La Pintada landslide—A complex double-staged extreme event, Guerrero, Mexico

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Abstract: Extreme storms commonly trigger landslides in regions of humid, warm tropical climate causing loss of life and economic devastation. The tropical mountainous areas of Guerrero in southwest Mexico are frequently hit by extreme hurricanes and cyclones and thus prone to landslides. On 16 September 2013, a huge landslide resulted in 71 fatalities and destroyed a large part of La Pintada Village. We applied remote sensing techniques using the LIDAR DEM and high-resolution images of the La Pintada area, a post-landslide field survey, geotechnical laboratory tests of colluvium material from the landslide, and a slope stability analysis. We also interviewed eyewitness accounts of the event. Our results suggest that the 2013 La Pintada landslide was a complex and two-stage event. An intense four-day-long rainfall event related to the landfall of Hurricane Manuel resulted in the oversaturation of soil, which was the main factor that caused the landslide. The effect of rainfall was amplified by the lack of high and dense vegetation on the 250-m-high slope. The lack of vegetation and slope-under-cutting likely contributed to the decreased slope stability. We suggest that increased intensity of extreme storms has contributed to increased landslides in this area. Furthermore, in tropical climate areas, where significant population lives in mostly developing countries, the combination of these phenomena makes them highly vulnerable to extreme storms and landslide hazards.

ABOUT THE AUTHORS
Maria-Teresa Ramírez-Herrera and Krzysztof Gaidzik's group research key research activities focus on the study of active tectonics, paleoseismology and tsunami deposits, and geohazards with emphasis on landslides. The reported research relates to a wider project on the Mexican forearc active deformation and geohazards as well to landslide automatic susceptibility mapping.

PUBLIC INTEREST STATEMENT
Landslides are one of the most important natural hazards causing loss of life and economic devastation. They are commonly triggered by extreme hurricanes and cyclones in tropical climate areas, such as Guerrero, southwest Mexico. Increasing intensity of extreme storms related to climate change increments landslide hazard in these areas and favors the occurrence of deadly landslides. This research was undertaken to provide a better understanding of a landslide that occurred on 16 September 2013, and resulted in 71 fatalities and destroyed a large part of La Pintada Village. The results of a detailed analysis of high-resolution digital elevation models, a post-landslide field survey, laboratory tests of soil material, and eyewitness interviews suggest that the studied landslide was a complex event triggered by an intense four-day-long rainfall related to the landfall of Hurricane Manuel. The lack of vegetation and slope under-cutting likely contributed to the decreased slope stability.
1. Introduction

Natural hazards can lead to disasters that result in human death, economic loss, and environmental impacts (e.g. Scawthorn, Schneider, & Schauer, 2006). Extreme precipitation events related to climate change have been increasing over the last decades (e.g. Allan & Soden, 2008; Intergovernmental Panel on Climate Change [IPCC], 2012, 2013; Knutson et al., 2010). The frequency, intensity, spatial coverage, and duration of extreme events have increased, corresponding with a greater number of natural hazards and disasters (UNISDR, 2012). Increasing extreme precipitation events can influence the occurrence of landslides (IPCC, 2012). Studies of the impacts of climate change on mass movements in different regions around the world have suggested that the number, temporal occurrence and size of mass movement phenomena will likely be altered by changes in precipitation and temperature (e.g. Crozier, 2010; Fischer, Amann, Moore, & Huggel, 2010; Ravanel & Deline, 2011; Stoffel, Tiranti, & Huggel, 2014). However, the societal impact of mass movements is not equally distributed around the world; over the last few decades, most fatalities (more than 95%) related to extreme events have been recorded in developing countries (UNEP, 2012).

A landslide occurred in La Pintada Village in Guerrero, southwest Mexico, on 16 September 2013 due to the unprecedented rainfall (ca. 500 mm in 4 days) produced by Hurricane Manuel (Pasch & Zelinsky, 2014). This landslide crossed the entire floodplain of the Coyuca River (Figure 1), nearly buried an entire village, and resulted in 71 fatalities, leading to its ranking as one of the deadliest landslides to occur in Mexico and as a significant landslide worldwide (Haque et al., 2016; Petley, 2012). The La Pintada landslide occurred on the S-SSE facing slope, which was ca. 250 m-high with a slope of 25°. The same slope had failed previously, and the most recent failure occurred in 1974 (Garcia Herrera, 2014). Here, we present the physical characteristics and processes that influenced the failure of this landslide. We focus on the analysis of a landslide at La Pintada as a complex and two-stage event because of its mobility, shape and deposits. We aim to provide a better understanding of this event and its implications for landslide hazard evaluation.

Figure 1. Location of the La Pintada landslide (red star) in southern Mexico on the right bank of the Coyuca River.

Notes: SMS: Sierra Madre del Sur. Data © LDEO-Columbia, NSF, NOAA, Image Landsat, Data © SIO, NOAA, U.S. Navy, NGA, GEBCO.
2. Study area
La Pintada is located ~60 km NW of Acapulco Guerrero State in southern Mexico (Figure 1) in the NW part of the Coyuca drainage basin (1,300.8 km²) and on the western bank of the Coyuca River (locally named the Pintada River). La Pintada Village is located at 1,073 m amsl in the Sierra Madre del Sur Mountains ~40 km from the coast (Figure 1). The elevation of the mountains surrounding La Pintada Village varies from ~1,150 to 1,200 m amsl on the eastern side of the river to almost 1,300 m amsl on the western side of the river above the village. The local base level, i.e. the elevation of the Coyuca River, is at ca. 1,050–1,060 m amsl near La Pintada Village, and the local relief reaches 240–250 m above the village on the S-SSE facing slope that produced the landslide. The hills on the other side of the river are much lower, reaching only 100–150 m above the level of the Coyuca River.

2.1. Lithology and soils
The lithology of the Coyuca drainage basin is homogenous. The La Pintada area sits on igneous rocks of mainly granite (Figure 2(b)). The following three main units can be distinguished in this area with increasing depth: red clay with low permeability (10–12 m thick), strongly weathered and fractured altered granite, i.e. regolith, with high permeability (ca. 10 m thick), and fresh, impermeable granite (García Herrera, 2014). Soils in the Coyuca River Basin are generally poorly developed, usually with little or no profile development, and shallow, gravelly or sandy with a very thin layer of organic matter. This is especially true for the mountainous part of the basin, where young soils with no profile development are predominant (IUSS, 2015). The area of La Pintada is characterized by cambisols, i.e. moderately developed soils with some initial horizon differentiation (Driessen, Deckers, Spaargaren, & Nachtgeraede, 2000). In the field, we observed reddish, very oxidized and clayey soil with a deeply weathered regolith, which is common of tropical environments.

2.2. Tectonic and seismic setting
The Coyuca drainage basin is in the Mexican subduction forearc where the oceanic lithosphere of the Cocos plate subducts beneath the North American continental plate at a convergence rate of 6.4–6.7 cm/year (DeMets, Gordon, & Argus, 2010) (Figure 2(a)). The seismicity pattern of the Guerrero section is distinctive. This section of the Mexican subduction forearc, known as the Guerrero seismic gap, has experienced no significant thrust earthquakes since 1911 (Anderson, Singh, Espindola, & Yamamoto, 1989; Kostoglodov & Ponce, 1994). Prior to 1911, four large earthquakes of Mw > 7 occurred in this section: 14 January 1900, 20 January 1900, 15 April 1907, and 16 December 1911.
(Ramírez-Herrera, Corona, & Suárez, 2016). Thus, this section has the potential for a large subduction earthquake with a magnitude of Mw 8.1–8.4 (Suárez, Monfret, Wittlinger, & David, 1990). The small magnitude seismicity in this area is characterized by shallow, interplate thrust events near the trench (mainly offshore) and crustal thrusts and normal events situated ~80–105 km from the trench (Pacheco & Singh, 2010) near the area of La Pintada (Figure 2(c)). Among the largest events to occur here is the Coyuca earthquake, Mw = 5.8, 8 October 2001, with an epicenter located near the town of Coyuca (Pacheco, Iglesias, & Singh, 2002; Pacheco & Singh, 2010) and approximately 40 km from La Pintada (Figure 2(c)).

2.3. Climate and precipitation

The climate of the study area is sub-humid, tropical, warm to very warm (Instituto de Geografía de la UNAM, 2007), with average annual temperatures above 20°C. On Figure 3 is shown the average annual precipitation, except for a station near Coyuca, is more than 1,000 mm/yr (Figure 3). The temporal distribution of rainfall is uneven, with most precipitation occurring during five months of the rainy/wet season, i.e. from June to October. The maximum monthly rates of precipitations during a year, which reached nearly 400 mm at the Rio Santiago station, were recorded in the month of September (Figure 3). The annual number of days with rain varies from ca. 50 near the Pacific Ocean to more than 70 in the central and western portions of the Coyuca River Basin. Notably, no meteorological stations are located upstream in the mountainous area of the Coyuca River Basin near La Pintada. We expect that the precipitation rates are higher uphill than downhill.

Figure 3. Precipitation: Rio Santiago, Tepetixtla, Carrera Larga and Laguna Coyuca stations in the Coyuca drainage basin, data from SMN (https://smn.cna.gob.mx/index.php?option=com_content&view=article&id=182:guerrero&catid=14:normales-por-estacion).

Notes: Average monthly mean precipitation (red line) and monthly precipitation in 2013 (blue columns); daily precipitation in September 2013 (green columns). Note that for the Carrera Larga station, the daily data ends on 14 September 2013.
September has the highest average rainfall and the highest number of days with rain and is when hurricanes and/or tropical cyclones occur. In 2013, a category 1 hurricane (on the Saffir-Simpson Hurricane Wind Scale), known as Hurricane Manuel, made landfall as a tropical storm on the coast of Guerrero from 13 to 19 September (Pasch & Zelinsky, 2014). The total amount of rainfall that fell on the Guerrero coast during this event reached the monthly average precipitation. In the mountains in the La Pintada area, Tepetixtla station recorded rainfall during 5 days, from 12 to 16 September, that was nearly three times higher than the average rainfall that occurred throughout the month of September (Figure 3). The amount of precipitation related to this hurricane at the Carrera Larga station nearest La Pintada is unknown because no data are available after 14 September 2013.

The exceptionally large amount of rainfall produced by Hurricane Manuel strongly impacted the discharge of the rivers draining the Sierra Madre del Sur and flowing into the Pacific Ocean on the Guerrero coast, destroying two stations. Thus, we combined data from the La Sabana River (east of La Pintada) to show the impacts of the rainfall related with Hurricane Manuel. On Figure 4 is illustrated the discharge of La Sabana River from 14–19 September that reached up to 900 times the average discharge for the years 1955–2012 and reached more than 10 times the previous record from 1984 (Figure 4). The water level rose to > 7 m, i.e. approximately 4 m higher than the average maximum water level (Table 1). The impact of the hurricane is also reflected in the runoff volume, which was more than 15 times the average annual runoff volume for the month of September 2013 (Table 1).

**Figure 4. The best track position for Hurricane Manuel, 13–19 September 2013 (Pasch & Zelinsky, 2014).**

Notes: Insert shows discharge from the La Sabana River (station km. 21,000; yellow triangle) for September 2013 (red line) and the average discharge for September 1992–2012 (blue line) (CONAGUA, [https://www.conagua.gob.mx](https://www.conagua.gob.mx)). Image from Google Earth. Based on Data © LDEO-Columbia, NSF, NOAA, Image Landsat, Data © SIO, NOAA, U.S. Navy, NGA, GEBCO.

| Parameter | Max. discharge (m³/s) | Max. water level (m) | Annual runoff volume (m³) | Average annual discharge (m³/s) |
|-----------|-----------------------|----------------------|---------------------------|-------------------------------|
| Time period          | Maximum (date)               | Average | Maximum (date) | Average | Maximum (date) | Average | Maximum (date) | Average |
| 1955–2012 | 1,096.6 (14 September 1984) | 321 | 5.7 (14 September 1984) | 3.1 | 436,549.3 (1984) | 119,566.6 | 13.8 (1984) | 3.8 |
| 2013     | 13,941.2 (15 September 2013) | 119,566.6 | 7.3 (15 September 2013) | 3.1 | 2,571,553.1 (September—2,102,494.5) | 82.2 (September—811.2) | 82.2 (September—811.2) | 82.2 (September—811.2) | 82.2 (September—811.2) |
3. Materials and methods

We applied remote sensing techniques using the LIDAR DEM and high-resolution images of the La Pintada area, a post-landslide field survey, geotechnical laboratory tests of colluvium material from the landslide, and a slope stability analysis.

The aim of the post-landslide field survey was to recognize the landscape and landforms, analyse the landslide features and material, obtain samples for geotechnical laboratory tests and gather residents accounts of the event. In the field, we took 356 photographs of the landslide from different perspectives and angles to produce a high-resolution DEM using the Structure from Motion (SfM) procedure (e.g. James & Robson, 2012; Johnson et al., 2014; Snavely, Seitz, & Szeliski, 2008) implemented by Agisoft Photoscan software. We collected six samples from three different locations along the landslide: 3 samples at different depths (from the surface up to a depth of 43 cm) from above the headscarp, 2 samples (from the surface to a depth of 55–60 cm) from the middle point of the landslide, and 1 sample from the toe slope (Figure 5(b)). We were unable to obtain colluvium from the landslide because it had been removed before we reached the site; thus, we sampled the material on the slope nearest the slide. At sites where we took samples for further analysis, we also obtained compaction measurements using the Lang Penetrometer (with a scale ranging from 1 to 20).

In the field, we studied a second, smaller, landslide near the town of El Paraiso and west of the landslide in La Pintada shown on Figure 5(a) and (c). We took 72 photographs from various perspectives and angles to produce a DEM of the landslide using the SfM method (Figure 5(c)). We collected a sample of the material moved by this slide for laboratory geotechnical tests.

During fieldwork, we also gathered La Pintada residents’ accounts. Among others, we talked with Mr. Galdino Alvarez Ocampo, who was the local governor (Comisario Municipal) of La Pintada at the time of fieldwork (April 2015).

3.1. Morphometric analysis and LIDAR derived DEM

To calculate the main morphometric parameters (e.g. steepness of slope) of the Coyuca River Basin, we used a 15-m-resolution DEM provided by INEGI. However, the resolution of this model was not sufficient to study the landslide itself. Therefore, we acquired LIDAR data for the study area of 15.7 km² in the upstream section of the Coyuca River Basin (Figure 5(b)). We used an airborne laser scanner (RIEGL Q-780) with a laser pulse repetition rate of 400 Hz and a field of view (FOV) of 60° (+30°/−30°) and gathered data with a density of 8 points/m² and 35 cm of horizontal and vertical a priori precision. A CESSNA TU206H aircraft flying at an elevation of 700 m above the ground was used to scan pulsed laser beams across the study area. The LIDAR data were collected on 19 March 2015. RIEGL software (e.g. RiAcquire, RiProcess, RiAnalyze and RiWord) was used to control the scanner and for data acquisition, visualization, projection, georeferentiation, and exportation. After adjusting the point cloud to the ground, the data were converted into “LAS” format. Later, the data were classified into ground and default points (e.g. vegetation, infrastructure, buildings, etc.) using TerraScan and TerraModeler. The automatic classification was later verified and improved using manual classification. To estimate the length and width of the landslide, the steepness of the slope that produced the landslide and the morphology of the La Pintada area, we produced a 1-m-resolution LIDAR-derived digital terrain model (DTM) from point cloud data classified and filtered in the previous stage (Figure 5(b)). We also obtained orthophotomaps using a Digital Airborne Scanner with one nadir RGB-sensor 1-DAS-1 from GeoSystem and digital elevation models derived from SfM using terrestrial photography (e.g. Figure 5(b) and (c)).
To calculate the morphometric parameters and visualize DEMs, we used ArcGIS and GlobalMapper software. Calculations based on our LIDAR-derived DEM are an estimate and show minimum values because the LIDAR postdates the event and was obtained after the slide material had been removed.
and the slope was covered with concrete. However, we reconstructed the morphology and other slope morphometric values based on air-photos (1: 20,000) and satellite images (DigitalGlobe) taken before the event. To calculate the depth of the slide, we subtracted the current topography (LIDAR) from the theoretical pre-slide surface (obtained by interpolating points on the edges of the niche).

3.2. Geotechnical data analysis
Geotechnical tests (shear strength, unconsolidated—undrained shear strength) on seven samples of slope material adjacent to the landslide collected in the field (6 from the landslide in La Pintada and one from landslide in El Paraiso) were conducted at the Laboratory of Engineering Solution for Electronic Measuring Devices (IDEM), Synergy Engineering Equipment and Supplies Company. Geotechnical tests resulted in the determination of the following parameters: water content (moisture), angle of friction, cohesion, dry and saturated sample weights, percentage of fine soils, percentage of saturation, Atterberg limits (liquid limit, plastic limit, plasticity index), and the soil classification according with Unified Soil Classification System, USCS.

3.3. Slope stability analysis and safety factor (F)
We conducted a slope stability analysis using the geotechnical test (mentioned above) results and the values of the morphometric parameters derived from the LIDAR DEM. To determine the slope conditions and the susceptibility of the slope to failure, we calculated the safety factor (F), which is usually defined as the ratio of forces resisting movement (strength) to the forces driving movement (load; e.g. Verruijt, 2012). Lower safety factors correspond with more unstable slopes, with a lower limit of 1. Thus, F values greater than 1 indicate a stable slope, i.e. forces resisting movement prevail over forces driving movement, and values less than 1 suggest a slope that is prone to failure, i.e. forces driving movement overpower forces resisting movement. We calculated the minimum safety factor using the following different methods: Bishop’s method implemented by SLOPE software, the Fellenius and Spencer method, Janbu’s method, and the Morgenstern-Price method, implemented by GEO5 2016 Slope stability software (Bishop, 1955; Fellenius, 1927; Janbu, 1954, 1973; Morgenstern & Price, 1965, 1967; Spencer, 1967; Verruijt, 2012).

4. Results

4.1. La Pintada landslide—historical development
The landslide that occurred at La Pintada on 16 September 2013 was not the first slide event to occur in this area. The occurrence of a landslide in this area during the rainy season in 1974 coincides well with the occurrence of Hurricane Dolores (HURDAT2, 2016), which is regarded as one of the strongest hurricanes to strike the coast of Guerrero in the twentieth century. We also corroborated the presence of at least three ancient slides on the same slope using satellite images. In the southern part of the village and outside the extent of the 2013 event, we observed large angular granite blocks of up to several cubic meters (up to ca. 60 m$^3$) in size that probably resulted from older landslides.

4.1.1. Pre-failure slope characteristics
Next to the La Pintada landslide site, the slope gradient is approximately ≥25°; thus, the pre-failure gradient of the slope was probably like this gradient. We reconstructed the pre-failure surface using LIDAR and the elevations of points at the approximate positions of the headscarp of the slide. This surface shows similar slope steepness.

Dense mountain forests with pine trees and evergreen oaks are predominant near the coffee-growing village of La Pintada. However, the landslide slope is devoid of vegetation, as shown on the INEGI orthophotomap from 1995 shown on Figure 6(a) and the satellite images from 2010 to 2011 shown on Figure 6(c) and (d), i.e. preceding the event. The headscarp was initiated at about the boundary between the lower part of the slope that was free of vegetation and the densely forested upper slope.
Figure 6. Orthophotomap (a) and satellite images (b and c; Image © 2016 DigitalGlobe) of the La Pintada area from before (a, b and c). (a) Orthophotomap E14C36E, scale 1: 20,000, 2 m resolution (Source: INEGI, Ortofoto Digital E14C36E, El Paraiso 1999), with the contours of the La Pintada landslide, (b) and (c) images showing the slope before the event almost completely devoid of vegetation.
4.2. Landslide characteristics

The landslide in La Pintada occurred on a moderately to steeply dipping (≥25°) S—SSE facing slope just north of La Pintada Village (Figure 7). The main morphometric parameters are presented in Table 2. Based on photographs taken after the event (Figures 7(b) and 8(b) and (d)), a clear bend and break occurs in the lower part of the slope that is emphasized by the presence of two ponds. The upper break marks a bench that extends beyond the landslide and likely corresponds to the outer scarp of an ancient river terrace that also has traces of ancient landslides.

Figure 7(b) and Table 2 show the La Pintada landslide presents two main zones divided by a “structural bench” and bend in the slope an upper zone (A) in the form of a symmetrical niche facing south and a lower zone (B) that continues up to the toe of the slope.

Table 2. Morphometric parameters of the La Pintada landslide

|                     | Height (m amsl) | Length (m) | Width (m) | Depth [m] | Area (m²) | Volume (m³) | Orientation of slope |
|---------------------|----------------|------------|-----------|-----------|-----------|-------------|---------------------|
| Entire landslide    | 1,190–1,085    | 300        | Up to ca. 100 | Up to ~15 | ~23,375   | 75,000      | Facing S-SSE        |
| Zone A (upper)      | 1,190–1,170    | 40         | 45        | ~10       | ~1,795    | 4,500       | Facing S            |
| Zone B (lower)      | 1,170–1,085    | 260        | Up to ca. 100 | ~15 in the upper part to 2–3 m downhill | ~21,580   | 70,500      | Facing SSE          |
According to our calculations based on LIDAR-derived DEM, the volume of remobilized material is approximately 75,000 m$^3$. The colluvium material (i.e. rocks, mud, soils, and trees) transported by the landslide was deposited at the bottom of the slope and the ancient Coyuca River flood plain, burying the central part of La Pintada Village, with an area of approximately 50,000 m$^2$, reaching the Coyuca River and ~500 m from the headscarp of the landslide (Figure 7(a), (b) and 8). The thickness of the material reached up to 10 m, with an average thickness of approximately 5 m. Considering the average density of the samples collected in the field from the landslide material (clay) of ca. 2,645 kg/m$^3$ and the calculated volume of the material, the weight of the colluvium material that buried La Pintada reached up to ca. 200,000 tons.

4.3. Geotechnical slope characteristics

The results from the geotechnical tests of six samples obtained from three sites on the slope adjacent to the landslide at La Pintada and from one sample obtained from a smaller landslide near the town of El Paraiso (Figure 5(b) and (c)) are summarized in Table 3. According with these results, the material on the slope above La Pintada consists of silt with low plasticity and silty sand (Table 3). The material taken from El Paraiso slope can be described as clay with high plasticity, i.e. fat clay. Samples taken from the surface or near the surface show an angle of internal friction of more than 30° or nearly 30° (samples 1a, 1b, 2a and 3, and sample from landslide in El Paraiso; Table 3); whereas, samples at depths of 55–60 cm showed smaller angles of up to 13° (Table 3, sample 2b). Differences between surface and deeper samples are also reflected in the values of the neutral stress coefficient, with deeper samples corresponding with larger values. The estimated values of cohesion range widely from ~4 kN/m$^2$ for the surface sample from the middle part of the landslide (sample 2a) to nearly 25 kN/m$^2$ for the deepest sample, i.e. sample 2b (Table 3). The weight of samples varied insignificantly, i.e. from less than 15 kN/m$^3$ to almost 16 kN/m$^3$ for dry samples and from
~25 kN/m³ (samples 1a and 1c) to almost 27 kN/m³ (sample 3) for saturated samples. The samples had variable fine grain contents (<0.074 mm). The slope adjacent to the location of the La Pintada landslide contains fine particles ranging from 20% (sample 2a) to 65% (samples 1b and 2b) among the studied samples. For the landslide in El Paraiso, the content of small grains is higher reaching ca. 75% (Table 3).

Using the results of geotechnical tests conducted on seven samples taken in the field (six from La Pintada landslide and one from the landslide in El Paraiso) and measurements taken in the field and using the LIDAR DEM, we conducted a slope stability analysis to determine the safety factor (F). The results of this analysis are presented in Table 4, where we summarized the values of the minimum safety factor calculated using different methods (i.e. Bishop, 1955; Fellenius, 1927; Janbu, 1954, 1973; Morgenstern & Price, 1965, 1967; Spencer, 1967; Verruijt, 2012). The slope adjacent to the location of the La Pintada landslide shows minimum and maximum safety factors of 0.95 and 1.36, respectively (Table 4). These results differ because different methods use different formulas and require different input data.

### Table 3. Results of field studies and laboratory tests conducted on seven samples taken from the landslide in La Pintada and El Paraiso (for location see Figure 5)

| Parameters                        | Samples     | La Pintada | El Paraiso |
|-----------------------------------|-------------|------------|------------|
| Latitude                          |             | 17°21′04″  | 17°20′08″  |
| Longitude                         |             | 100°10′02″ | 100°14′33″ |
| Depth (cm from the surface)       | 0-2         | 20-26      | 0          |
| Results of field studies          | Penetrometer values | 15.5 15.0 6.5 | 16.0 17.2 11.7 |
| Results of laboratory tests       | Angle of friction (φ) | 32.9 28 23 | 32 13 34 | 34 34 |
|                                   | Neutral stress coefficient (K₀) | 0.46 0.53 0.61 | 0.47 0.78 0.44 | 0.44 0.44 |
|                                   | Cohesion (kN/m³) | 0 21.58 3.92 | 24.52 13.73 13.73 |
|                                   | Weight of dry sample (kN/m³) | 15.79 15.79 15.79 | 15.79 14.51 15.89 | 15.89 15.89 |
|                                   | Weight of saturated sample (kN/m³) | 24.91 26.18 25.01 | 25.99 26.09 26.87 | 25.79 25.79 |
|                                   | Water content (moisture) of natural sample (ω%) | 10.70 11.00 8.60 | 5.80 11.60 2.80 | 7.20 7.20 |
|                                   | Water content (moisture) of saturated sample (ω%) | 49.85 52.70 52.35 | 53.81 52.01 55.26 | 36.00 36.00 |
|                                   | Percentage of fine soils (<0.074 mm) | 51.30 64.60 46.70 | 21.20 63.90 58.30 | 74.60 74.60 |
|                                   | Percentage of saturation (%Sr) | 91.78 90.95 93.47 | 92.13 90.52 91.36 | 91.39 91.39 |
|                                   | Liquid limit (%Ll) | 73.60 53.20 52.70 | 53.20 36.00 |
|                                   | Plastic limit (%Pl) | 48.50 23.70 | 23.70 23.70 |
|                                   | Plasticity index (%Pi) | 25.10 29.50 | 29.50 29.50 |
|                                   | Classification according to USCS | ML ML SM SM ML ML | CH CH |
|                                   | Description | Silt, low plasticity | Silt, low plasticity | Silty sand | Silty sand | Silt, low plasticity | Silt, low plasticity | Clay of high plasticity, fat clay |

Notes: Values from laboratory tests were used in the slope stability analysis. USCS: Unified soil classification system.

\[ K₀ = 1 - \sin \phi \] (Verruijt, 2012).
4.4. Seismic signals produced by La Pintada landslide

We analyzed the seismograms from the nearest seismological station, i.e. El Cayaco (CAIG), which is located ca. 40 km from La Pintada, to determine if the landslide caused any visible ground motion effects that were reflected on seismic record (Servicio Sismológico Nacional [SSN], 2017). We found that the landslide produced seismic signals at 3:23.50 pm on 16 September 2013 (Figure 9). A difference of nearly 7 s between the time of arrival of the P and S waves suggests that the landslide was located some 50 km from the El Cayaco station, which approximately corresponds with the location

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Table 4. Values of safety factor ($F$) calculated using different methods

| Method                      | SLOPE software | GEOS 2016<sup>a</sup> | GEOS 2016<sup>b</sup> |
|-----------------------------|----------------|------------------------|------------------------|
| Bishop analysis<sup>c</sup> | 1.11           | 1.36                   | 1.04                   |
| Fellenius<sup>d</sup>       | 1.29           | 0.95                   |                        |
| Spencer<sup>e</sup>         | 1.33           | 0.96                   |                        |
| Janbu<sup>f</sup>           | 1.36           | 0.99                   |                        |
| Morgenstern-Price<sup>g</sup> | 1.35          | 0.99                   |                        |

<sup>a</sup>Using data from geotechnical tests.
<sup>b</sup>Using average values based on soil classification according to USCS (see Table 3).

Sources: <sup>c</sup>Bishop (1955), <sup>d</sup>Fellenius (1927), <sup>e</sup>Spencer (1967), <sup>f</sup>Janbu (1954, 1973), <sup>g</sup>Morgenstern and Price (1965, 1967).

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Figure 9. Shaking related to the La Pintada landslide registered on seismograms at the CAIG (El Cayaco) station on 16 September 2013, data from SSN (https://www.ssn.unam.mx).

Notes: Upper graphs refer to the first stage of the landslide at 3:23 pm local time, whereas the lower graph refers to the second stage (8:05 pm).
of the La Pintada landslide. The timing of the seismic signals nearly corresponded with the time range indicated by most of the eyewitnesses, around 3:30 pm.

At 8:05 pm, additional smaller seismic signals were recorded by the seismogram at approximately the same time and on the same day according to people that experienced near the landslide. These two seismic signals recorded in one station, El Cayaco, 50 km away from La Pintada, suggest a surficial ground motion, equivalent to two small magnitude Mc 3.2 and 3.1 events (SSN, 2017).

4.5. Failure mechanisms of the 16 September 2013 La Pintada landslide

Based on our post-landslide survey observations and interviews to people that experienced near the landslide, we hypothesized that the 2013 La Pintada landslide was complex and occurred in two sequential stages of movement. The different styles of sliding are marked by the two zones described above; an upper zone (A) with a rotational plane that produced a deep-seated slide (rocks, trees, and mud), and a lower zone (B) with a semi-rotational to planar plane that produced a debris slide (Figure 7(b)–(d)). The two hypothesized stages of sliding are supported by testimonies of people that experienced near the landslide and the seismic signals, though small in amplitude, recorded in the seismograph at Cayaco station that show two sequential events. The first event was significantly larger than the second event, producing a thunderous noise likely related to slope failure, the impacts of huge blocks on the ground, and the flow of mud and trees over the houses and flood plain topography (Figure 8). This event occurred in ca. 17 s, which did not leave enough time for people to leave their houses. The second stage consisted of a smaller landslide event that occurred 5 h after the first sliding episode. This event consisted of a smaller debris slide. The seismic signal of the second event was smaller and lasted less than 10 s. These seismic signals of the first and second events, have been attributed to landslide related ground vibrations resulting from flow over smaller scale topographic features, such as the scarp at the La Pintada failure plane, frictional processes, and impacts of individual blocks, such as the ones observed at La Pintada (Figure 8) (e.g. Allstadt, 2013; Wartman et al., 2016).

5. Discussion

The main contributing factor to trigger the deep-seated La Pintada landslide was extreme and long-duration rainfall, i.e. the amount of accumulated rainfall. Although residents of La Pintada have witnessed evidence of the landslide creeping prior to the large-scale event, our data indicate that the main direct factor that initiated the large-scale landslide in La Pintada, on Monday afternoon, 16 September 2013, was an immense rainfall, 600–800 mm in 4 days, related with Hurricane Manuel that affected the western coast of Mexico. Detailed mapping based on satellite images revealed that more than 1,500 landslides were provoked by this hurricane in the central and eastern parts of Guerrero State (Aranza Rodríguez, 2014). However, the exact number of landslide events for the entire state could be much higher. Most landslide events provoked by the hurricane are represented by debris-flows and shallow soil slips, which are typical for high-intensity, short-duration rainfall events. Deep-seated landslides, such as the studied event at La Pintada, are less common. These events are generally triggered by low-intensity, long-duration rainfall events (Larsen & Simon, 1993). The already creeping La Pintada landslide and many other large deep-seated landslides throughout Guerrero State in southwest Mexico resulted from prolonged rainfall over five days (12–16 September 2013) during Hurricane Manuel that pushed a section of the slope over the failure point. Four-day-long rainfall events resulted in oversaturated soil, which significantly increased the weight of the slope material (Table 3). Small landslides and debris flows that were observed in Guerrero State after Hurricane Manuel, such as the studied landslide near El Paraíso, likely resulted from local severe storm cells that formed during the passage of Hurricane Manuel.

The impacts of Hurricane Manuel can be observed in the variations of discharge of the main rivers flowing into the Pacific Ocean. Data from the station nearest the La Sabana River were more than 10 times greater than from the previously recorded data from 1984 (Table 1), and more than 900 times greater than the average discharge recorded for 1955–2012 (Figure 4). Extreme meteorological events, such as Hurricane Manuel, play a major role in landslide activity in regions of humid, warm
tropical climate, provoking thousands of landslides, from shallow soil slips and debris flows to catastrophic, large deep-seated landslides (e.g. Buckham et al., 2001; Cannon et al., 2001; Harp, Hagaman, Held, & McKenna, 2002; Larsen & Simon, 1993; Larsen & Torres-Sanchez, 1992). For example, Hurricane Mitch triggered a large, deep-seated landslide (volume of 400,000 m$^3$) in El Reparto, Honduras (Harp et al., 2002), and 11,500 landslides in Guatemala that were triggered by the same meteorological event (Buckham et al., 2001).

The calculated safety factors, for the slope adjacent to the location of the La Pintada landslide, minimum and maximum, are 0.95 and 1.36, respectively (Table 4), indicating that the slope was meta-stable under normal conditions and that a powerful direct factor was needed to initiate the landslide processes. Rainfall related to Hurricane Manuel was the triggering factor. Furthermore, the material that failed had low safety factor values. Thus, the slope adjacent to the La Pintada landslide is meta-stable to unstable and is a high landslide hazard for the local community.

The La Pintada landslide originated on a slope that was devoid of vegetation (Figure 6). Almost absent vegetation on the steeply inclined slope above the La Pintada Village potentially contributed to more intense erosion and, consequently, slope failure. The lack of vegetation played a significant role in reducing slope stability, i.e. it was a preparatory and causal factor of the landslide and played a role in the susceptibility of the slope to movement over time without initiating it (e.g. Knapen et al., 2006). In addition, the landslide headscarp is located roughly on the border between high and dense forest areas uphill and the slope without vegetation downhill (Figure 6). As mentioned earlier, residents in La Pintada also indicated that the cutting the vegetation contributed to the generation of the landslide and that the slope should have been forested to prevent the soil from moving down the slope. Thus, this absence of trees on the studied slope was an important factor that contributed to the occurrence of this devastating landslide. As proven in many different regions, deforestation could lead to increased slope instability and erosion, a lower safety factor due to root decay (e.g. Knapen et al., 2006), and result in increased rates of landslide activity (e.g. Kamp, Growley, Khattak, & Owen, 2008). Studies in various environments worldwide have demonstrated a clear correlation between the absence of vegetation (or the presence of only small amounts of vegetation) and the occurrence of landslides; e.g. New Zealand (Glade, 2003; Phillips & Watson, 1994), Andes region (Vanacker et al., 2003), Himalaya (Kamp et al., 2008), and African highlands (Davies, 1996; Knapen et al., 2006; Mugagga, Kakembo, & Buyinza, 2012; Nyssen, Moeyersons, Poensen, Deckers, & Mitiku, 2003). The continued deforestation of landslide-prone areas is a major factor that contributes to a constant increase in landslide activity in the twenty-first century (Schuster, 1996). Mexico and Central America are not exceptions. Increases in landslide activity due to deforestation and changes in land-use have been reported for Mexico and Central America (e.g. Caballero et al., 2006; Restrepo & Alvarez, 2006). The landslide in La Pintada followed a similar pattern, where the absence of vegetation decreased the slope stability and rainfall related with Hurricane Manuel was the direct factor that triggered the landslide.

Two important questions are: How often do extreme meteorological events happen, and do all extreme meteorological events trigger devastating landslides? Exceptionally high rainfall produced by extreme meteorological events has occurred before in Guerrero. Hurricane Pauline (also known as Paúlina) triggered landslides and other damage in Oaxaca and Guerrero from the 5th to 10th of October in 1997 (Lawrence, 1997; Matias Ramírez, 1998). Moreover, six other hurricanes and tropical storms occurred between 1921 and 1996 on the coast of Guerrero and produced fatalities and landslides (Matias Ramírez, 1998). A more complete record suggests the occurrence of 35 hurricanes that had catastrophic impacts on the Guerrero coast between 1949 and 2015 (HURDAT2, 2016). Thus, considering that only the largest hurricanes are reported (HURDAT2, 2016; Matias Ramirez, 1998), the recurrence time for extreme meteorological events is approximately 3–10 years. Therefore, the main direct factor that contributes to landslide activity, when most often soil creeping has already spanning days to years prior to a major slip, in the study area is the occurrence of extreme meteorological events (tropical storms, cyclones and hurricanes). Numerous examples from Central America and other regions of humid, warm tropical climate show that extreme
meteorological events, such as hurricanes and tropical cyclones, are major factors that contribute to the landslide activity in these areas (e.g. Buckham et al., 2001; Cannon et al., 2001; Harp et al., 2002; Larsen & Simon, 1993; Larsen & Torres-Sanchez, 1992). Mass movements triggered by Hurricane Manuel on September 2013, such as the catastrophic landslide at La Pintada that caused more than 70 fatalities and thousands of smaller landslides in Guerrero State (Aranza Rodríguez, 2014), indicate that the study area is highly susceptible to landslides. Hazard warnings of this type of event could be forecasted long before a large event occurs or at the very least geotechnical analysis can be performed on susceptible slopes that are at high risk of failure.

Human activity, e.g. deforestation, steepening of slopes, slope under-cutting, loading of slopes due to the construction of houses, changes in the local relative relief due to the creation of artificial slopes or by grading with construction machinery, etc. might disturb slope equilibrium and lead to the occurrence of mass movement processes with time (e.g. Alexander, 1992; Schuster, 1996). In La Pintada, landslide activity has a long history. The portion of the village significantly destroyed by the landslide on 16 September 2013 was built on the colluvium material from an older historic slide. Moreover, evidence of even older paleo-events has been observed. However, although landslide activity in this area has been proven, the government rebuilt houses and reconstructed the village in the exact pathway of the 2013 landslide, which is now known as La Nueva Pintada. Although the local community is aware of the relationship between vegetation and landslide activity, efforts toward reforestation of the slope have not been introduced by official authorities. Thus, the slope without vegetation still might present a high landslide hazard.

Earthquakes are a major trigger for landslide events (Malamud, Turcotte, Guzzetti, & Reichenbach, 2004). Examples from around the world prove that large earthquakes can produce numerous landslide features, e.g. the 7.9 Wenchuan earthquake (2008) in China (Gorum et al., 2011), the 7.8 Gorkha earthquake (2015) in Nepal (Kargel et al., 2015), the 7.4 Khait earthquake (1949) in Tajikistan (Evans et al., 2009) and the 6.6 Chuetsu earthquake (2004) in Japan (Wang, Sassa, & Xu, 2007). Seismic events with magnitudes > 4.0, which is the smallest earthquake magnitude known to produce landslides (Keefer, 1984), are common in the study area (Figure 2). However, for small-magnitude earthquakes, the main provoked events would mainly be represented by rock falls, rock slides, soil falls, disrupted soil slides, soil slumps and soil block slides (Keefer, 1984). Earthquakes with a magnitude > 5.5 have occurred recently in Guerrero, including the magnitude 5.8 earthquake that occurred in 2001 with epicenter located ca. 40 km from La Pintada (Pacheco & Singh, 2010; Pacheco et al., 2002).

This sector of the Mexican subduction zone could potentially experience large subduction earthquakes of Mw 8.1–8.4 (Suárez et al., 1990). Such events would produce from ca. 60,000 to more than 300,000 landslides in an area spanning nearly 90,000 km² (Table 5). Moreover, seismicity not only

| Earthquake Magnitude, $M$ | Area affected by landslides, $A$ (km²) | Number of triggered landslides, $N$ | Number of triggered landslides, $N'$ | Magnitude of landslides, $m_L$ |
|---------------------------|-------------------------------|----------------------------------|-----------------------------------|--------------------------|
| 5.5                       | 109.65                        | 88                              | 28                               | 1.45                     |
| 5.8                       | 218.78                        | 206                             | 68                               | 1.83                     |
| 8.1                       | 43,651.58                     | 139,675                         | 62,951                           | 4.80                     |
| 8.4                       | 87,096.36                     | 326,949                         | 153,461                          | 5.19                     |

a$\log_{10}(A) = M - 3.66$.  
b$\log_{10}(N) = 1.2312 M - 4.8276$.  
c$\log_{10}(N') = m_L$.  
d$m_L = 1.29 M - 5.65$.  
Sources of formulas: a$^{Keefer (2002)}$ and b$^{Malamud et al. (2004)}$. 

Table 5. Area affected by landslides and number of landslides triggered by earthquake of a defined magnitude.
triggers landslides directly after the earthquake, but multiple earthquakes can also have long-term effects on slope integrity, decreasing the slope stability by seismically inducing damage (Walter, Gischig, Stead, & Clague, 2016). The effect of seismicity on the study area can also be amplified by deforestation processes, which occurred in the western Himalayas, where deforestation contributed significantly to landslides during and shortly after earthquakes (Kamp et al., 2008). Therefore, the effects of tropical cyclones can be amplified by the decreased long-term slope stability resulting from seismicity.

6. Conclusions

Our results suggest that the 2013 La Pintada landslide was a complex, two-stage event: a deep-seated slide (rocks, trees, and mud) from the rotational plane in the upper zone, and a semi-rotational to planar plane mechanisms produced a debris/mudflow in the lower zone.

The most important and direct factor that initiated the already creeping landslide in La Pintada was a four-day continuous and high rainfall event that was produced by Hurricane Manuel, which affected the western coast of Mexico. The 1974 landslide was also triggered by rainfall related to another extreme meteorological event, i.e. Hurricane Dolores. Thus, anomalous precipitation appears to be the most important factor that contributed to triggering the large event in the humid and warm climate of La Pintada. The lack of high and dense vegetation on the slope potentially amplified erosion and acted as a causal factor of the landslide, i.e. making the slope more prone to mass wasting processes. It is likely that the decrease of slope stability that resulted from cutting the slope to build houses on the toe slope contributed to landsliding in this region. Seismic activity, even if did not contribute directly to the initiation of the La Pintada landslide, could promote a decrease in slope stability, and it is likely that large subduction earthquakes produced numerous landslides in the past.

Could La Pintada landslide and other landslides in the area be forecasted? At La Pintada pre-existing slope conditions (topography, soil characteristics, lack of vegetation, changes in land use, presence of ground fractures and cracks, soil creep, and the history of landsliding in this area) suggested that this area was susceptible to landslides. Landslide susceptibility mapping produced after this event confirms that the slope condition and characteristics made this area highly susceptible to landslides (Gaidzik et al., 2017). Furthermore, the amount of accumulated rainfall, 4 days of consecutive rainfall produced by Hurricane Manuel, was the ultimate triggering indicator for a large landslide to occur. If an early warning system was implemented, indeed, this event could at least be identified as a landslide hazard, with a high-level threat. Most recent studies in Central America suggest that early warning systems combining operational flash flood guidance systems with landslide susceptibility mapping can be used for real-time landslide hazard assessment (Posner & Georgakakos, 2015a, 2015b, 2016).

The study area is extremely vulnerable to landslides. The major factor triggering landslide activity in this area was the anomalously high precipitation related to extreme, short recurrence, meteorological events that might trigger landslides from small debris flows and shallow soil slides to large deep-seated landslides. Other factors contributed to mass wasting in this area: (1) absence of vegetation on slopes and increased slope erosion, i.e. a preparatory causal factor of landsliding; (2) subduction earthquakes that could produce thousands of mass movements in a large area and the seismicity of small-magnitude earthquakes could contribute to decreased slope stability over time; and (3) the increasing human population. Finally, the increased intensity of extreme storms that trigger landslides has been associated to climate change. Therefore, in tropical climate areas, where significant population lives in mostly developing countries, the combination of these phenomena makes them highly vulnerable to extreme storms and landslide hazards.
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