Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Hydrothermal Eruption during the 2017 M6.5 Leyte Earthquake: The How's, Why's, and Lessons Learned

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Keywords: hydrothermal eruption, earthquake, Philippines, Leyte, rupture

ABSTRACT

Common earthquake hazards include ground rupture, landslides, liquefaction, and tsunamis. However, the M6.5 earthquake that hit the Leyte Geothermal Field in Eastern Philippines last July 6, 2017 triggered the formation of a basin-like feature that extends 235 m in diameter and 19 m deep, removing an estimated 215,000 cu.m. of ground material. This breached part of the access road towards some critical facilities including the wellhead of one of the producers that is just 28 m away from the edge of the basin rim. Field investigation shows the presence of biased burning and oriented deformation of surrounding vegetation whilst there is an apparent grading of sediments that have formed around the rim. Locals also report the formation of a dark plume immediately above the area which happened just shortly after the first ground shaking due to the earthquake. These observations are consistent with the occurrence of a hydrothermal eruption, and combined with a landslide and a debris avalanche, the eruption crater was enhanced then breached, resulting to its present-day morphology. The sequence of events suggests that the frictional heating from the slipping fault during the earthquake may have triggered an increase in the subsurface pressure underneath existing hydrothermal manifestation that eventually resulted to the eruption. This illustrates a complex effect from large earthquakes occurring within geothermal fields, and thus should be considered in the geological hazard assessment and mitigation planning.

1. INTRODUCTION

On July 12, 2017, a M6.5 earthquake occurred in Leyte Island as a result of the movement of the sinistral Philippine Fault. The epicenter was located two kilometers east of the Mahanagdong-A Power Plant, which is part of the Leyte Geothermal Field (LGF). The earthquake triggered shallow and deep-seated landslides, ground ruptures, lateral spreading amongst others, damaging the facilities of the geothermal field, which resulted to at least a five-day electricity black out in Leyte and its neighboring islands. These hazards are somewhat expected from a large and shallow earthquake, what is otherwise is the formation of a 235 m diameter *crater* around what was originally a quiet Upper Mahiao Thermal Area that breached part of an access road in the northwestern area of the LGF. This paper explores the possible mechanism behind the damaging reactivation of the thermal area as a seismic effect of the July 2017 Leyte earthquake.

2. THE UPPER MAHIAO THERMAL AREA

The Upper Mahiao Thermal Area (UMTA) is a poorly studied and less documented thermal manifestation within LGF. Based on old photographs and local accounts, it existed as a very weak steaming ground, barely noticeable being situated 500 m east of the much impressive Kapakuhan Thermal Field. In 1995, the area of the UMTA served for soil disposal during the construction of the adjacent Upper Mahiao Power Plant, where it eventually got covered by backfill materials, and got lost in the maps. Historical accounts suggest a small eruption occurred, that formed a three meter diameter eruption center, although no clear geological assessment was made. Based on the digital elevation maps that were collected since 1995 to 2017, the once location of UMTA became generally flat and at similar levels to an access road to nearby geothermal well pads. There are, however, inconsistent reports on the observation of a very weak steaming ground that existed thereafter.

On July 12, 2017, UMTA was re-exposed by a breached basin-like feature concaving to the west-WSW. It has a total arcuate length of 340 m (diameter of 235 m), and a meandering toe that extends to at least 800 m generally to the west, formed from a massive debris flow post-earthquake. The slope is characteristically high within the first 40 to 50 m of the northern (as much as 86°) and eastern (30 to 51°) rims, then decreases gently towards the toe. The rim typifies a landslide crown and is dissected by a series of arcuate tension cracks. The rims have breached the north-south-oriented access road exposing a maximum of 19 m depth of what is originally covered material – from the top: (1) 10 cm thick of pebble to cobble-sized clast-supported compacted layer (likely road leveling material), (2) 50 cm thick of generally loose, boulder to cobble size matrix-supported (60%) layer, and (3) more than 1 m heavily oxidized red, grey in part, matrix-supported (90%) section. The deeper section in the northern rim reveals the presence of a bright orange layer, which from afar, appears as a thick heavily clay-altered part, the only likely original rock in these mentioned exposed materials. Crude estimation of the volume of material removed within the arcuate feature is 2.15×10^5 m^3.

At the center of the basin-like feature, confined within the central 10,250 m^2, are approximately 30 one to five meter-diameter low-relief maar-like structures and nine steaming vents. The steaming vents, of variable strength (decreasing in energy with time) are widespread and mostly occur along recent pseudo-channels that formed from the runoff. No geochemical sampling has been carried out yet on these thermal areas due to safety issues the area poses. The feature and its surroundings are covered by grey deposits, petrographically identified as loosely consolidated clays (smectite and kaolinite) with pyrite, fine quartz, altered ferromagnesian minerals, and glassy tuff fragments (Concepcion, 2017). These occur between one and seven centimeters thick in the immediate access road to the east and can be more than 30 cm thick in part, as observed in the southern rim where an apparent distribution bias is noted. These thicknesses, however, may no longer be true considering the heavy rains which have transpired between the deposition event and the field surveys.

2.1 Evidence of a high temperature, high pressure release

Several locals, who were nearby UMTA when the earthquake occurred, account that an explosion was heard barely a few seconds after the start of the main ground shaking. This explosion was followed by a rumbling sound and the formation of a dark plume above the field, which gradually cleared. These are consistent with the field observations around UMTA and its present-day morphology indicating a release of high temperature and high pressure has occurred, summarized in Figure 1A.

Evidence include the biased distribution of the clay materials, directed bending of grasses, graded deposition of recent fragments/sediments, and the burning of surrounding vegetation. Recent clay deposits around the main collapse feature appear to be the thickest in the southern portion of the rim. Clays are also noted on the leaves and on the trunks of the trees, but limited on the side facing UMTA (Figure 1a/iii). Lumps of these clay materials are also observed on the access road as fallouts, thus their appearance as *splatters (*Figure 1a/i).

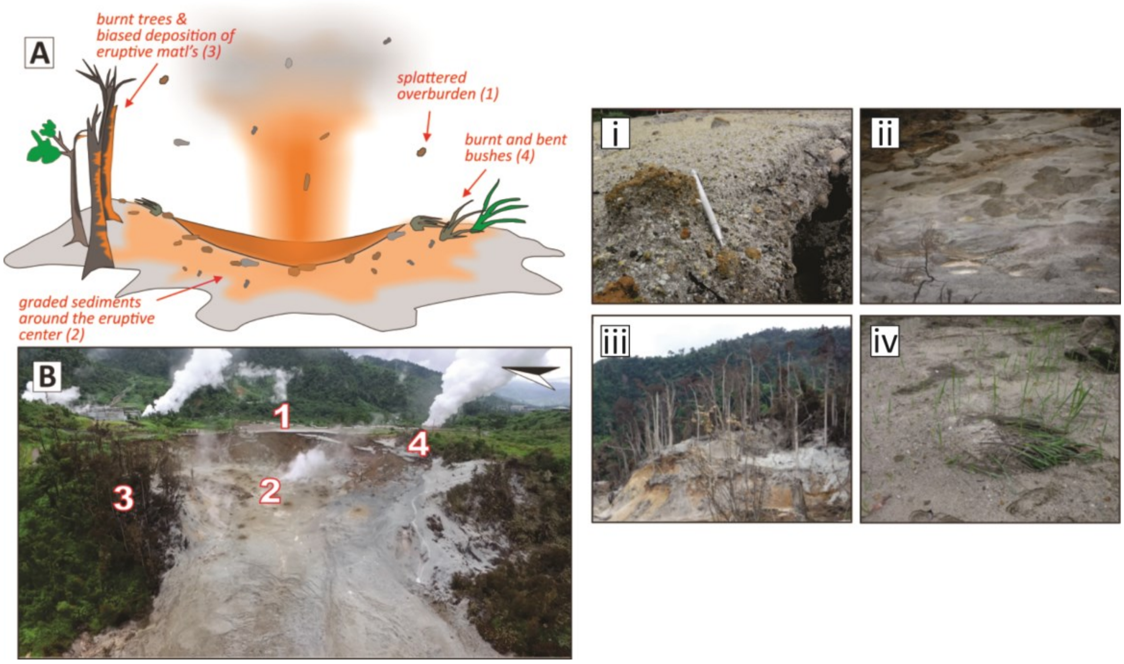

Figure 1. (A) Cartoon summarizing the expected observations around an eruption, such as what have been observed in UMTA and delineated in (B). This includes (1) splatters of subsurface material, (2) grading of sediments around the maar-like features, (3) burning of surrounding trees, and (4) bending of grasses. Location of these photos is marked in (B) accordingly.

Vegetations in the immediate area of the UMTA are also burnt and/or bent. Tall shrubs (at least 30 cm high) in the eastern and southern rim bend consistently away from the collapse feature (i.e. radial direction, Figure 1a/iv). There is also an observed color contrast, from dark brown to green, as one goes away from the rim, as a result of the charring of the trees in the area. Burnt fragments have been randomly observed on the access road as large as 10 cm, and even in thin sections. Although faintly observed, grading of loose sediments is noted around the individual maar-like features. The sediments appear to be fining away from each center (Figure 1/ii) wherein pebble to cobble-size rock fragments can be seen closest to the features, and are replaced by mostly pebbles and coarse sand-size materials further away from them. This observation, however, could not be discussed in detail as it was unsafe to get closer to the center of the collapse when the field survey was carried out.

3. DISCUSSION AND PROPOSED MECHANISMS

Physical observations and local accounts indicate that two main processes were involved that resulted to the formation of the large collapse feature of UMTA – (1) an eruption, and (2) a landslide. Geologically, eruptions can generally be either hydrothermal or volcanic in nature. In the absence of active volcanism in Leyte, and consequently the non-observation of juvenile eruption materials around the eruption crater, the eruption in UMTA is well likely hydrothermal in nature. As discussed in Bromley and Mongillo (1994) and Lawless and Browne (2001), there are several types and mechanisms of a hydrothermal eruption – (1) when pressures exceed the lithostatic pressure, (2) when there is an accumulation of steam and/or gas, (3) when there is sub-surface pressure release, (4) when there is an addition of magmatic heat or gas, and (5) during progressive flashing. The first mechanism is the most common and simplest, as it only requires a lithological cover that induces the pressurization of the reservoir, until such time that the reservoir pressure exceeds the overburden pressure. The hydrothermal eruption of this type is often small and short-lived, occurring near-surface (Lawless and Browne, 2001).

Based on the historical accounts and the present physical characteristics around UMTA, the initial impression is that the hydrothermal eruption presented here is likely a Type 1, with the power plant backfill material as the lithological cover. This is strongly supported by the fact that a hydrothermal eruption occurred, although of smaller scale, shortly after the backfilling activity happened in 1995. The backfill material introduced an impermeable cover above the steaming ground that resulted to the accumulation of pressure near surface, as the pores which were previously *freely breathing*, were smothered by a thick matrix-supported material. As this small eruption crater was again covered by the same material, eruption recurrence is definitely not surprising. However, this exact simple process could not completely account as to why the present crater is 40 times larger than the older one. It is most likely that a combination of other mechanisms and processes may have taken place, particularly, introduced or a consequence of the large earthquake that occurred almost contemporaneous to it. With the data on hand, two possible processes can occur following this pore pressurization, thus, two models are herein presented – one that involves a sub-surface pressure input (Model 1), and another that requires the deformation of the overburden (Model 2). The preceding processes, however, are the same, detailed below (Figure 2a-d). Note that the discussion of pressures only involves those within the pores and the overburden. The relationships are merely qualitative and do not consider other parameters (e.g. tensile strength of rocks, etc).

1. *The existence of a smaller steaming ground* (Figure 2a)*,* coined here as the Upper Mahiao Thermal Area. Initially, the near-surface pore pressure, P_{pore}, is greater than the lithostatic or overburden pressure, P_{lith1}, comprised of clay-altered tuffs, enabling the continuous steam emanation.
2. *The covering of the UMTA by fill materials from the Upper Mahiao Power Plant construction* (Figure 2b). This introduced an additional overburden pressure, P_{lith2}, from the backfill materials, resulting to a total overburden pressure, $P_{lithtotal} = P_{lith1} + P_{lith2}$. The exact volume of material added is still unclear but likely between 10 to 19 m thick, which is equivalent to 196 to 373 kPa of P_{lith2}, using a rock density of 2000 $kg.m^{-3}$ (density of a conglomerate).
3. *Pressurization of the near-surface pores, resulting to an increase in* P_{pore}. The initial backfill may have been very impermeable (i.e. compacted) resulting to an abrupt rise in P_{pore}, which immediately exceeded $P_{lithtotal}$. This marked the first but small hydrothermal eruption in 1995 (Figure 2c), which was again blanketed by backfill material (Figure 2d). It is possible that the succeeding backfill may no longer be that compact and impermeable, in contrast to that prior to the first eruption, thus the P_{pore} increase was now more gradual. This could also tie in the unconfirmed account that there was still some steam emanation in the area, although rather faint (Figure 2d), suggesting that the pressure build up was not as aggressive, thus, no smaller eruptions occurred thereafter. Since then, $P_{lithtotal}$ was just slightly more than P_{pore}.
4. *Exploitation of the geothermal resource.* The extraction and eventual drawdown of the LGF resource should be highlighted as this resulted to the deepening of the boiling conditions, and thus the formation of a thicker and shallower steam zone.
5. *The M6.5 earthquake happened*. The earthquake on July 6, 2017 could have initiated several processes, hence, Models 1 and 2 are presented and discussed as follows:

3.1. Model 1 – sub-surface pressure input

The M6.5 earthquake may have driven the hydrothermal eruption following the Type 3 mechanism, as mentioned earlier in this section. As the main earthquake occurred in June 6, 2017 and perhaps even the smaller ones before this, seismic waves were released, liberating pressures that triggered steam formation at depth (Figure 2/e1). Similarly, as fracturing occurred at depth during the earthquake, fractures may have opened, releasing trapped hot fluids, allowing them to flow from zones of higher to lower pressures (Browne and Lawless, 2001), consequently, at depth towards the surface. During seismic slip (i.e. an earthquake), frictional heating from the slipping fault could increase the temperature of the pores and rocks around it. This temperature rise can likewise induce steam formation at depth. One may argue that the trace of the earthquake generator (i.e. Philippine Fault) is too far from UMTA (straight-line distance of 2.5 km) for it to effectively transfer pressure. However, in the context of well-connected sub-surface fractures, this is geologically sound. Moreover, the fault movement transpired on the eastern part of the field which was previously considered as the mobile block (Caranto and Jara, 2015). Hence the high likelihood of this mechanism.

Earthquakes triggering hydrothermal eruptions have been documented elsewhere. At the Yellowstone geothermal area, more than 200 geysers formed just within 24 hours following a M7.3 earthquake centered at the Hegben Lake, USA (Browne and Lawless, 2001). Migration of hydrothermal fluids accompanied by several but smaller seismic events was likewise noted prior to a hydrothermal eruption in Nisyros, Greece in 1873 (Zlotnicki *et al.,* 1992 in Browne and Lawless, 2001). Thus, this mechanism is not unique, and considering the similarity in the sequence of events, it is very likely that the sub-surface pressure input from the July 2017 earthquake drove the eruption of UMTA, succession of processes continued below:

6A. *The formation of steam from the sub-surface pressure input from the seismic slip(s) at depth* (Figure 2/e1). The steam then likely accumulated near-surface, increasing the initial P_{pore}.

7A. *The eruption* (Figure 2f). Since $P_{lithtotal}$ was only slightly higher than P_{pore}, even a small addition in P_{pore} could trigger over-pressurization, and thus, a hydrothermal eruption occurred immediately following the earthquake. The eruption ejected the clay-altered rocks, which were the original overburden of the steaming vents, and lifted the backfill material. Based on the biased distribution of the eruptive deposits (Figure 1), the eruption was most likely oblique, not completely vertical.

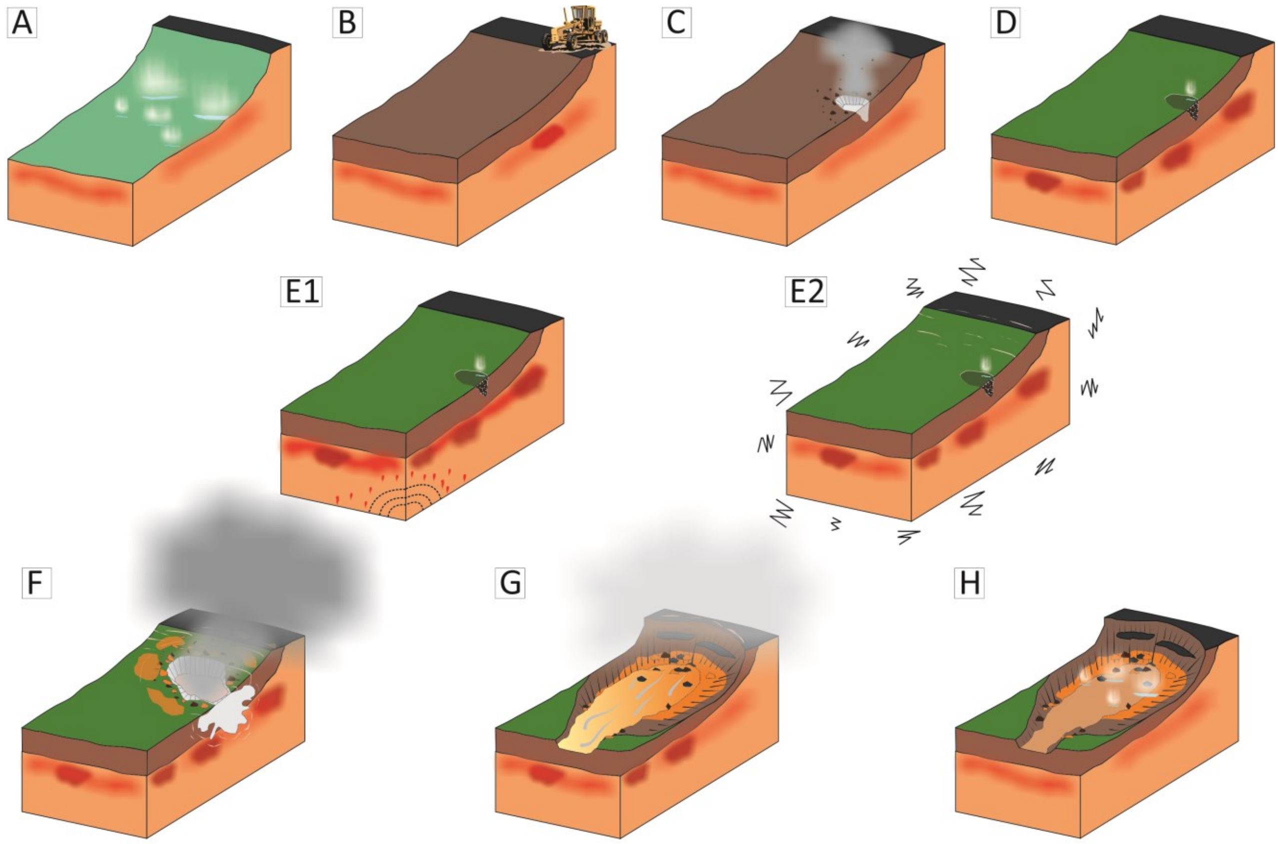

Figure 2. The suggested mechanism/sequence of events leading to the formation of the UMTA as discussed in-text, from pre-1995 (A) to the present-day (H). Two models are proposed, which differs only at the immediate effect of the earthquake – sub-surface pressure input (E1) versus overburden deformation (E2). The hue of red zones at depth represents degree of pressure accumulation which has been changing with time.

3.2. Model 2 – deformation of the overburden

On the other hand, another possible mechanism of the eruption is the deformation of the overburden, thereby decreasing the overburden pressure. As seismic waves propagated from the earthquake focus, rapid acceleration of the ground increased resulting to ground shaking. This could have induced local surface to near-surface fracturing (e.g. tension cracks) particularly within the loosely consolidated overlying rocks of the UMTA, resulting to the decrease of the lithostatic pressure. The cracks may not necessarily be large in scale nor do they need to propagate through the entire thickness of the two overlying lithologies (i.e. lith1 and lith2). Considering that the pressure difference between the pores and the overburden is so small, even a small drop in the lithostatic pressure can result to an eruption. This mechanism is a fine example of the first type of a hydrothermal eruption discussed earlier.

6B. *Deformation of the overburden as a result of the ground shaking* (Figure 2/e2). The fracturing reduced $P_{lithtotal}$.

7B. *The eruption* (Figure 2f). Since $P_{lithtotal}$ was only slightly higher than P_{pore}, even a small decrease in $P_{lithtotal}$ could lead to a significant pressure difference and a depressurization of the accumulated near-surface steam, thus, a hydrothermal eruption occurred immediately following the earthquake. The eruption ejected primarily the clay-altered rocks, which were the original overburden of the steaming vents, and the backfill material.

There is a thin line that separates these two processes (6A versus 7A) as they all occurred within a very short timeframe (seconds), almost simultaneously in human perspective. With the absence of real-time ground monitoring prior to the earthquake, explicitly identifying which of these two indeed happened remains a big challenge. What is definite is that the M6.5 earthquake was the main trigger for the eruption to proceed.

Following the eruption, the deformation continued in the area which eventually enlarged the feature, as discussed below:

8. *The landslide* (Figure 2g). As the main eruption occurred, a large volume of material was ejected near surface and drawn out underneath. This volume loss and the continuous ground shaking destabilized the area around the eruptive center, leading to a massive landslide. The landslide breached the crater and removed more material, thus, the present impression that the crater extends more than 200 m in diameter. The occurrence of the landslide after the earthquake is consistent with the accounts of the witnesses that the rumbling sound was heard only after the explosive thud.

9. *The debris flow* (Figure 2g). Considering the heavy rainfall on the day and the morning before the earthquake, the overburden was likely saturated with water. Additionally, since the rocks underneath the backfill material are mostly clays, which could have been saturated by the condensed steam released from the explosion, water content in the landslide debris is likely high, thus, their higher tendency to flow. Following the natural slope of the area, the debris flowed to the west. This process eroded majority of eruption materials. It is also likely that the eruption may have continued, although perhaps waning, depositing more of the clay overburden, until it ceased when the vents got quenched or when the overpressure has completely been released.

4. CONCLUSIONS, LESSONS LEARNED AND MOVING FORWARD

This experience of an eruption in UMTA highlights two key things – (1) an earthquake can cause devastating effects not just limited to mass wasting and ground rupture, and (2) disturbing surface thermal activity is not ideal and may even be catastrophic. Lawless and Browne (2001) briefly discussed that disturbing existing or past thermal manifestations should be avoided to minimize the chance of triggering hydrothermal eruptions. Should excavation or covering of areas of thermal activity be necessary, they recommend surrounding the immediate vents with a gravel pack fill to allow the steam to continuously escape, avoiding any accumulation of pressure. Although the magnitude of the recent eruption was only so because of the M6.5 earthquake that triggered it, the early pressurization near-surface was initiated by the backfilling activity in 1995. This should be a lesson learned to avoid disrupting past and existing thermal areas, regardless of size of the steaming ground. In the Philippines, particularly in Leyte and Bicol where larger magnitudes should be expected associated to the seismically active Philippine Fault, the chance of an eruption of similar size to occur will always be present. Thus, eliminating some of the components of the process (under the same mechanism) is necessary to minimize the likelihood of it happening.

Apart from being the cap rock of the UMTA, the cut material from the power plant construction also served as the fill material to support the adjacent access road expansion (Figure 2b). During the earthquake, the massive landslide that followed primarily removed this backfill material (Figure 2g), suggesting that the instability was likely accumulated on it. This is not surprising as the backfill material as observed in the landslide scarp is loosely consolidated. Rock strength is expected to be low in such kinds of rock, as pores are likely uncemented (at least in the matrix) and strength anisotropy is high, making them more susceptible to damage. Saturation from earlier rainfalls further exposed them to deformation. This observation is not exclusive in UMTA but in other areas of the Leyte Geothermal Field as well (i.e. mapped post-earthquake damages are common on altered grounds, backfill, and loose soil as reported in Pastoriza and Austria (2017) and Amora(2017). Thus, it is strongly suggested to fully evaluate the mechanical properties of the cut material before using it as ground fill, especially where the original slopes are already high and when the location will be for critical facilities or for an access road.

At present, UMTA remains to be exposed and is freely emanating steam, although no longer as intense compared to the July 2017 observations. The landslide scarp which supposedly supports the nearby access road is now stabilized by benching. The arcuate tension cracks around the crown have been cemented to minimize rainwater infiltration that may aggravate the fracture formation and erosion. Pipelines running parallel to the crown have been rerouted and the access road has been resurfaced, regarded, concreted, and widened away from the landslide hazard. A drainage system has also been installed to redirect water flow that may induce erosion of the slope and the surface is now filled with vegetation to further support the area. A fleetwide approach on reviewing historical activities (both natural and man-triggered) of thermal manifestations that aims to identify similar hydrothermal eruption hazards is also underway.

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