The May 27, 1937 catastrophic flow failure of gold tailings at Tlalpujahua, Michoacán, México

by

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Abstract

On 27 May 1937, after one week of sustained heavy rainfall, a voluminous flood caused the death of at least 300 people and the destruction of the historic El Carmen church and several neighborhoods in the mining region of Tlalpujahua, Michoacán, central Mexico. This destructive flood was triggered by the breaching of the impoundment of the Los Cedros tailings and the sudden release of circa 16 Mt of water-saturated waste materials. The muddy silty flood, moving at estimated speeds of 20–25 m/s, was channelized along the Dos Estrellas and Tlalpujahua drainages and devastated everything along its flow path. After advancing 2.5 km downstream, the flood slammed into El Carmen church and surrounding houses at estimated speeds of ~7 m/s, destroying many of construction walls and covering the church floor with ~2 m of mud and debris.

Revision of ~~E~~eyewitness accounts, and newspaper articles, together with analysis of archived photographic materials, indicated that the flood consisted of three muddy pulses. This interpretation is confirmed and extended by the results of our geological investigations during 2013 and 2014. Stratigraphic relations and granulometric data for selected proximal and distal samples show that the flood behaved as a hyperconcentrated flow along most of its trajectory. Even though premonitory signs of possible impoundment failure were reported days before the flood, and people living downstream were alerted, authorities ordered no evacuations or other mitigative actions. The catastrophic flood at Tlalpujahua provides a well-documented, though tragic, example of impoundment breaching of a tailings dam caused by the combined effects of intense rainfall, dam weakness, and inadequate emergency-management protocols—unfortunately an all too common case-scenario for most of the world's mining regions.

1 Introduction

“Tailings” is the general term for milled waste materials from processing of ore that are successively accumulated during the course of mining activities (Rico et al., 2008). Such tailings are usually accumulated upstream/downstream valleys or ring impoundments and, in all cases, these are retained by an outer dam wall or dyke generally made of wood (Klohn, 1972, Blight, 1997; Sammarco, 2004; Blight and Fourie, 2003). As summarized by Blight and Fourie (2003), if for any reason the dam wall breaks, there is the danger that the settled tailings can escape the impoundment, causing mass movements and/or a flow failure, which commonly results in serious socio-economic and environmental consequences. Several dam failures have occurred during the past century, with key examples studied in South Africa (Blight et al., 1981; Nierkirk and Vlijoen, 2005), Spain (Ayala-Carcedo, 2004; Gens and Alonso, 2006), Italy (Genevois and Tecca, 1993; Chandler and Tosatti, 1995; Berti et al., 1997), Chile (Dobry and Alvarez, 1967). Sammarco (2004) grouped dam breakouts into two categories: *i*) failures in which water flows over the tailings causing erosion and transportation of the material progressively deposited downstream (overtopping) and, *ii*) failures in which liquefaction of the tailings and/or breakout of the dam produces a highly hazardous flow that rushes downhill. Blight and Fourie (2003) documented different types of dam failures from mine tailings and municipal dumps by analyzing a database of 184 cases (US National Committee on Large Dams, 1994). These authors documented at least 22 failures over a period of 72 years (1928 to 2000) that caused 1400 casualties. Rico et al. (2008) documented 147 cases worldwide of dam tailings failures triggered by 16 different factors, including: management operations, seismic liquefaction, rise of the phreatic surface, mass movement slope instability, fluvial undermining, inadequate/insufficient beach or free board, piping/seepage, dam overtopping/overflow, foundation failure, water level rise, snowmelt, inadequate decant pipe construction, unusual rainfall event~~/period~~, insufficient perviousness of filter drain, mine subsidence, and structural failure. However, the most common incidences were caused by unusual rain/snow periods, accounting for as much as 26 % of all factors, or 39% for a combination of one or two factors (Rico et al., 2008a). As documented by these authors, breaching floods are usually composed of highly water-saturated oozy sediment, which exhibits a wide range of fluid behavior from debris flows to muddy floodwater (Rico et al., 2008a). Considering outflow volume versus runout distance, these authors ~~classify~~ grouped these floods into two categories: 1) floods with high viscosity spilled mine waste, and 2) floods with large volume of water within the tailings dam (70-85 %) related to heavy rains and dam overtopping. Despite all these data, there remains an evident gap between the diversity of the tailings dam characteristics in the world and the relative few studies documenting them, especially for cases in Latin America. Consequently, modern geotechnical, hydrological, and hydraulic studies are critically needed to improve the environmental regulations relevant to safe management of mine wastes.

In this work, we present a ~~very~~ well -documented case study of a dam failure on May 27, 1937, caused by a combination of unusual rainfall and breaching of the tailings impoundment that generated a catastrophic flood in the town of Tlalpujahua, Michoacán, central México. Based on eyewitness accounts, information in printed reports, and ~~past and present photographs~~pictures, we present ~~herein~~ new~~additional~~ results from detailed field ~~reconnaissance~~ survey and ~~selected~~ laboratory analyses, we were able to reconstruct the flow type, behavior and dynamics downstream as well as its impact to settlements.

2. Methodology

We compiled all available information of the Dos Estrellas mining activities as well as the eyewitness accounts, new papers and printed reports, including the historical and photographic archive of the historic gold tailings flood at Tlalpuhajua Michoacán, México. Mining and geological data were set into the geographic spatial database from the National Institute of Statistics, Geography and Informatics (INEGI, 2007): For digital elevation models (DEM) of 10 x 10 m resolution digital the “E14A16” topographic maps of 2007 (1:50,000) were used. DEM’s were used to arrange the thematic patterns: slope, drainage pattern and shading models. Six printed aerial photos (1:75,000) of two flight lines (L12 and L13), two orthophotos (E14A16E1 and E14A16F1) panchromatic (1: 10,000), and the SPOT5 panchromatic satellite image (2.5m / 10 m multispectral resolution) were used to build a preliminary map which includes lithological contacts, drainage patterns and characterization of the tailing dump. All geographical information was processed using the commercial software ArcGIS 9.1 and Erdas 9.3. Fieldwork lead to the final map (Fig. 8) accompanied by detailed 23 stratigraphic columns carried out along the pattern of tailing flood. From these sections 14 samples were selected for particle size analysis. Matrix samples were dry sieved 1φ ranges between -5 and 4 φ, and wet sieved fractions between 5 and 9φ (31-2 m), using the laser fence meter instrument Universidad Michoacana de San Nicolás de Hidalgo. The results were normalized to obtain a full-size spectrum (Kellerhals and Bray, 1971). Granulometric statistical parameters (Md φ and σφ) were calculated for each sample, according to Inman (1952) and Folk and Ward (1957) (Fig. 9).

3. Background geology and geography

The Mining District El Oro-Tlalpujahua (MDOT) is located within the states of Michoacán and Mexico and is part of the hydrological basin "Lerma Santiago River”, region 12 (Fig. 1). In terms of geologic setting, the MDOT is located within the Miocene-Pliocene Trans-Mexican Volcanic Belt (Gómez-Tuena et al., 2007). However, the geological unit that actually hosts the MDOT ore deposits is comprised of Jurassic-Early Cretaceous basement rocks (Silva-Ortiz and Salgado-

Soto, 1988; De La Teja Segura, 2000; Centeno-García et al., 2003). Even though MDOT is essentially known as a gold deposit, the mineralization in the district is part of an extensive silver metallogenic province (Ostroumov and Corona Chávez, 1999; Albinson et al., 2001) (Fig. 1). The mineralized structures are hosted in a NW-SE hydrothermal vein system, which has a roughly tabular form, ~3.5 km in length and with thicknesses varying from 0.5 to 33 m. Au-Ag minerals are essentially hypogenic sulphides and sulfosalts associated with a gangue of calcite and quartz (Flores, 1920; Reiniery, 1955).

Geographically, the MDOT lies within a mountainous area, with average elevations of 2600-3000 m and moderately steep slopes ranging from~~of >~~16 to 35°. The morphology of the MDOT basin ends abruptly to the north because of the active tectonics of the Morelia-Acambay Graben system. To the East, the MDOT is adjacent to El Oro region, where monogenetic cinder cones coexist with shallow lacustrine basins containing wetlands. The MDOT has humid temperate climate, with summer rainfall averaging 900 mm per year (CNA, 2013; http://www.conagua.gob.mx/; Fig. 2). The driest months are from January to May and November to December with precipitations under 40 mm (see Figure 2). The region's annual average temperature varies between 12 and 18°C, with the lowest in January (~3-18°C) and higher temperatures during April and May (>22°C).

4~~3~~. Summary of the MDOT development

Industrial mining in Mexico began during the Colonial era, during which the MDOT was known as the "Real de Minas of Tlalpujahua". During this time, a series of exposed veins were exploited within areas of the present-day cities of El Oro and Tlalpujahua (Fig. 1). During the following centuries (XVI-XX), the mining works were continuous and large, medium, and small mining companies succeeded to create a culture linked to the work of mineral extraction and processing of silver and gold. The largest production period began in the early XIX ; since then, the mining activity can be summarized in three periods (Fig. 3~~2~~): I) during the first one (1820-1870), the British El Oro Company committed capital and technology towards the rehabilitation of mines that were destroyed or abandoned during the Mexican Independence War; ii) in the second one (1898-1938) (Fig. 1B and Table 1), the richest gold veins were discovered under the Cerro Somera and were exploited intensively; and iii) the third one (1939-1959), when the Mining Cooperative "Las Dos Estrellas" in El Oro and Tlalpujahua and the Commission of Mining Development started operations (Uribe Salas, 2008; 2009). The towns of Tlalpujahua (XVI century) and El Oro (XVIII century) became increasingly developed with the construction of the mineral separation and metal-casting plants, roads, shafts or pits to access mineral deposits, and accumulation of dumps and mine tailings (Uribe Salas, 2008) (Fig. 1). Many investigations of mining exploration in the DMOT have been carried out, but there are no published records of industrial mining production since the 1960s. Nonetheless, despite the demise of active mining, the villages of El Oro and Tlalpujahua have survived during recent decades, coexisting with the piles of tailings and archaeological industrial remains. At Tlalpujahua, there is a museum that focuses on the history and the remains of the region's mining past, including a very informative and pleasant tour inside a mine.

5.4 The Los Cedros Tailings dam

On December 14, 1907, the mining company received the authorization to construct a tailings dam by a Federal Agency (Secretaría de Fomento). On January 25, 1908, the company submitted a project plan (involving 33 acres) to the Federal agency and constructed within its property the base of the dam at the Sangria stream at an approximated elevation of 2850 m above sea level, besides the Los Cedros metallurgical plant and ~500 m near the village of Tlalpujahua.

The impoundment began with the construction of a wood retaining wall and during more than three decades, these tailings dam, well-known as “Lamas Los Cedros” considering their proximity with Los Cedros metallurgical plant were associated with the exploitation and generation of mine wastes from the “Las Dos Estrellas” mine (Fig. 3). These tailings filled areas upstream of the gullies of Sangría and Dos Estrellas and drastically modified the morphology of the terrain around the village of Tlalpujahua. Consisting of soft unconsolidated material associated with cyanidation processes, the mass of accumulated tailings was prone to remobilization.

The dam was built with wood to form a rectangular base where mine wastes were deposited after crushing, milling, cyanidation and concentration processes were performed. The thickness of the tailings increased rapidly (ca. 35 m thick) to an approximated elevation up to 2875 m and acquired a platform-like form (Fig. 4). From 1908 to 1936, the dam had an approximated volume of 14.7 Million tons of mine waste (Uribe Salas, 2009; Corona Chávez et al., 2010; Table 1). In 1934, the mine had its largest production (820,603 tons, ~2 thousand tons/day). By 1935, the mining company was projecting the construction of a new dam, suggesting that Los Cedros dam was already at or near its capacity. However, this new project of the company never materialized.

~~4~~5.1 Premonitory signs of a catastrophe

Prior to the 27 May catastrophe, dam caretakers had reported cracks and softening of the impoundment surface, but apparently, these reports were considered of no immediate danger (Bernal-Navarro, 2012). However, this author concluded that the base of the impoundment had softened due to the persistent rains and a permanent stream that existed at the base of the gully. In fact, on May 26, at 5:30 pm a ~4 tons block detached from the lower part of the impoundment leaving a 30 m-wide hole. After this small landslide, mine dam caretakers warned villagers downstream to leave their homes because a large landslide may occur. Unfortunately, only a few paid any attention and this warning went unheeded. That same day, at around 11:20 pm, another block detached from the impoundment, flooding the road to the Los Cedros metallurgical plant and the Juarez bridge. Intense rain accompanied by lightning persisted throughout the night.

~~4~~5.2 The May 27 1937 flood known as “Las Lamas”

At around 5:20 am of May 27th, a large block (6-8 tons) of tailings collapsed (Bernal-Navarro, 2012), producing a din followed after a few seconds by a powerful air blast “that we interpreted as an air pressure wave” that flattened trees, fences, and houses. Eyewitnesses described the flood as a muddy to sandy fetid mass that rapidly channeled into, and filled, the stream. The ensuing flood rushed downstream, first hitting the Los Cedros metallurgical plant (Figure 5A-B) and then the Trigueros hill. Inhabitants felt the ground shaking caused by the flood impact.

As the flood crashed against Trigueros hill, it diverted into an eastern upstream flood and a western downstream flood. The upstream flood flowed moved eastward to the Los Cedros metallurgical plant a few hundred meters and then it waned and stopped. Instead the downstream flood rapidly transformed into a huge catastrophic wave at least 30 m in depth that swept towards the village of Tlalpujahua and San Jesus del Monte hill that was crowned by a church. Between, Los Cedros Metallurgical plant and San Jesus del Monte hill at least eight neighborhoods were completely destroyed (among which La Cuadrilla, Chinches Bravas, El Dos, and Las Cabecillas). Unfortunately, no detailed census of these neighborhoods existed; in fact, many people who were oblivious of the happenings at Tlalpujahua were working at the Dos Estrellas mine at the time.

Eyewitness accounts gathered by Bernal-Navarro (2012) described the flood phenomena observed by inhabitants of Tlalpujahua that are next summarized to better understand the nature of the flood. The huge rushing flood uprooted everything along its path as houses, trees, electrical poles, people, and animals were swept away. The electrical poles and wires downed by the flood generated short circuits, producing explosions, lightning, and gases. The explosions burned trees everywhere, initiating short-lived fires. During all this chaos, the windy storm persisted. Some people climbed the hills of Trigueros and San Jesus del Monte to save themselves (Fig. 6). Survivors who that reached these, or lived at higher elevations, described that the flood had the appearance of a fetid lake moving downstream. The muddy flood scoured the outskirts of Tlalpujahua and move around Jesus del Monte hill downstream along the Tlalpujahua River. Eyewitnesses observed roofs, logs, furniture, and plants floating on the flood.

After advancing one kilometer, the flood encountered El Carmen village, including the church, cemetery, and hamlets located along the eastern bank of the river. The flood partly destroyed the structures, buried the church with at least 2 m of mud. Some walls of the El Carmen church were destroyed while others withstood the impact of the flood including the painting of the “Madonna El Carmen” (Fig. 6).~~ One of these intact walls protected the painting of the “Madonna El Carmen” this was considered as a miracle by the surviving inhabitants~~. Days after the catastrophic flood, inhabitants dug out the undamaged painting and paraded in a religious precession to transport it to the Tlalpujahua Cathedral. Beyond El Carmen Village, the muddy flood did not weakened but continued downstream for several more kilometers, but without encountering any other churches or hamlets. Because the muddy deposits had a whitish to light-gray color, the inhabitants nowadays know it as the “Las Lamas” flood deposit. The flood catastrophe produced a casualty toll of circa 300 people.

6~~5~~ Mineralogy and chemistry of the tailings

The physical and chemical characteristics of the MDOT tailings ~~were previously~~are studied in ~~(~~Corona Chávez et al.~~,~~ (2010). Most of the tailings have silt to clay textures (Siebe et al., 1996) with a grain- size distribution of silt (<80%) and significant variations of clay (7-10%) and fine sand (7-38%). pH varies from neutral to slightly alkaline (7.8-8.46) with variable conductivity (predominantly> 800 moh/cm) which indicates a minor and variable concentration of metals. Mineralogically, the tailings consist of quartz (> 42%), clay (9-19%), and calcite (11-12%). The amounts of opaque minerals vary little (> 2-3%) and consist of pyrite, argentite, galena, goethite, ilmenite, magnetite, hematite, arsenopyrite, chalcopyrite, and pyrrhotite (Maldonado Villanueva, 2008). The analyzed samples contained abundant silica (56-92 wt. %), aluminum (5-13 wt. %), iron (3-5 wt. %), calcium (2.5-5 wt. %) and potassium (1-2 wt. %) (Corona Chávez et al., 2010). The samples have values that are potentially profitable, with Au 0.6 to 4.4 g/ton and Ag 1.8-178.3 g/ton. The potentially toxic elements (PTE) show values ranging from: 3.0 to 83.9 ppm for As, 7.4 to 808.6 ppm for Cu, 16.5 to 317.5 ppm for Pb, and 63.8 to 548.2 ppm for Zn. Some of these concentrations exceed the official safe levels established by the Mexican government. Finally, the nature of the tailings with respect to water chemistry anomalies (Nieto Monroy, 2007) is dominated by relatively neutral water and, therefore, the PTE values of the tailings did not seem to generate acid drainage.

7~~6~~ Tailings Flood Deposit (TFD)

The tailings flood deposit (TFD) is easily recognized along its extent because it is a light-gray to white color that contrasts with the local basement rocks, such as red, yellow and brown alluvial deposits, brown paleosols, and modern soil. The TFD appears as scattered outcrops along the Dos Estrellas and El Carmen (Tlalpujahua) streams.

7~~6~~.1 Distribution and volume.

Proximal exposures of the TFD (or Las Lamas) deposit occur around the San Jesus del Monte hill. At the top of this hill stands the San Jesus del Monte church (Fig. 6), which withstood the worst part of the 1937 flood. Today, this hill and church lie within the Tlalpujahua village limits. Proximal outcrops of Las Lamas flood are found on the San Jesus del Monte hill at minimum and maximum elevations of 2,500 m and 2,540 m, respectively. From this site on, the deposit can be traced downstream along the Tlalpujahua River (Fig. 7A). The deposit appears either as flat terraces (1-2 m thick) or as an overbank layer (20-40 cm thick) resting on top of older alluvial deposits and local basement rocks (andesites, schists, and paleosols). On the other hand, distal deposits occur as far as 9 km from San Jesus del Monte hill, at site 23 and at an elevation of 2350 m (Fig. 8), where it is 45 cm thick. Here, an eyewitness described that the flood travelled more than 1 km from this location where it was still able to carry meter-size boulders. The most distal locations are further north at elevations of 2270 m along the Venta de Bravo Valley and close to the Federal Highway 15 where it connects to the cities of Maravatio and Atlacomulco. By considering a minimum extent of 11 km for the deposit and the present exposures, we estimate the deposit to cover a minimum area of about 982,000 m^2. If we assume an average thickness of 1 m for the deposit, we would obtain a minimum volume of 982,000 m^3 of material (0.00098 km^3). ~~By using~~ We used a digital elevation model for estimating the volume by using a common cut and fill command ~~the contour lines and thicknesses and the Spatial Analyst software of ArcGIS we~~ obtaining~~ed~~ a volume of 1,492,000 m^3 (0.00149 km^3). As described below, the flood moved with sediment-water concentrations of ~50%, therefore, if we assume such concentrations existed at the time of the flooding, it might have had a minimum volume between 0.0019 and 0.0029 km^3.

7~~6~~.2 Description and granulometry

Twenty-two stratigraphic sections were measured of the remnants along the path of the Tailings Flood Deposit (TFD) (Fig. 8). From ten of these sections, we sampled 14 specimens to perform granulometric analyses from -8 to +12 ϕ grain-sizes (Fig. 9). The correlation of these sections suggested that the deposit mainly consists of one massive layer. However, at two locations (El Carmen Church TL08 and TL14) three and two beds were described, respectively. At locations between San Jesus del Monte and El Carmen the deposit is soft and loose, but beyond El Carmen church it is partly indurated and contains void spaces in all sections..

The TFD shows a light-gray to whitish color and has a flat planar lower contact and an upper contact grading into the modern soil. It usually overlies a brown to orange paleosol that may contain pottery or other artifacts (site TL13) or over the local green-schist basement (site TL-18) (Fig. 10C). At section TL14, the TFD deposit overlies the 1937 soil, a brown hyperconcentrated flow, a brown paleosol, a debris flow deposit with rounded to angular blocks pieces of broken glass in a coarse sand-matrix, and the underlying schists (Fig. 10A). All this sequence stands beside or atop the remains of an old bridge wall. This stratigraphic column suggests that other historical fluvial debris flows have occurred at Tlalpujahua.

Along its extent, the TFD has variable thicknesses, for instance around 40 cm at section TL-13 (San Jesus del Monte Church), 2.8 m at site TL16 (0.8 km downstream), and 40 cm at the farthest location (TL-23) (Fig. 8). As a whole, the deposit is massive, matrix-supported (>56 %), and composed of sandy to clayey particles (Fig. 9, Table ~~2~~3). These characteristics indicate that the deposit had an unimodal granulometric distribution with the main mode shifting from 1 to 4 ϕ (Table ~~2~~3) and good sorting (0.55-1.35 σϕ). The structure, texture, and grain-size characteristics of TFD suggest it corresponds to a hyperconcentrated flow deposit (Fig. 9). In some sections, however, the deposit may contain scattered gravel to boulder -size fragments, as in section TL-01B (up to 40 %) or at section TL-21 (43 %) (Table ~~2~~3). In these sections, the granulometric distribution of TFD is bimodal, with a coarse mode (-5 to -3 ϕ) not shown at other locations, a fine mode (1.8-4 ϕ) and medium sorting (5.2 to 1.1 σϕ). The structure, texture, and grain-size characteristics of the deposit at these specific locations allow us to classify them as debris- flow deposits.

At site TL13, along the steps of the San Jesus del Monte church, the TFD varies in thickness from 80 cm to 40 cm. It overlies an anthropogenic layer rich in pottery shards, charcoal and other remains, and older debris flow and the basement green schists (Fig. 11).

Site TL01 (remains of the El Carmen Church) exhibits an extraordinary sequence of the TFD made of three different layers (A-C) separated by erosive contacts. The intermediate unit, which is rich in boulder size fragments and church blocks, seems to correlate with the deposit at all other locations (Fig. 12A-B). These layers are light-tan in color, massive, and partly indurated with voids. The lowermost layer A rests on the 1937 El Carmen church floor (Fig. 12B). It is a 40 cm thick and contains sporadic subangular clasts usually smaller than 3 cm set in silty to clayey matrix (~95 %).

Layer B (≤0.85 cm thick) consists of angular to subangular clasts (30-84 cm in diameter) set in a clayey-silty matrix (80 %). This layer contains stone church blocks, glassware, pottery, bricks, wood chips, and charcoal. Layer C (≤60 cm thick) is heterolithologic with ignimbrite and metamorphic subangular fragments ranging in size from 1.5 to 6 cm in diameter. The clasts are dispersed in the middle part of the bed within a sandy to silty matrix (70-75 % wt.). The upper portion of layer C grades into the modern soil.

8~~7~~ Discussion

Mining activity in the MDOT reached its ~~climax~~ apex during the first half of the XX century, when the “Las Dos Estrellas Company” was established. At that time, ≥ 2 mil tons of rock were extracted daily producing alike amounts of waste materials disposed into the tailings. As mentioned previously, the construction of the Los Cedros tailings dam in 1908, and accumulation of waste materials within it, drastically modified the geomorphology and the drainage system around the village of Tlalpujahua. The mass of >2 million tons of soft unconsolidated material associated with cyanidation processes was prone to remobilization. Such morphological and hydrological modifications of the landforms were primed for some triggering phenomenon to release a large amount of material in a catastrophic way.

Taking into account all the previous information of the event, the worldwide literature of similar events, ~~and our own research,~~ we conclude that several factors combined to produce the terrible flood catastrophe as summarized by Rico et al. (2008, 2008a). First at all, the impoundment was built upstream, infilling the Dos Estrellas valley and changing the morphology and drainage pattern of the perennial and seasonal streams. Secondly, prior to the breaching of the dam, some people witnessed diverse small landslides caused by softening of the impoundment. This was likely facilitated by seepage of a small stream that flowed at the bottom of the tailings dam (Bernal Navarro 2012). At that time, the people living downstream were alerted, but the authorities did not evacuate them or took any additional preventive measures. Therefore, a combination of bad management operations and the lack of preventive measures to evacuate people at risk played an important role in the catastrophe, as it has been emphasized by Gipson (2003). These anthropogenic factors compounded the effect of sustained torrential rainfall in the region that saturated and softened the tailings dam material, culminating in the breaching of the impoundment that suddenly released a silty, fetid mass that rapidly transformed into a catastrophic flood. To date, no Mexican regulations exist to prevent the environmental impact of tailings ponds as it has been proposed in other countries several decades ago (e.g., Yet, despite recent advances, environmental problems and dam failures continued to occur (East, 2000), even during the past decade (Azam and Li, 2010). For example, the October 4, 2010 dam failure in Hungary released 700,000 m^3 of tailings with fatal consequences, underscoring the critical importance to understand, and possibly to mitigate, these failures. A step forward regarding the study and analyses of dam failures was proposed by Neves Correia et al., (2011) who applied a Failure M~~m~~odes and E~~e~~ffects A~~a~~nalysis (FMEA) at Cerro do Lobo tailings, Portugal.

~~7~~8.1 Failure of the Tlalpujahua tailings dam

Unfortunately, no local weather stations existed around the MDOT before the failure. The first station (15183-Oro), which became operational in 1972, is relatively close to the Los Cedros metallurgical plant (Fig. 15). This station has a continuous rainfall record from 1972 to 2002, with some small gaps in 1988, 1993, and 1994. By using descriptive statistical methods. Martínez-Medina et al. (2012) concluded that the MDOT showed an average precipitation of 900 mm per year ~~(904 mm mode and a median of 34 mm)~~. These results resemble the regional rainfall weather (see Figure 2). However, it is worth noting that, during this period, at least two years had atypical rainfall (exceeding >1200 mm) one of them ~~. The first is evidently related to the May 27, 1937 catastrophic flow failure and, the second~~ occurred ~~during~~ in ~~the~~ 1986~~ year~~, when the rainfall exceeded 2000 mm (Fig. 13). With this study, Martínez-Medina et al. (2012) ~~argued~~ concluded that return periods for 1800-2100 mm rainfalls occurred every 29 years. On the other hand, there is evidence that atypical rainfall periods have caused other catastrophic debris flows along the Tlalpujahua-Americas stream as it has been attested by at least two historical floods (older than 1937) observed in the stratigraphic record (site TL-14). One of them, had a coarser granulometry than the 1937 flood, and contained broken glass and blocks from an old bridge destroyed by this debris flow suggesting that previous events along the Tlalpujahua-Americas stream have had larger magnitudes. By considering the time recurrence of the most recent extreme rainfall event (in 1986) and the sedimentological record, we may expect that an atypical event may occur in the near future in Tlalpujahua and consequently the risk is still present.

~~7~~8.2~~3~~ Reconstruction of events

Eyewitness accounts clearly described the passage of at least two floods on the morning of May 27, 1937. At 5:40 am (Bernal Navarro, 2012). The first landslide from tailings dam caused a huge roar that was suddenly accompanied by an air pressure wave. The roaring noise likely alerted people in Tlalpujahua and spurred them to try to escape. By natural instinct, people in their pajamas or partly nude were seen walking, crawling, and running uphill to Trigueros, Tlalpujahua and to Jesus del Monte Church. It is not clear how many people were able to flee this first flood wave, which was as deep as 20 m around Tlalpujahua. People who managed to save themselves observed the horror of terrified, screaming people being engulfed by the flood and disappearing downstream. Some survivors were able to rescue other people, although they failed in their attempts to either save lives or rescue their belongings, when they were cut off by the flood. ~~Eyewitnesses mentioned that a woman with her head poking out of the flood was asking for help when another wave of mud dragged her to death.~~ From such accounts, it is clear that the main devastating flood was followed by several smaller waves and surges.

~~Based on our reconnaissance fieldwork and the sedimentological analyses of samples collected of the TFD along the Sangria and Dos Estrellas streams and the Tlalpujhaua river, we conclude that the~~The stratigraphic reconstruction of the deposit ~~record~~ shows at least three hyperconcentrated/debris flow deposits associated with the same number of floods. The best exposure of this interpretation is seen at El Carmen church (TL-01). This conclusion was confirmed by the detailed governmental report carried out by an expert who described three flow surges and several other details and facts of the tragedy (Antonio López Portillo, 1937 in Juárez Bobadilla, 2007).

~~7~~8.3~~2~~ Flood behavior

As previously discussed, there were at least three flow surges. The first and largest flow originated in the Sangria gully, and the later smaller flows involved sources at the Dos Estrellas stream. Eyewitness accounts, historical photographs, and recent fieldwork helped us to understand the dynamic behavior of the largest flow. The flow was sourced from someplace along the Sangria gully, the initial mass fed by the fine-grained tailings (silt and sand material) and cyanide mixed with water that rapidly rushed down the gully. At ca. 0.7 km from the probable source, the flow initially struck the Los Cedros metallurgical plant and impacted against Trigueros northern side hill scraping ca. 30 m of forest (Fig. 14A).

~~$\int_a^b y\,dx = Q/v \int_a^b y\,dx v Q = \int_a^b y\,dx\,(\sqrt[2]{2g\,h})$~~

Velocities of the flow were estimated from runup obstacles aligned perpendicular to the flow b~~n~~y using the simple relationship v = √2gh in which is the runup height g is the acceleration due to gravity (Sheridan et al., 2005). High mud marks observed in photographs were about 30-m high, suggesting flow speeds of 25 m/s. As emphasized by Sheridan et al. (2005) these estimates are considered minimum velocities because this equation does not account for friction.

To determine the discharge of the flood along its path we used the OriginLab program to create cross sections of the channel and we defined the polynomial best matched topographic profile of the channel (0.97 ratio) with order three to nine polynomials. Once the area of the section was obtained then equation (1) was used to determine the discharge.

$$\int_a^b y\,dx = Q/v \quad ....1$$

Where:

$\int_a^b y\,dx$ = function that satisfied the shape of the channel bottom (polynomial)

Q = Discharge

v = Velocity obtained from equation (2).

$Q = \int_a^b y\,dx\,(\sqrt[2]{2g\,h})$ ......2 without considering basal friction (Sheridan et al., 2005).

At the breached dam we considered a thickness of 40 m and a width of 200. The calculated area with the OriginLab program was 3,870 m2 for which we obtained a flow discharge of Q = 108,360 m3/s with flow velocities of 24 m/s.

The impact of the flood against Trigueros hill split caused its split into a short-lived, less powerful upstream surge that only advanced a few hundred meters and the huge sustained flow wave that rushed downstream towards the village of Tlalpujahua, scouring the old road, trees and tailings from the retaining wall of the dam (Fig. 14B). Unfortunately, several neighborhoods stood downstream and were completely devastated by the flood (Fig. 14C). Pictures of the places and remains of these neighborhoods show the maximum thickness of deposits and the high-water marks suggesting that the wave was moving as an hyperconcentrated flow (ca. 50 % sediment concentration). Downstream, the Tlalpujahua river carved a gully between the outskirts of the Tlalpujahua village and the Jesus del Monte hill that was surrounded by several neighborhoods, including La Cuadrilla, at its base.

The catastrophic flood reached depths of approximately~~ca.~~ 20 m in this area destroying everything in its path, knocking down all standing things, and scouring the ground to the base of the Jesus del Monte church located at ca. 1.4 km from the flood source (Fig. 14D-E). Eyewitnesses reported that the moving flood was striking the frontal walls of the church to the point of tilting them. The flood reached a maximum elevation of 20-m at the church for estimated speeds of 20 m/s (60 km/hr). Here, the flow discharge was calculated at Q = 20,643 m3/s (for a section of 10 high and 235 m wide section and flow velocities of 14 m/s). After the Jesus del Monte hill the flood was confined within the gully, along which several neighborhoods were located, including El Carmen village that was ~~After the Jesus del Monte hill the flood was confined within the gully, along which several neighborhoods were located, including El Carmen village.~~

~~El Carmen village was very typical of the region because it was perhaps one of the oldest settlements of Tlalpujahua, and it was~~ dedicated to the “Maddona El Carmen” with an historical cemetery behind the church. The flood hit El Carmen village, which is located at 2.4 km from the flood source, at speeds of 7 m/s (25 km/hr) knocking down the western walls of the church, while the entrance and altar were able to resist the impacts. The flow discharged calculated here was Q = 8,722 m3/s (for an area of 10 high by 235 m wide, and velocities of 10 m/s).

The flood buried the church with 2.5 m of debris and mud. Behind the church, the flood was able to move and tilt grave markers as they are exposed nowadays. High-mud marks 5 m above the deposit that partially buried the church corroborated that the flood was moving as a hyperconcentrated flow. The flood was able to incorporated chunks of church walls as large as 30 cm. ~~Kinematical structures of the flow~~Flow dynamics suggest that these blocks were suspended and rolled downstream.

Downstream and beyond this area, there are a lot of scattered remnants of the TFD deposit at several locations as far as 8 km downstream. In all these sections, the tailings deposit appears as a massive hyperconcentrated flow deposit without any signs of dilution into a sediment-laden flow. At section TL19 (one of the furthest sections from dam breakout) the flow had a discharge of Q = 2,297 m3/s (4 high by 97 m width) with flow velocities of 8.8 m/s.

~~8~~9. Conclusions

An extreme rainfall event, which lasted at least five days, triggered the softening, and ultimately, the breaching of the Los Cedros tailings dam at Tlalpujahua, Central Mexico. The tailings dam during 30 years accumulated >2 MT of rock waste milled by cyanidation at Las Dos Estrellas mine. The sudden breaching of the dam generated a muddy flood that moved with hyperconcentrated amount of sediments, destroying several settlements, a church, and killed circa 300 people. This study used historical photographic materials, eyewitness accounts, and data from recent field and laboratory studies to reconstruct the flood behavior with increasing distance from the source. We believe that our results provide a useful insight on such collapses. Worldwide databases of dam failures suggest that a combined effect of rainfall and dam rupture of the dam is the dominant case for nearly 40% of all cases (Rico et al., 2008). Thus, careful analyses of past catastrophic floods of tailings in inactive and active mining districts must be conducted to collect the knowledge analyzed and considered as a basic knowledge to improve governmental regulations and oversight related to minimize the risks of future hazardous events that may threaten human lives and property.

Author contribution: All authors, carried fieldwork at Tlalpujahua and participate during manuscript writing. P. Corona, M. Martínez and V.H. Garduño revised the archive data of the mine and resumed local geology and mining activities. J.M. Sánchez analyzed grain size data, F. García performed granulometric analysis, and G. Cisneros managed the GIS database. J.L. Macías prepared the manuscript with contributions from all co-authors.

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Figure Captions

Figure 1. Location of the Mining District of El Oro-Tlalpujahua (MDOT) in Central Mexico (inset), showing the principal rock types, ore veins, and tailings dams. Geological map of the MDOT from Corona-Chavez et al. (2010).

Figure 2. Annual precipitation and temperature data recorded at the meteorological stations at from El Oro (15183) and Presa Brockman (15070) of the Comisión Nacional del Agua (CNA).

Figure 3. Historical record of the amounts of material extracted by the Mining Company (1898-1938) and Cooperativa Minera "Dos Estrellas" (1939-1959) and the relationships with the metallurgical processes used (after Uribe Salas, 2008).

Figure 4. Panoramic views in 1937 from the southeast that show A) Los Cedros tailings dam with a platform-like form prior to the collapse; and B) The tailings and the Dos Estrellas Stream scoured by the flood after the collapse. See people standing on the hill in the foreground.

Figure 5. Panoramic view of Los Cedros Metallurgical plant of "Las Dos Estrellas" Mining Company at the Sangria stream, A) before and B) after the collapse. The white squares show the same location in both images, and an undisturbed roof of the Metallurgical plant (white arrows).

Figure 6. A) Panoramic and B) close-up view from the southwest of San Jesus del Monte hill and Church after the May 27, 1937 flood with rubble, and wood planks dispersed on the surface and the striped slopes of the hill. C) View of the same hill prior to the flood that shows houses on its southern slope.

Figure 7. Different views of El Carmen Church after the 1937 flood and extent of the deposit along the Tlalpujahua river (A), and rubble and high-mud marks (yellow arrows).

Figure 8. Shaded relief map of the MDOT displaying the location of Tlalpujahua and Venta de Bravo villages, the extension of Los Cedros tailings in 1937 as well as the present extension of the 1937 flood deposit. Red circles are stratigraphic sections measured during this study. Insets are cross profiles indicating the shape of the flow channel and some flow indicators as High Mud Marks.

Figure 9. Cumulative curves of the TFD deposit at different distances from the source. Most of the deposits are fine-grained (hyperconcentrated flow deposits) while a few exposures contained boulder and gravel-sized particles set a silty matrix (debris flow deposits). See Figure 8 for locations of the samples.

Figure 10. Aspects of the Tailings Flood Deposit (TFD) at three sections along its path. A) At section TL-14, the TDF rests over a paleosol, a thin hyperconcentrated flood deposit (HFD), another paleosol, and a basal debris flood deposit (DFD) that contains pieces of bottle glass. The

DFD forms a paleo-channel that stands against the remains of an old stone bridge. B) View of the TFD at section 17 overlying a paleosol and the lower brown hyperconcentrated flood deposit (HFD) rich in sand-size particles. C) At section TL-18 the TFD overlies a poorly developed paleosol, a reworked bed with gravel-sized fragments and schists from the local basement. D) At section TL-19 the deposits rests directly on top of a thicker paleosol.

Figure 11. View of section TL13 looking to the west at the steps of San Jesus del Monte Hill. The section shows from the base schists, a debris flow deposit that turns into pottery rich soil, and the whitish TFD atop grading into the modern soil cover with trees.

Figure 12. A) Panoramic view from the east of the remains of El Carmen church buried by the Tailings Flood Deposit (section TL-01). The excavation of the church remains exposed the ancient floor of the sanctuary also observed in insets. B) Stratigraphic column showing three beds separated by dashed yellow lines and their granulometric bimodal distributions.

Figure 13. Timeline showing the 1986 year with exceptionally high precipitation recorded in the region of MDOT. Data from the 15183-El Oro meteorological station from ~~. The Las Llamas flood occurred during sustained intense rainfall in May 1937 when no weather station existed. It is interesting to note two atypical precipitation events have return periods of 49 years (~~Corona Chavez et al.~~,~~ (2010).

Figure 14. Views of damage caused by the Tailings flood in 1937 at different locations of this study: Los Cedros metallurgical plant (A), Trigueros Hill (B), the Dos Estrellas stream between Trigueros and Jesus del Monte (C), and Jesus del Monte (D-F). HMM = High Mud Marks.

Table 1. Summary of extracted metals and amount of waste produced at Tlalpujahua

Year	**Extracted** (tons)	**Silver** (Kg)	**Gold** (Kg)	**Waste** (tons)
1900				
1901	22435	2000	0	20435
1902	52722	4700	1000	47022
1903	67305	6000	1500	59805
1904	75157	6700	2000	66457
1905	89740	8000	2000	79740
1906	131133	11690	2321	117122
1907	325309	29000	3227	293082
1908	432000	28127	3075	400798
1909	341111	35000	5000	301111
1910	424198	47685	6530	369983

1911	479723	62627	6775	410321
1912	505000	63000	6000	436000
1913	673053	60000	4000	609053
1914	245664	21900	1000	222764
1915	191820	17100	4000	170720
1916	229959	20500	4300	205159
1917	463655	41333	5200	417122
1918	482354	43000	5000	434354
1919	509770	45444	4000	460326
1920	504789	45000	3300	456489
1921	503533	44888	3000	455645
1922	473313	46675	2750	423888
1923	493857	41966	2699	449192
1924	533772	35428	2548	495796
1925	665316	37024	2805	625487
1926	632056	45627	2096	584333
1927	752198	51132	2351	698715
1928	693460	55850	2328	635282
1929	693257	64461	1914	626882
1930	676962	76425	2034	598503
1931	593835	46447	1856	545532
1932	786936	38385	1812	746739
1933	821645	31702	1585	788358
1934	829663	40111	2416	787136
1935	777759	46339	2138	729282
1936	717755	40000	2000	675755
1937	628129	28452	1258	598419
1938	589275	--	--	589275
1939	761431	--	--	761431
1940	772083	--	--	772083
1941	758148	--	--	758148
1942	759625	--	1500	758125
1943	744709	--	--	744709
1944	614713	--	--	614713
1945	379183	--	--	379183
1946	266073	2676	228	263169
1947	178750	--	--	178750
Total	**23344333**	**1372394**	**109546**	**21862393**

Table 3~~2~~. Granulometric analyses and statistical parameters of samples collected along the Tailings Flood

Deposit.

Sample	Gravel	Sand	Silt	Clay	Fines	Matrix	Mdϕ	σϕ	Skewness	Curtosis
	(-8ϕ a -2ϕ)	(-1ϕ a 4ϕ)	(5ϕ a 8ϕ)	(≥ 4ϕ)	(Silt + Clay)	(-1ϕ a 9ϕ)				
TL-01A	4.2	64.41	27.93	168.98	196.91	95.23	6.2	2.73	-0.21	0.97
TLA-01B	39.67	56.54	2.26	105.59	107.85	59.05	-1.1	2.8	-0.32	0.83
TL-01C	7.06	66.14	23.71	57.11	80.82	91.97	2.12	4.15	-0.38	1.53
TL-13D1	3.39	94.22	2	18.44	20.44	96.39	2.3	0.93	-0.19	1.34
TL-13D2	0	98.96	0.84	19.78	20.62	99.9	2.6	0.55	0.09	1.01
TL-14D	0	96.35	2.98	29.82	32.8	99.65	4.3	0.57	-0.04	0.95
TL-14C	0	97.41	2.08	32.69	34.77	99.73	2.55	0.7	0.07	0.99
TL-15B	0	97.7	2.01	19.3	21.31	99.85	1.75	1.35	0.26	0.8
TL-18	0	89.04	9.26	51.11	60.37	99.11	1.8	0.98	0.38	0.9
TL-19	0	89.3	8.98	36.71	45.69	99.09	2.6	0.75	0.11	1.67
TL-20	0	93.3	5.87	42.42	48.29	99.56	3.15	1.15	-0.48	0.71
TL-21	43.04	50.04	5.9	29.01	34.91	56.38	-6.25	5.23	0.73	0.51
TL-22	7.05	88.9	6.67	39.92	46.59	95.94	2.6	1.05	-0.19	2.41
TL-23	11.16	88.74	0.05	4.81	4.86	88.8	0.95	1.73	-0.3	1.24