Animation: Crustal Deformation in the Nicoya Peninsula Associated with the September 5th, 2012 Earthquake

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Abstract

For the past fifteen years, the Volcanological and Seismological Observatory of Costa Rica (OVSICORI) in cooperation with American Universities, has been recording crustal deformation data prior a potential earthquake in the Nicoya Peninsula, anticipation which came true on September 5th, 2012 with the occurrence of a 7.6 moment magnitude (Mw) earthquake.

The historical importance of this earthquake is based on continuous monitoring of the Nicoya Peninsula before, during and after the earthquake, making it one of the best documented earthquake in history. The objective of this project is to visualize earthquake data in order to view displacement in two and three dimensions. Another goal is to make the method for showing the behavior of the crust during the earthquake, more intuitive. The target question of the visualizations is only one: to show how the earth?s crust moved previous and during the earthquake in each of the affected areas.

We know of no other visualization that use a 3D environment to visualize one earthquake with actual data in this detail level.

Keywords: human state visualization, human factor, pie charts, human resources management.

1. Introduction

The Nicoya Peninsula, located in the northweast of Costa Rica, is considered to be an area of seismic importance, given its unique location, sitting right over the seismogenic zone of large earthquakes within a subduction zone, a trait shared by only 2% of the world's territory [13].

Since 1995, the Costa Rica Volcanological and Seismological Observatory, at the National University (OVSICORI-UNA) has performed active monitoring activities of the Nicoya Peninsula using a geodynamic monitoring network to record deformations [5]. For more over a decade, OVSICORI has maintained that the Nicoya seismic gap had the potential to generate an earthquake with magnitude of moment magnitude (Mw), $Mw = 7.8 \pm 0.1$.

This evaluation of the seismic potential came true on September 5, 2012 when an earthquake of 7.6 Mw, recorded at 8:42 a. m. Data from the GPS stations showed that slippage in the fault reached an average of 1.85 meters of, approximately, 4 meters of potential displacement that existed below the Peninsula; some small patches of the fault moved up to $4\ m$ [12].

The objective of this project was to develop various visualizations of the crustal movement produced by the September 5th, 2012 earthquake in the Nicoya Peninsula based on recorded data, reported in [12].

The reason why the Nicoya 2012 earthquake is considered to be one of the best documented earthquakes in history is not due to the number of stations in Costa Rica, but the density (distance between stations) and their relative location over the seismogenic zone. "Japan has 1,000 stations, thereby outnumbering those in Costa Rica. Yet, in Costa Rica, monitoring stations are located just above the fault" [13].

Although earthquake-monitoring stations in the Nicoya Peninsula are more densely distributed than in the rest of the country, visualizations require many more intermediate points. This project defined a matrix of one point every kilometer at the latitude and longitude axes where data was extracted from each station and interpolated on the plane with data from neighboring stations to achieve data for every kilometer.

The deterministic Inverse Distance Weighting (IDW) [16], which is based on a power of 4 method, was selected to produce spatially continuous displacement maps in x, y, and z-axes based on all available ground-GPS stations.

The IDW interpolation method was chosen on the basis of: (a) previous use in literature, (b) continuity of recorded data, (c) topography and geomorphology, (d) sparse location and distribution of GPS ground stations (which prevented the use of Kriging or other geospatial interpolation method) and (e) computational cost. Spatial resolution remained a constant of 1000 m, mostly on the grounds of computational costs.

Spatial data processing was executed using the R programming language [14], along with specialized R packages (mainly Gstat, Sp, Raster and Automap) [17-20]. All spatial products adhered to the official Transverse Mercator projection system (CRTM05) [21]. After clean and homogenous data was obtained in the desired resolution, the next step was the visualization design stage.

2. Related Works

There are different earthquake visualization studies, which focus on earthquake animation from data recorded in a particular area of interest. For example, in Chourasia

[4], the objective was to estimate the movement of the crust during the San Francisco earthquake, which occurred in 1906 and characterize the behavior of similar earthquakes for various hypothetical scenarios north of the San Andreas Fault.

The work in [4], considers various aspects of the interface allowing it to be more intuitive. For example, it provides a rendering with an intensity that is more precise than movement in real time with visual realism. Its system integrates color, texture and regular mesh deformation while depicting rapid seismic wave dispersal. They recommend simulation requirements that involve intuitive and precise earthquake renderings. Chourasia provides a visual representation workflow for ground motion data in a simulation of the great 1906 San Francisco earthquake. The Chourasia tool considers aspects about the interface that we also consider to be important. For instance, the system uses mapping textures with a high degree of visual realism and integrates color to represent shaking or movement intensity. The simulation represents the earthquake rupture since it creates a dislocation, which propagates at the finite elements mesh. Ground shaking is calculated by resolving the wave equation in three dimensions for elastic material. This entire simulation is done in three dimensions and includes topography of the terrain.

Despite similarities between the aforementioned study and this study, the objectives are completely different. The core idea of our study is to, intuitively, demonstrate how the crust reacted to the earthquake so that viewers can better identify the conditions of the ground beneath the subduction zone. Chourasia´s focus, on the other hand, uses the data to simulate future movement and does not use visualization techniques to understand the actual behavior of the studied area.

A study by Cheng-Kai et al. [3] attempts to analyze how certain structures, such as bridges, respond to earthquakes. This methodology is based on breaking down data into various frequency bands in order to isolate and compare specific features. This simulation considers various features of the surrounding bridge terrain to maximize accuracy. Although these features are similar to our study, Cheng-Kai focuses on civil structures, while our focus is the visco-elastic behavior of the earth´s crust.

QuakeSim [8,10], is a rather complex project. It was developed with the objective of better understanding tectonic activity and the processes that occur during an earthquake, a common objective for our project. QuakeSim incorporates various instruments such as: database systems directed at research, a collaborative portal and three known scalable parallel simulation codes: GeoFEST, PARK and Virtual California. Even though several tools are presented, the emphasis of the work is on the simulation of the behavior of waves across the Earth's crust, the different models used for these predictions and how the results look. For this reason, the crustal deformations in its various parts are not evident in any of them, but rather deepen in the underground behaviors of waves.

Castanie, Bosquet y Levy [1] propose volume-rendering algorithms based on transfer function integration. This system is dedicated to effectively encapsulating visualization of different high-quality volumes in the rendered algorithm and the possibility of visualizing iso-surfaces interactively and covering it with another attribute, the basis of this visualization are seismic amplitudes below the ground surface level. This project is alike the previous projects, they use simulation to understand the seismic dynamic, while we have the same objective, but we reach it through animation with real data.

Finally, in 2013 OVSICORI/UNA [12] together with other institutions, developed an animation of the 7.6 Nicoya earthquake that occurred in 2012 in Costa Rica. The animation depicts the displacement field. This visualization shows an animated image of the coseismic rupture as observed by GPS and Geomorphic changes in the coastline (see figure 1). However, even though it is a three-dimensional representation, only arrows with considerable lengths are shown, that does not explain in any way what the relationship is in the crustal deformations between the different parts during the earthquake.
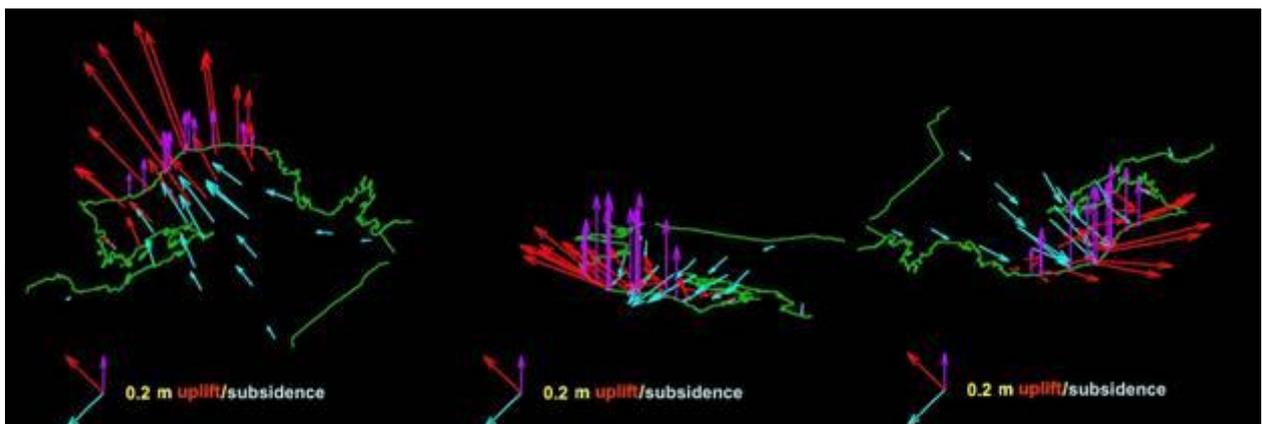

Fig. 1: 3D Coseismic Displacement Field.

3. Visualization Design

The target question was analyzed in order to develop the [6], thereby suggesting a paradigm based on the visualization objective. After analysis of similar cases and exploring various visualization paradigms, it was decided, along with scientists, that the best option was to present three different types of visualization: (1) 2D visualization of longitude and latitude displacement, (2) 2D visualization of altitudinal movement and (3) 3D animation of both types of movement. For 3D naviga-

tion, we use our customized approach of the conventional virtual trackball, Virtual Sphere or Sphere View [15].

3.1 Technical background

The entire visualization was programmed in the Processing programming language, which is a Java version, specially developed for visual and media design. The 3D visualization engine of the Processing environment (P3D) is based on OpenGLES, which is quite efficient in using large amounts of data in 3D environments.

Before making the decision to use this environment, a comparative study was made between JavaScript (with the 3D library Three.js), Swift (Apple programming language) and Processing, the performance of the latter was better by a factor of 10; details of this comparative study can be found by [22].

To generate the geography of Costa Rica we used models in PLY format (Polygon File Format) which is a simple format for handling 3D objects used to store 3D scanner results. We used the ASCII version of this format with geo-referenced points with latitude, longitude (in degrees) and height (in meters) [22].

For the navigation inside the 3D visualization environment, a customized system of the "Virtual Sphere Navigation Paradigm" was used, which is restricted to simplify the navigation problem in case of terrains [23].

The data of crustal deformation during the earthquake were provided by the OVSICORI-UNA utilizing a geo-referenced data table in CSV format. CSV format is the most straightforward format for transferring data in the form of spreadsheets or tables in ASCII. The tables have a matrix of $375{\times}353$ (132,375) points, which represents one point per square kilometer in Costa Rica, between the longitudes of [-86, -82.6] and latitudes [8,11.3] where our country fits comfortably.

The rendering technique used for this tool is not very demanding because the geography must have a chromatic code according to the magnitude of the deformation and not according to some lighting or general shading environment. In this way, the wireframe technique is used for displaying nodes with a color-code according to the intensity of the displacement.

3.2 Visualization of longitude and latitude displacement

Each two-dimensional visualization represents an important earthquake characteristic. The first visualization showed latitude and longitude movement, which reflected the direction and magnitude associated with movement of that area during the minutes that the earthquake lasted.

Fig. 2 shows the entire country. The background color codes movement intensity. The darker the color, the larger the displacement. In that same visualization, the arrows represented movement magnitude and its direction. The longer the arrow, the greater the displacement. Also, the figure exhibits three cursor positions showing magnitude and displacement direction at that   point.

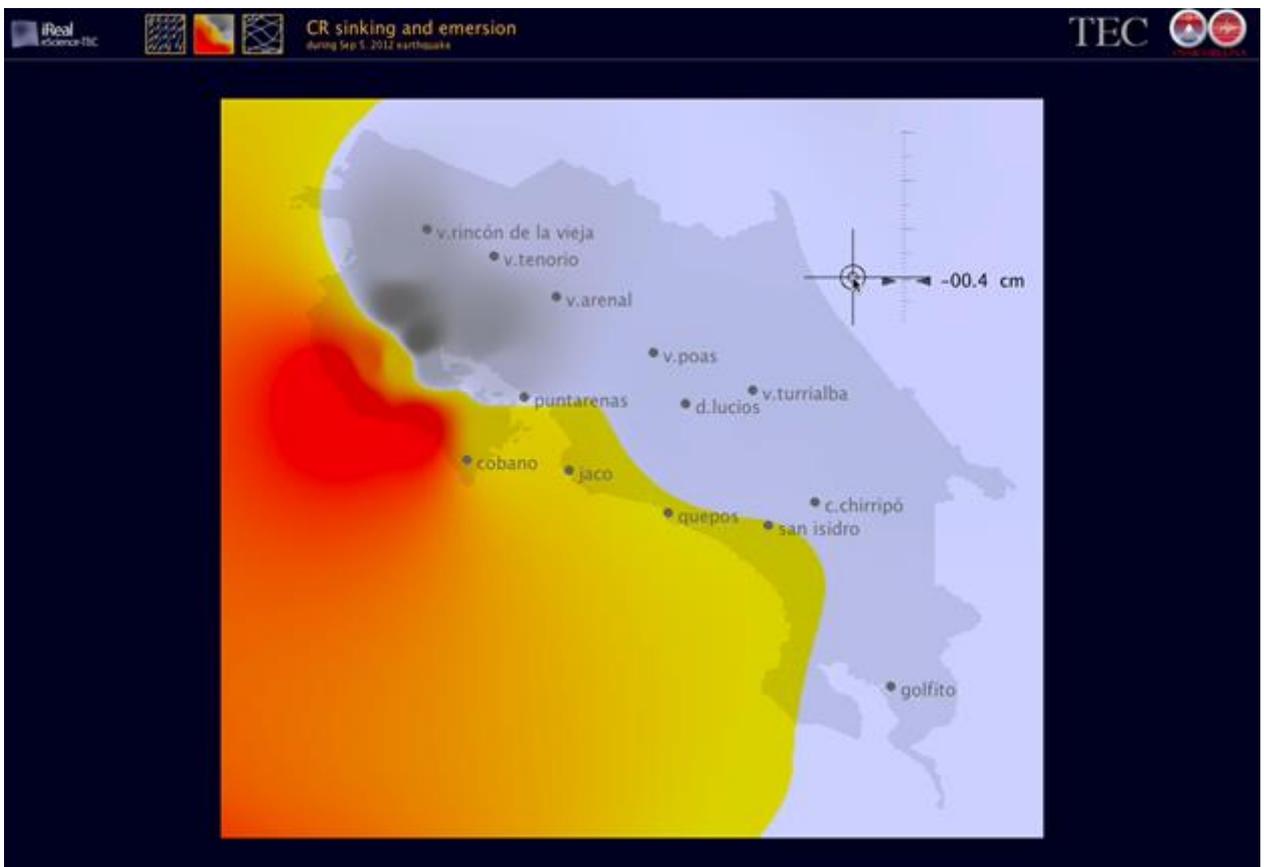Fig. 2: Two-dimensional visualization of latitudinal and longitudinal displacement

Fig. 3: Two-dimensional visualization showing upwards or downwards displacement of different areas in the country

3.3 Visualization of movement in altitude

The second type of two-dimensional visualization chromatically encodes upwards and downwards displacement of the earth´s crust during the earthquake.

Fig. 3 shows the map of Costa Rica divided into two large areas – a grey and reddish-yellow zone. The grey zone represents the part of the country that experienced ground sinking from the earthquake (subsidence: reduction of height above sea level). The darker the grey, the deeper the ground sunk. The reddish-yellow zone shows those regions in the country that were lifted by the earthquake. The darker the red, the greater the height. Conversely, as the yellow becomes lighter, the lower the impact on ground height.

Again, the figure has four positions of the mouse to show how the dashboard moves and better understand vertical displacement at each point.

3.4 3D Animation of both movements

A third type of visualization is developed in three-dimensions of horizontal and vertical movements simultaneously (Fig. 4), that is, the actual three-dimensional movement throughout the country. This animation depicts the movement produced for the energy accumulated in the last fifty years and released in the event on September 5th.
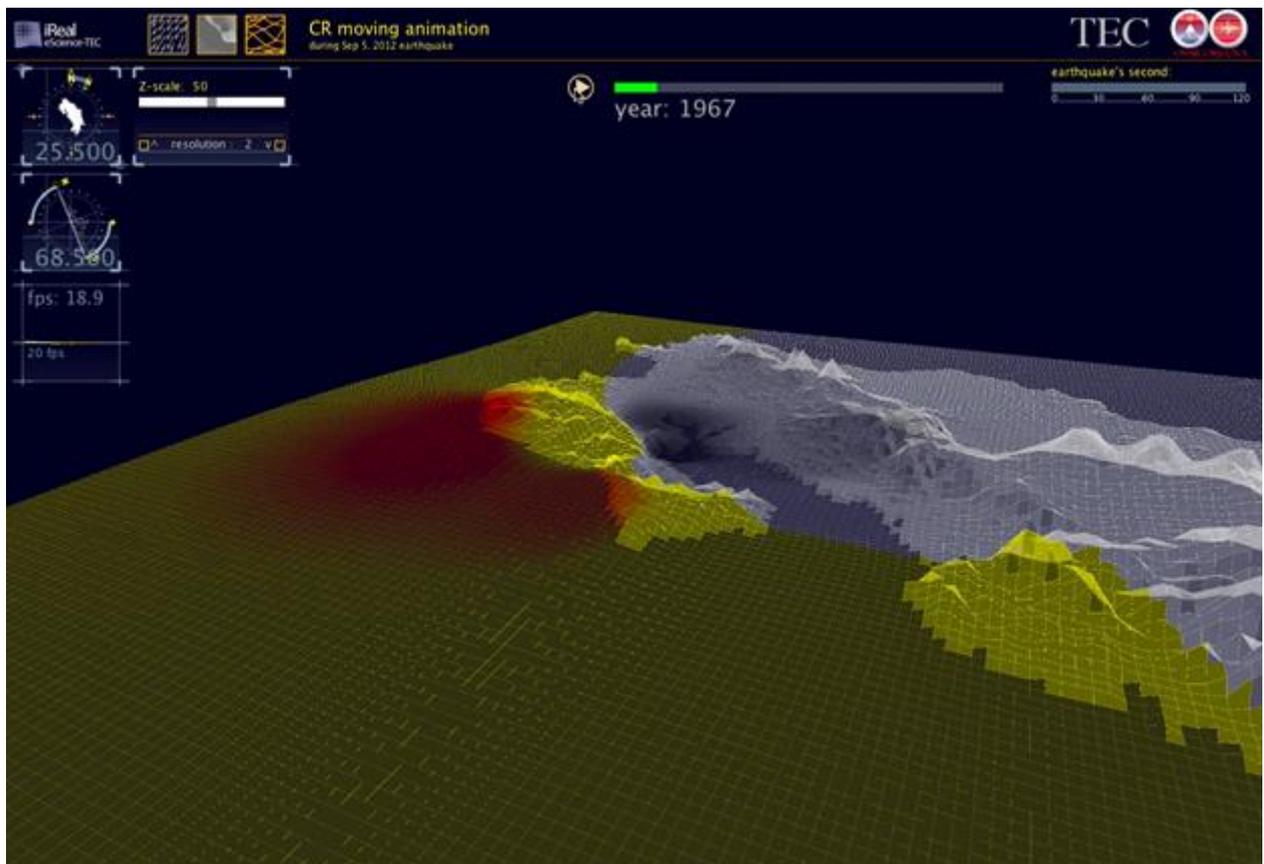

Fig. 4: 3D animation showing entire movement of the country during the two minutes of the earthquakes and its 5 dashboards

4. Usability evaluation

To evaluate and further guide the design of our visualization we conducted a user study through which we define, together with the seismologist of OVSICORI, a few user cases to test.

4.1 User-case longitudinal and latitudinal displacement

After several discussions with the domain scientists, the target question for our visualization was to, clearly as possible, show the relationship between the different displacements that occurred during the quake.

To achieve this goal, a cursor in the form of two "targets" (see Fig. 2) was designed for latitude and longitude displacement. The user can use the mouse to move the cursor over any visualization point and the two targets will move according to the displacement experienced in that area during the earthquake. This reflects the direction and gives a good idea of the magnitude. In addition, a numerical indicator is displayed to show combined displacement in centimeters.

Scientists use this visualization to obtain an overall picture of all of the information. The distribution of the arrows is particularly important in magnitude as well as in direction. Although, it is readily visible that the country is divided into two regions, the northern region affected by the subduction of the Cocos plate under the Caribbean plate and the southern region where the Cocos plate subducts under the Panama Block. This scenario is clear when it is understood that the behavior of the arrows also changes in both regions. This shows that horizontal movement in the Northern Region is much greater than those in the Southern Region. This is due to the fine extension of the earthquake´s rupture area.

4.2 Use-Case Z Displacement

The following case visualizes sinking and rising of areas throughout the peninsula. In the same work process as in the previous case, we discuss with seismologists the better way to obviously show in the visualization the movements up and down of earth's crust. The solution was similar, a color code for surface and new cursor to have the data in centimeters.

Also, another cursor was designed to visualize this type of motion. The cursor is a vertical scale that moves upwards or downwards according to the displacement of the point (Fig. 3).

Color-coding was used with red to represent ground elevations and blue for ground that subsided. In this manner, data could be visualized more intuitively with less of a cognitive burden, given that even the movement of the dashboard is in the same direction as the movement visualized.

Another advantage of this type of visualization for scientists is that the inflection line can be seen within the country. The "inflection line" marks the limit between the territory that was uplifted from the one that experienced subsidence. The colors clearly show this line through the peninsula and shows how most of it is located in firm ground, a phenomenon that is present in only 2% of the areas throughout the planet where faults are found [13]. As a result of interpolation among the station data, it is possible to graphically view an approximation of this line throughout the country.

4.3 Three-dimensional Earthquake Animation: User Case

As was previously stated, a three-dimensional animation was executed to analyze different displacement perspectives of the Nicoya Peninsula during the 50 years and the two minutes of the earthquake separably. Fig. 5 shows the dashboards available in the animation: Navigation, Resolution, Z Scale, Animation Time Data and Frame Rate.
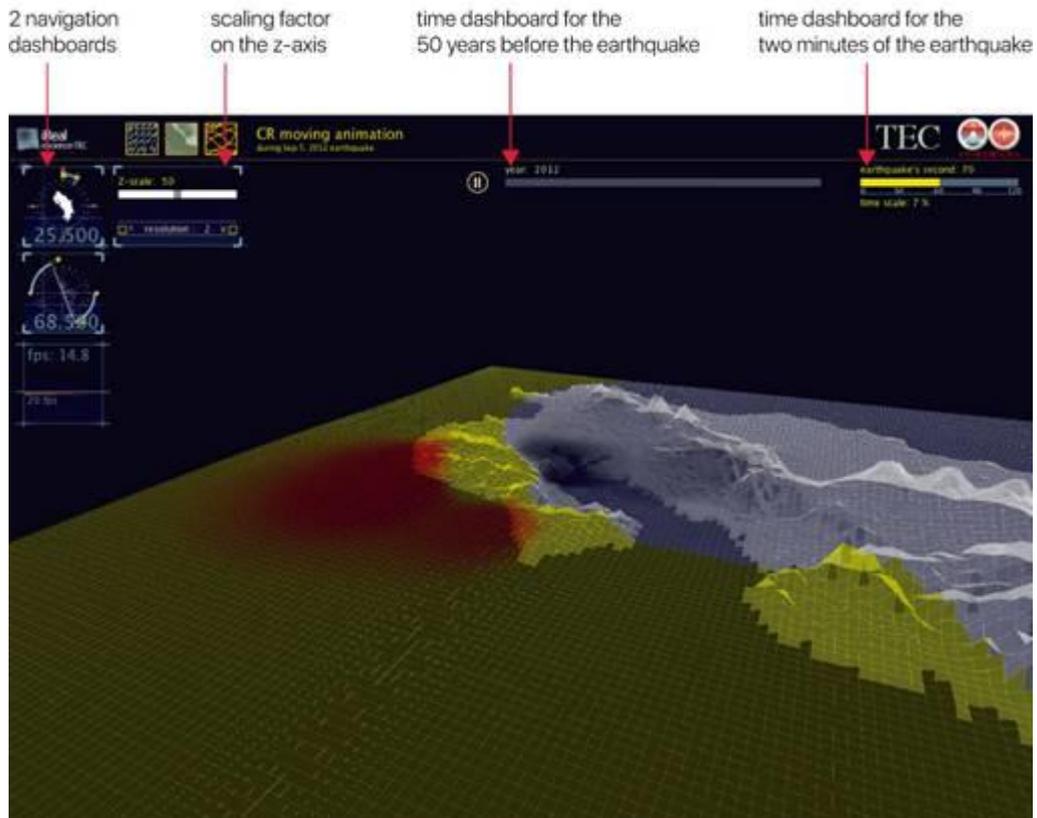
Fig. 5: Several dashboards on the animation

4.3.1 Navigation Dashboard

For 3D navigation, we use our customized approach of the conventional virtual trackball, Virtual Sphere or Sphere View [15].

In this case, the arrow keys are used to rotate and certain letters are used for close-ups and panning. In addition, there are two dashboards that show the incline of the animation as well as the North-South direction, as is the case in vertical rotation. See Fig. 5.

This feature of the animation was very useful for scientists since displacement, from all perspectives, can be perceived more intuitively and they can understand the exact movement of the earth´s crust in these crucial moments.

4.3.2 Z Scale Dashboard

A dashboard was implemented to be able to modify the movement scale in the Z-axis. It is obvious that at no point in time, movement in the Z-axis can be ani-

mated to a real-life scale, since the highest displacement was under 70 centimeters. Although this is lengthy for a peninsula, it is not visible in an animation in real-life scale. This allows scientists to see more clearly the relationships between the deformations in different parts of the peninsula.

Animation initially runs from a Z scale of 1:50 that can be adjusted to 1:100 using the slider. Scientists may increase the movement of Z from 50 to 100 in a continuous manner, thus allowing a better understanding and view of movement relationships throughout the different regions in the peninsula.

Although not a true to scale, movement relationships are present, such as, an area that sinks while another is elevated or a part that is displaced more towards the south while another area moves towards the west. This is the type of target question that the dashboard helps respond.

This feature was so well received by scientists that they may implement it for other displacements in future visualizations.

4.3.3 Grid Deformation

The animation was developed on a grid pattern in order to show the extent of the movement and the direction of the deformation. This was a particular request from scientists since it explains why certain parts of the country sink when they are "stretched" or "pulled" by the detachment of other regions, as is shown in Fig. 6.
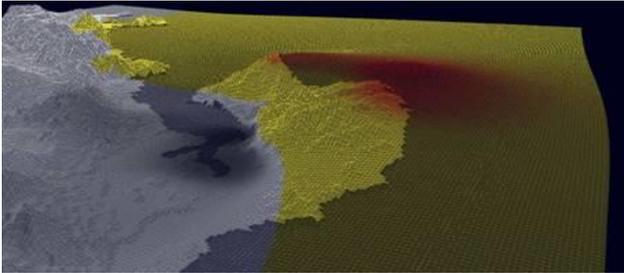

Fig. 6: Deformation of the original grid during a specific movement of the earthquake

After many additions and adjustments in the visualization with the observations of the scientists, they coincide in the utility of the animation: "Crustal deformation is the elastic response to strain accumulation and visco-elastic deformation results from sudden stress drop. The first is very slow and the seconds fast; both are quite small to represent in real time as time series". Other induced crustal deformation could also occur and be only recorded with GNSS (Global Network Satellite Systems such as GPS). In many cases these deformations occur on very long-time scales and are even difficult to deduct from regular time series of daily GPS solutions. Under these conditions, having a visualization tool that allows for both, magnification of the signal as well as acceleration of time, permits identify events that otherwise could be missed by the scientific community.

5. Conclusion and Future Work

This type of earthquake visualization offers an array of possibilities, such as using the same techniques for other earthquakes or geographic areas for purposes of examining a specific technique more in depth. Two-dimensional latitude and longitude displacement visualization is already scheduled for 2017-18. However, this time the visualization will not be limited solely to an earthquake, but to movement of the entire country for one year with time, speed and geographic filters. This project arose as a reaction from seismologists after viewing these types of current visualizations. The controlled acceleration of the motion will also permit the visualization of slow-slip events that occur over several weeks and do not leave a record on seismograms.

The possibility of viewing all data in a single view and being able to compare the different parts of the peninsula simultaneously with regards to the specific moment of movement during the earthquake has been welcomed by scientists who regard visualizations as a very simple summarized method of understanding the complex mechanics of an earthquake.

In the other hand, the environment in which the tool was developed is multi-platform and can be co-worked in Linux, Windows, and macOS, in the same way, it can generate applications to run on all three operating systems.

The whole system automatically adapts to the data, even the camera takes the average longitude and latitude of the data provided and positions itself in the middle of the analyzed area with a height defined by the width of the geographical area so that the camera can visualize the entire area. In this way, any data group, or any geographic area can be viewed and analyzed by the tool by merely changing the CSV files.

We opted for this parameterized programming scheme to be able to visualize other earthquakes easily, since in Costa Rica they are frequent, as well as earthquakes in other areas of interest, such as the Caribbean or the Pacific Ring of Fire, all of which are seismically related to our country.

As a tool developed in a public university in Costa Rica, it is open to collaborating with any other university or research center to help in the analysis of an issue so relevant for countries suffering from seismic activity.

6. Acknowlegment

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