end, a test case was employed, namely an earthquake of magnitude 7.2 that hit California in April 2010, referred to as 30.8 mi SSE of Calexico, CA with an Event ID 14607652 in PAGER. The event was selected such that it was recent and had a reasonably large magnitude. In the geographic hierarchy, the United States is the country in which the event occurs, California the state, San Diego and Imperial the counties. The data related to the earthquake was available on the PAGER archive [17] and ShakeMap archive [18]. The Event Data Extractor in the APE-ELEV architecture fetches data related to the event from the PAGER archive in .xml format and instantiates the ELE module.

Geometry data for the geographic levels was obtained from the Global Administrative Areas Database [19], as shapefiles. The shapefiles obtained were large in size containing accurate boundary specification. Since the experiment reported here was a preliminary test, approximate boundary specifications were sufficient, and therefore the shapefile was simplified using the MapShaper tool [20].

After the ELE module is instantiated, the estimation of losses are performed as considered in Section 3. The EV module is then employed to visualize the estimated losses.

Figure 3 is a screenshot of the visualizer. The inline map shown on the screenshot represents the ShakeMap representation of the earthquake. The earthquake related data is shown on the right-hand side of the map. The four visualizers of the EV module are listed under Google Earth Visualization as Static Data, Exposure Data, Hazard Data and Loss Data. The visualization techniques (choropleth in the screenshot) are available in a drop-down box. The ShakeMap link presents the ShakeMap on the Google Earth application. The Ground Up and Net of Facultative losses computed by the ELE module are displayed under Global Earthquake Loss Model. The Portfolio Loss link presents four pie charts that compares the losses and exposures by line of business such as industrial, personal and commercial.

Figure 4 is a set of screenshots obtained from the visualizer. Figure 4a is a representation of the MMI of the

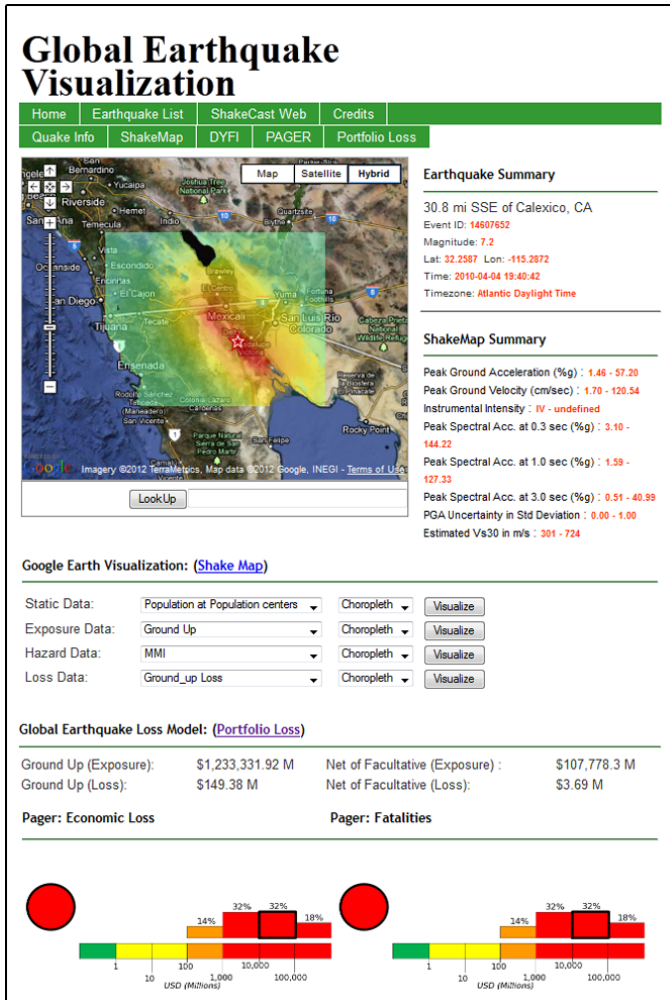
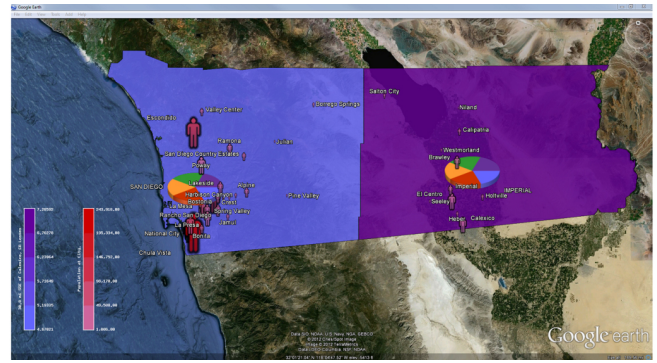


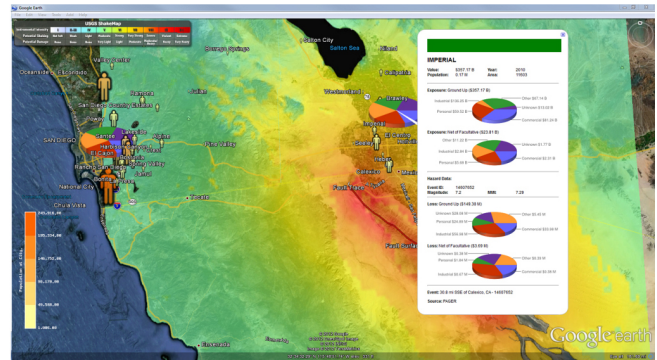
Figure 3: Screenshot of the Visualizer module of APE-ELEV

San Diego and Imperial counties overlaid with population at cities in these counties. The choropleth visualization technique is employed for representing the MMI whereas the human push pins are used to show the population. Two gradient scales are shown in the bottom left of the figure. The first gradient scale represents the range of MMI; with lighter shades representing low values and darker shades representing high values of MMI. The second gradient scale represents the population; with lighter shades representing low values and darker shades representing high values of population. The two pie charts shown in each county presents both the Ground Up and Net of Facultative exposure and loss for different line of businesses.

Figure 4b is the representation of ShakeMap data overlaid with population at cities within the San Diego and Imperial counties using human push pins. The pop-up on the right hand side of the figure presents the Ground Up and Net of Facultative exposure and loss for different line of businesses of the Imperial county. Static data related to the event, such



(a)



(b)

Figure 4: Screenshot of Experimental Test Case. (a) Visualization of the MMI at the affected counties and the population of cities within these counties using choropleth and human push pins respectively. (b) Visualization of ShakeMap data, population using human push pins and region level data of exposure and loss using pie charts.

as the Event ID, MMI and magnitude, and geography, such as population and area are also presented in the pop-up. The gradient scale shown in the bottom left of the figure represents the population; with lighter shades representing low values and darker shades representing high values of population. The gradient scale on the top left is provided by ShakeMap.

VI. CONCLUSION & FUTURE WORK

This paper presented an automated system, referred to as APE-ELEV, for post-event analysis of an earthquake to estimate and visualize losses. Three primary modules of APE-ELEV, firstly, the Earthquake Loss Estimator (ELE) that comprises the mathematical loss model, secondly, the Earthquake Visualizer (EV) that presents the losses at the country, state, county and city levels and thirdly, the Earthquake Loss Estimator and Visualizer Database (ELEV-DB) that contains data from multiple sources were considered. The functionalities of the modules and their working have been presented. The losses estimated by the ELE module,

which are the Ground Up and Net of Facultative losses, are visualized on a geo-browser.

Looking forward, this research aims to validate the accuracy of the loss estimates obtained from the model proposed in this paper. For this, industrial (historic) data of earthquakes will be collected and compared against the results of the proposed model. This comparative evaluation will enable the refinement of the proposed model. Immediate efforts will be made towards visualizing global earthquakes using global geometric data. Efforts are also being made towards deploying APE-ELEV as a client-server setup.

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