geosciences

Article

Impacts of a Moderate-Sized Earthquake: The 2023 Magnitude (M_w) 4.7 Leyte, Leyte Earthquake, Philippines

Jeffrey S. Perez *, Deo Carlo E. Llamas, Daniel Jose L. Buhay, Ryan Christian C. Constantino, Crystel Jade M. Legaspi, Kristine Dionne B. Lagunsad, Rhommel N. Grutas and Marc Marion Y. Quimson

Department of Science and Technology, Philippine Institute of Volcanology and Seismology (DOST, PHIVOLCS), Quezon City 1101, Philippines
* Correspondence: jeffrey.perez@phivolcs.dost.gov.ph

Abstract: On 15 January 2023, a shallow, moderate earthquake with a magnitude (M_w) of 4.7 and a depth of one kilometer struck the northern part of Leyte Island in the central Philippines. Originating along the northern Leyte segment of the Philippine Fault, a well-established creeping fault, the earthquake caused significant geologic, structural, and socio-economic impacts despite its low magnitude. Probable surface rupture and landslides were reported, leading to a comprehensive field investigation. Our investigation revealed an ~8 km discontinuous surface rupture along the northern Leyte segment of the Philippine Fault, with a maximum left-lateral displacement of 2 cm. This was the first documented occurrence of such a phenomenon associated with an earthquake of a magnitude less than 6, particularly along a creeping fault segment. The maximum ground shaking felt was reported on the PHIVOLCS Earthquake Intensity Scale (PEIS) to be VI (very strong), equivalent to a Modified Mercalli Intensity (MMI) of VI along the fault strike. However, strong motion accelerographs recorded a peak ground acceleration (PGA) of 0.407 g, equivalent to PEIS VIII (very destructive), attributed to local site amplification influenced by subsurface geology. In the area where the local site amplification occurred, limited liquefaction was observed on marshlands with recent and alluvial deposits. Two landslides were observed in the mountainous area west of the fault. Structural damages were noted in areas with PEIS VI intensity and areas transected by the surface rupture. Despite the earthquake's low magnitude, the event documented significant impacts, including surface ruptures, liquefaction, landslides, and severe structural damage. The peculiarities of this event are attributed to the shallowness of the earthquake source, and local site conditions, including geology, geomorphology, and soil properties, contributed to the severity of the impacts. Moderate in size, this earthquake emphasizes the importance of documenting moderate-sized earthquakes as a tool and guide for medium- and long-term earthquake risk assessment and resiliency.

Keywords: Philippine Fault—Leyte segment; PHIVOLCS Earthquake Intensity Scale (PEIS); surface rupture; liquefaction; landslide; site amplification; disaster risk reduction

check for updates

Citation: Perez, J.S.; Llamas, D.C.E.; Buhay, D.J.L.; Constantino, R.C.C.; Legaspi, C.J.M.; Lagunsad, K.D.B.; Grutas, R.N.; Quimson, M.M.Y. Impacts of a Moderate-Sized Earthquake: The 2023 Magnitude (M_w) 4.7 Leyte, Leyte Earthquake, Philippines. *Geosciences* **2024**, *14*, 61. https://doi.org/10.3390/geosciences14030061

Academic Editors: Bruno Massa, Daniela Di Bucci, Zhonghai Wu and Jesus Martinez-Frias

Received: 28 December 2023
Revised: 16 February 2024
Accepted: 22 February 2024
Published: 23 February 2024

1. Introduction

Being along a complex tectonic boundary, the Philippines is one of the most seismically active countries in the world. For the past decade, at least 10 damaging earthquakes with magnitudes > 6 have affected the country and were documented. These earthquakes include the 2012 magnitude (M_w) 6.7 Negros Earthquake [1]; the 2013 M_w 7.2 Bohol Earthquake [2]; the 2017 M_w 6.5 Surigao Earthquake [3]; the 2017 M_w 6.5 Leyte Earthquake [4]; the 2019 M_w 6.1 Central Luzon Earthquake [5]; the 2019 Cotabato-Davao del Sur Earthquake Sequence, with five (5) M_w > 6 earthquakes in three months (October to December 2019) [6]; and the 2020 M_w 6.6 Masbate Earthquake [7].

In 2022, a major earthquake with M_w 7.0, impacted the northern part of the Philippines with maximum ground shaking of PHIVOLCS Earthquake Intensity Scale (PEIS) VII (destructive), equivalent to Modified Mercalli Intensity (MMI) VII. The 2022 M_w 7.0

Northwestern Luzon Earthquake, despite its significant magnitude, exhibited no identifiable surface rupture. Nevertheless, the earthquake resulted in widespread landslides, liquefaction, and sea level disturbances [8]. It affected more than 574,000 persons, with eight (8) deaths and more than 600 injuries, and an estimated cost of damages to structures of about PHP 2.6 billion (USD 46 million) [8].

Most of the past large-magnitude and damaging earthquakes in the Philippines were documented and assessed by the Department of Science and Technology—Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS), a government institute, at the academe and disaster risk reduction and management (DRRM) offices [1–8]. The reports for these events have been widely used by different stakeholders for relief operations, the assessment of future seismic hazards, and policy recommendations. Very seldom were moderate-size earthquakes in the past documented, assessed, and studied by any institutions in the country.

The 2023 M_w 4.7 Leyte, Leyte Earthquake was a moderate-sized earthquake (Figure 1A), and we expected that no significant geologic impact and structural damage would result from this event. However, preliminary information gathered from broadcast (print, television, and radio) and social media (Facebook, Twitter, Instagram, etc.) revealed that several structures in the municipality of Leyte (population approximately 41,000), in the province of Leyte, were damaged, and landslides and probable surface rupture were reported. Based on the Philippine National Disaster Risk Reduction and Management Council (NDRRMC) Progress Report No. 3, the estimated cost of damage to structures was about PHP 27.6 million or USD 502 thousand, and the event affected more than 430 families, or 1775 persons, with 18 injuries [9].

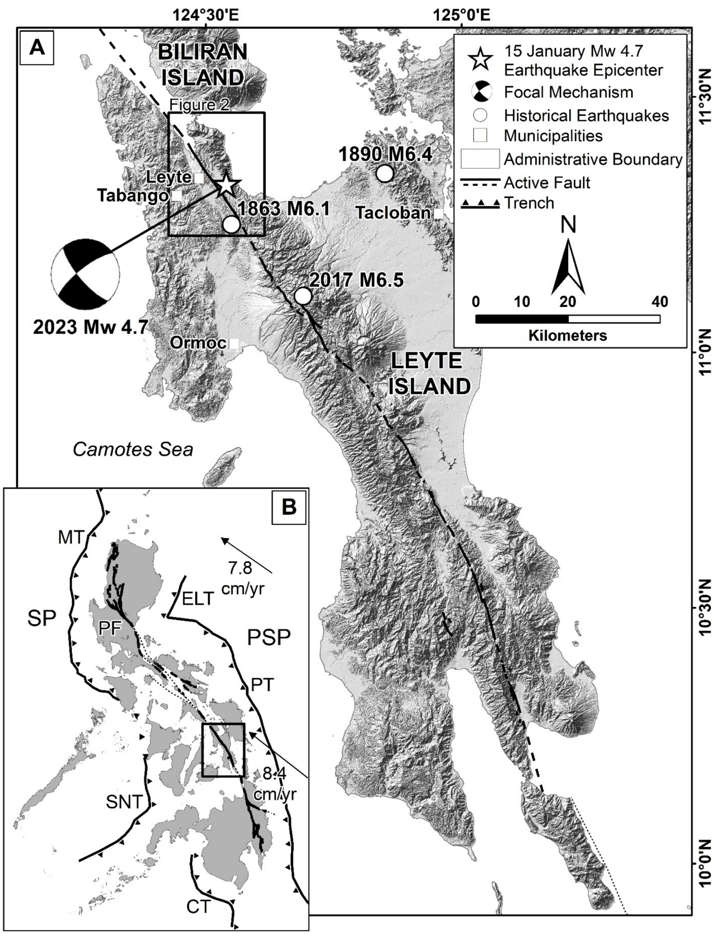

Figure 1. The seismotectonic setting of the 2023 M_w 4.7 Leyte, Leyte Earthquake. (**A**) The Philippine Fault—Leyte segment and historical earthquakes. The Philippine Fault (PF) trace was obtained from

Tsutsumi and Perez [10], and historical earthquakes from Bautista and Oike [11]. (**B**) The geodynamic setting of the Philippines. The Philippines is on a complex boundary between the PSP and the SP. Arrows indicate the relative motion of the PSP. ELT—East Luzon Trough, PT—Philippine Trench, MT—Manila Trench, SNT—Sulu-Negros Trench, CT—Cotabato Trench. The base map is IFSAR-DEM from the Philippine National Mapping Resources and Information Authority (NAMRIA). The rectangle in (**A**) shows the location of Figure 2.

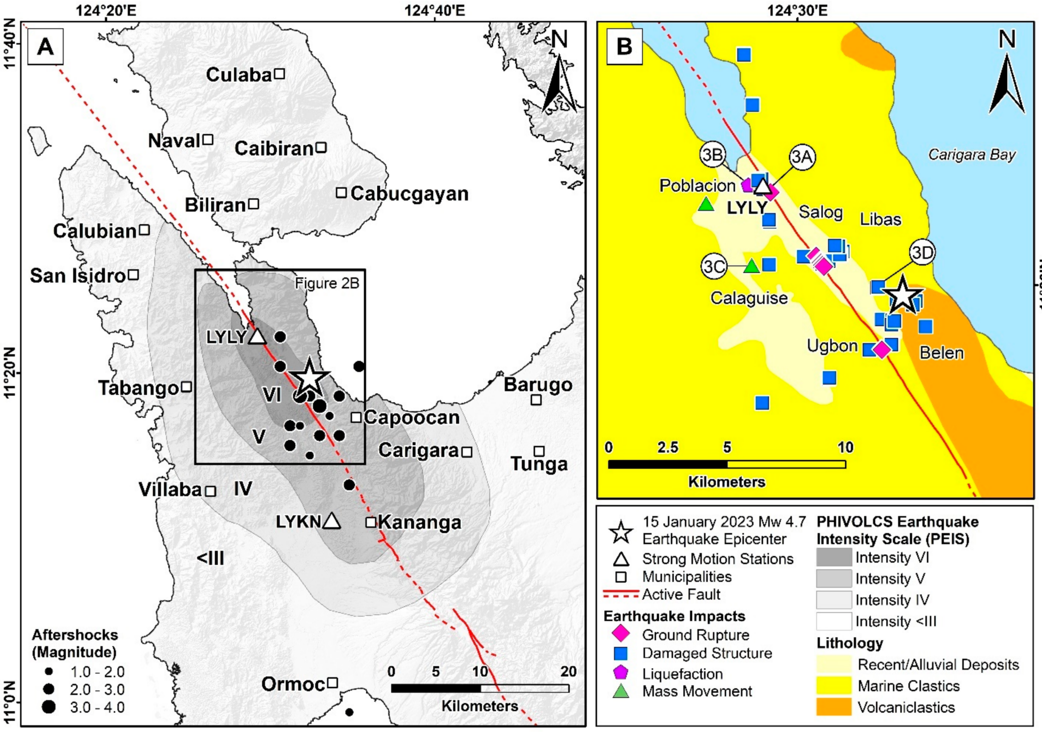

Figure 2. The 2023 M_w 4.7 Leyte, Leyte Earthquake isoseismal, aftershock distribution, and earthquake impact maps. (**A**) The isoseismal map was based on the latest earthquake information from DOST-PHIVOLCS [12] and the detailed intensity survey and impact assessment conducted in this study. Aftershock distribution (black circle) from 15 to 23 January 2023 was recorded by the Philippine Seismic Network [12]. (**B**) Spatial distribution of documented damages and geologic impacts (ground rupture, liquefaction, and mass movement). The geologic map was modified from Aurelio and Peña [13]. Circles with letters and numbers show the locations of photos in Figure 3. The active fault trace (red line) was obtained from Tsutsumi and Perez [10].

For this paper, we present the results of our field investigation, which included detailed assessment and documentation of the geologic and socio-economic impacts of the moderate-sized earthquake. We discuss the severity of the impacts and possible explanations. We recommend actions that should be taken to lessen the impacts of future earthquakes. We also emphasize the importance of documenting earthquake impacts as a tool for medium- to long-term earthquake risk assessment, especially in populated areas.

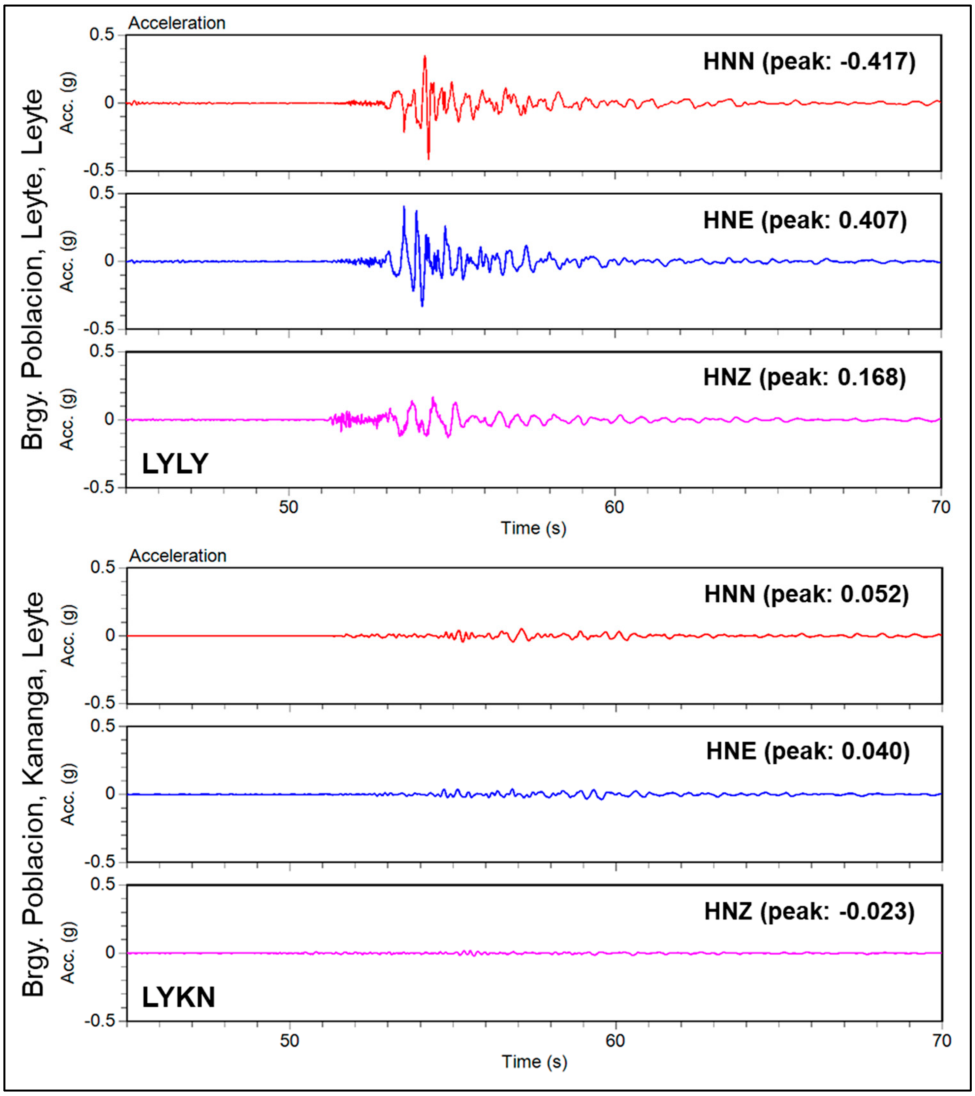

Figure 3. Peak ground acceleration (PGA) record from the Philippine Strong Motion Network (PSMNet) stations in Brgy. Poblacion, Leyte (station code: LYLY) and Brgy, Poblacion, Kananga (station code: LYKN). PGA values for the two sites correspond to the expected ground shaking felt in the area and were influenced by the soft sediment subsurface, as manifested by the geology and geomorphology of the area. Refer to Figure 2 for the location of the two (2) accelerographs.

2. Tectonic Setting

Leyte Island, located in the central part of the Philippines, is transected by the Philippine Fault, a north-northwest-trending, 1500 km long, sinistral strike–slip fault that traverses the entire Philippine archipelago from Luzon Island in the north to eastern Mindanao in the south (Figure 1A) [10,14]. This fault resulted from the slip partitioning from the oblique convergence of the Philippine Sea Plate (PSP) and Sunda Plate (SP) [15] (Figure 1B). The Philippine Fault stands as a prominent active fault on a global scale, having produced over 20 surface-rupturing earthquakes in the last 400 years. It is accountable for more than half of the significant and destructive historical earthquakes in the country [11].

Tsutsumi and Perez [10] mapped and characterized the Leyte segment of the Philippine Fault in detail. This segment traverses the middle part and the backbone range of Leyte Island for about 140 km, and is characterized by linear valleys, stream offsets, hillside ridges, and wind gaps (Figure 1A). In the northern section of the Leyte segment, Perez et al. [16] documented the creep of the Philippine Fault in the municipality of Leyte by observing offsets in concrete structures and asphalt roads. Meanwhile, additional studies have proposed that a significant part of the fault in Leyte exhibits creeping, as indicated by InSAR analysis and field observations conducted by other researchers [17–19].

Unlike other segments of the Philippine Fault, the Leyte segment exhibits distinct seismicity, with no occurrence of large, destructive earthquakes (M > 7) over the past 400 years (Figure 1A) [10,11]. The most recent damaging earthquake was the 2017 M_w 6.5 Leyte Earthquake that ruptured the 26 km stretch of the Leyte segment, with maximum horizontal and vertical displacements of 1.1 and 0.5 m, respectively [4]. An isolated locked patch along the fault generated this earthquake [16,17], resulting in liquefaction that manifested as lateral spreads, subsidence, sand boils, and extensive landslides [4]. Damages to infrastructure amounted to PHP 220 million or USD 4.4 million. Three persons died and 448 were injured. Other magnitude >6 earthquakes in Leyte include the 1863 (M 6.1) and 1890 (M 6.4) [11] (Figure 1A).

3. Methodology

To better understand the characteristics of this event, we analyzed different earthquake data gathered from various institutions and from field surveys. The earthquake parameters, focal mechanism solutions, and aftershocks used for this event were gathered from the Philippine Seismic Network (PSN), while ground motion data were obtained from the Philippine Strong Motion Network (PSMNet). To assess and document the impacts of this earthquake, the DOST-PHIVOLCS deployed a quick response team (QRT) from 27 January to 1 February 2023 in the affected areas. Our fieldwork includes the identification and documentation of geologic impacts using handheld GPS, remotely piloted aircraft (RPA), and photo documentation. We also conducted an earthquake intensity survey and eyewitness interviews to verify and assess the severity of ground shaking near and around the epicentral area. The results of this intensity survey are presented as an isoseismal map in Figure 2 and Table 1.

Table 1. Summary of reported intensities on the PHIVOLCS Earthquake Intensity Scale (PEIS) of the 2023 M_w 4.7 Leyte, Leyte Earthquake, based on DOST-PHIVOLCS earthquake information, intensity surveys, and impact assessment conducted in this study (refer to Figure 2 for the isoseismal map).

Earthquake Intensity	Province	City/Municipality
VI (very strong)	Leyte	Along the strike of the Philippine Fault—Leyte segment in Leyte and the easternmost part of Tabango
V (strong)	Leyte	The rest of Tabango and Leyte; Capoocan and Kananga
IV (moderately strong)	Leyte	Calubian, Carigara, and San Isidro
III (weak)	Biliran	Biliran, Cabucgayan, Caibiran, Culaba, and Naval
	Leyte	Alangalang, Babatngon, Barugo, Jaro, San Miguel, Tunga, Villaba, Ormoc City, and City of Tacloban
II (slightly felt)	Biliran	Almeria
	Leyte	Albuera, Matag-ob, Santa Fe, Pastrana, Merida, Palompon, Palo, and Isabel
I (scarcely perceptible)	Cebu	City of Bogo
	Eastern Samar	City of Borongan

4. Earthquake Parameters, Focal Mechanism, and Aftershocks

The hypocenter for the 2023 M_w 4.7 Leyte, Leyte Earthquake was located at 11.33° N and 124.54° E or 7 km S55° E of Leyte, Leyte at a very shallow depth of 1 km [12] (Figure 1A). The earthquake's focal mechanism was derived from the PSN by waveform inversion in the frequency domain of body waves. This method adopted the source parameter determination based on the waveform inversion of the Fourier-transformed seismogram (SWIFT) that determined the centroid moment tensor (SWIFT-CMT) of the earthquake [20–22]. The calculated SWIFT-CMT solution for this earthquake (Figure 1A) indicated that the preferred nodal plane trended northwest, with a strike, dip, and rake of 140°, 83°, and −23°, respectively, indicating a left-lateral motion, following the trend of the Philippine Fault—Leyte Segment. A seismic moment of (Mo) of 1.22×10^6 N.m. and M_w 4.7 was obtained from the inversion.

The PSN recorded 26 aftershocks from 15 to 23 January 2023, of which 15 were plotted and 12 were felt (Figure 2A) [12]. The magnitudes of the recorded aftershocks ranged from 1.7 to 3.9 (Figure 2), and the highest magnitude was felt at PEIS III (weak), equivalent to MMI III, in Leyte, Leyte. The recorded aftershocks were relatively few, with abrupt decay from 16 on the 1st day, 5 on the 2nd day, and fewer than 3 to zero from the 3rd to 9th day [12]. The distribution of the aftershocks also indicates that the earthquake generator for this earthquake was the Philippine Fault—Leyte Segment.

5. Geologic Impacts

5.1. Ground Shaking and Intensity Distribution

Based on the earthquake information from DOST-PHIVOLCS, the maximum reported earthquake intensity was PEIS VI (very strong), equivalent to MMI VI, and was widely felt in the municipalities of Leyte and Tabango, in the province of Leyte. Ground shaking was felt as far as 100 km away from the epicenter [12]. Areas that reported PEIS VI (very strong) suffered significant damage to poorly built structures on sloping ground, most of which were schools and concrete hollow block (CHB) houses made from substandard materials. Many people in these areas were frightened, many ran outdoors, and some exited their houses.

To verify the limited reported intensities, we conducted a detailed intensity survey and damage assessment in the affected area. Table 1 shows the result of our survey and is illustrated as an isoseismal map in Figure 2A, while Figure 2B summarizes the location of the geologic and structural impacts.

The strongest ground shaking (PEIS VI) was felt in areas or barangays (smallest political unit in the country; abbreviated as Brgy.) in the municipality of Leyte, along the strike of the Philippine Fault and the easternmost part of the municipality of Tabango (Figure 2 and Table 1). These barangays where the strongest ground shaking was felt were also the locations where the surface ruptures along the trace of the fault were documented. This manifested in the elongation of isoseismal lines on the isoseismal map along the strike of the fault (Figure 2). The intense ground shaking in this area damaged several structures and induced geologic impacts such as liquefaction and mass movement.

For a more detailed assessment of the ground motion, data from two (2) accelerographs positioned near the epicenter were examined, both belonging to the PSMNet (refer to Figures 2 and 3). The first accelerograph (station code: LYLY) was located in Brgy. Poblacion, Leyte, and ~7 km NW of the epicenter. It recorded a peak ground acceleration (PGA) of 0.407 g, equivalent to PEIS VIII (very destructive) [23], while the second accelerograph (station code: LYKN), located in Brgy. Poblacion, Kananga and ~16 km southeast of the epicenter, recorded a much smaller PGA, 0.052 g, equivalent to PEIS V (strong) [23].

5.2. Surface Rupture

Surface rupture is commonly observed for shallow inland earthquakes (0–10 km) with magnitudes ≥6 [24,25]. The last surface-rupturing event on Leyte Island before this event occurred during the 2017 M_w 6.5 Leyte Earthquake [4].

It is uncommon for an earthquake of magnitude <6 to have surface rupture [24]. However, our field investigation revealed an 8 km long northwest-trending discontinuous rupture associated with the 2023 M_w 4.7 Leyte, Leyte Earthquake that occurred along the previously mapped Philippine Fault—Leyte segment [10,16,17]. Detailed ground and drone surveys conducted during the investigation showed that the surface rupture affected at least three barangays (Brgys. Poblacion, Salog, and Ugbon) in Leyte (Figures 2B and 4A). The surface rupture manifested as a continuous crack with discernable left-lateral displacement or parallel *en-echelon* visible cracks identified as Riedel shear structures. Measured displacements ranged from 1.5 to 2 cm. Figure 4A shows a portion of the surface rupture manifested as hairline cracks along a road with 2 cm horizontal displacement, coinciding with the previously mapped active fault. Eyewitness accounts verified that the hairline cracks were caused by the earthquake. It also affected residential houses traversed by the active fault. These residential houses had also previously been identified to be damaged by fault creeping in past studies [16,17]. A detailed discussion of this rare surface rupture is presented in Llamas et al. [26].

Figure 4. Geologic and structural impacts of the 2023 M_w 4.7 Leyte, Leyte Earthquake. (**A**) Observed road cracks (red line) along the national highway in Brgy. Poblacion, Leyte, coinciding along the trace of the Philippine Fault—Leyte segment [10]. Inset: 2 cm left-lateral displacement measured along the offset road paint. (**B**) Lateral spreads (cracks) formed on the earth dikes beside fishponds in Palaypalay District, Brgy. Poblacion, Leyte. (**C**) A shallow landslide consisting of soil rock and debris partly covered a road in Brgy. Calaguise, Leyte. (**D**) Damaged house (concrete hollow block) in Brgy. Belen, Leyte. Refer to Figure 2B for the locations of photos.

5.3. Liquefaction

The lowlands of the municipality of Leyte are characterized by recent sediments along the broad valley plain traversed by the Palaypay River and its tributaries [13]. This river drains to the northwest, towards Leyte Bay, with marshlands lining the mouth of the river. Some of these marshes are still covered with mangroves and nipa, while other portions have houses built on top or modified to be fishponds.

Documented liquefaction occurrences were limited to the marshlands with recent and alluvial deposits in the Palaypay District, Brgy. Poblacion, Leyte (Figure 2B) [13], and occurred near the epicentral area. In these sites, lateral spreads were observed along the earth dikes of a fishpond (Figure 4B). These dikes were made up of soil dug up from the adjacent fishponds. Ground cracks measuring up to 20 m in length and 4 cm horizontal gaps were documented. These cracks were all nearly parallel to the length of the earth dikes and spread towards the fishponds. A house beside the fishpond was also damaged. Portions of the house sank into the soil by 3 cm. According to the owner, the house was built on top of the sandy fill dug out from the nearby fishpond. In other areas of the Palaypay District, ground failures also caused damage to some built-up structures. In two houses, the floorings were made up of concrete. They sustained cracks, sank, and tilted towards the nearby marsh. In another two houses, the comfort rooms made of CHB also sank and tilted.

In the absence of sediment and water venting (or sand boils), it was difficult to attribute the lateral spreads and structural damages solely to liquefaction. The lateral spreads of the earth dikes may have been gravity-driven, and the tilted CHB structures and damaged concrete floorings may have just been poorly built. To determine whether liquefaction could have caused these impacts, soil samples up to 3.5 m deep from the marshlands in Palaypay District were collected using a hand auger for grain size analysis.

Figure 5 shows a summary of the grain size analysis of soil samples which we collected and compares it to liquefaction limits on grain sizes suggested by Tsuchida [27] and Numata and Mori [28]. The majority of the collected soil samples had grain sizes ranging from very fine to very coarse sand (0.0625 to 2.0 mm), and were within the boundaries of most liquefiable soils (Figure 5) [27–29]. While, for the soil sample collected from 1.5 to 2 m depth, 30% of its grains were granule- to pebble-sized (2.0 to 8.0 mm), this is still within the boundary for potentially liquefiable soils. With these soil properties and geomorphology coupled with the measured PGA of 0.407 g (recorded by LYLY, 500m from Palaypay District) (Figures 2A and 3), and as evidenced by the subsidence and tilting of some buildings and lateral spreads on some earth dikes, we are therefore more certain that liquefaction occurred in these soils.

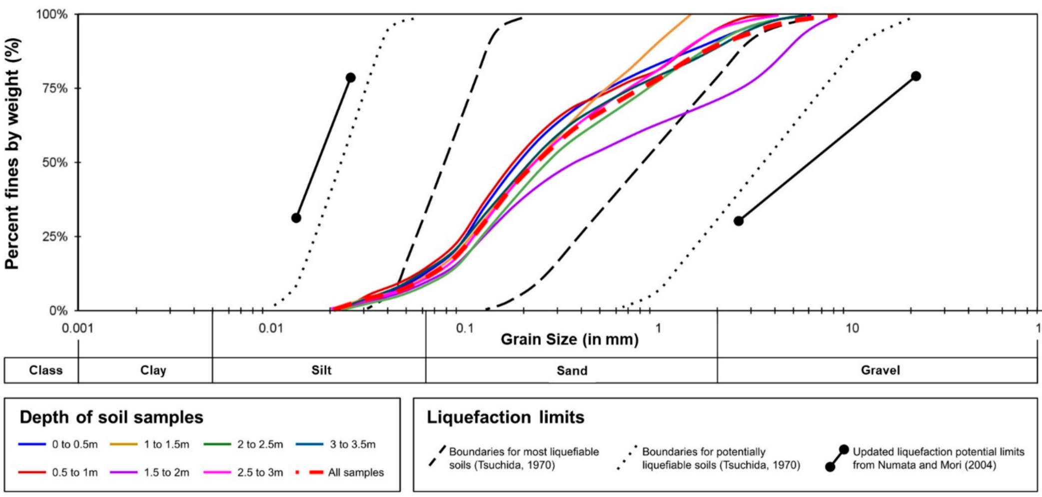

Figure 5. Grain size analysis of soil samples taken on the earth dikes that liquefied in Palaypay District, Brgy. Poblacion, Leyte, with liquefaction limits set by [28,29].

5.4. Landslide

The municipality of Leyte is flanked by mountains on its eastern and western perimeters. Only two instances of landslides were observed, as illustrated in Figure 2B. A rockfall was recorded along a densely vegetated hill in Brgy. Palid Uno in Leyte, while a shallow landslide occurred in Brgy. Calaguise, Leyte (Figures 2B and 4C). The shallow landslide, composed of earth debris and rocks, partially covered sections of the Calaguise-Calubian Road. The landslide took place on a steeply sloping road cut of a highly jointed sedimentary bedrock. Fortunately, no casualties or damages were reported due to mass wasting.

6. Structural and Socio-Economic Impacts

Based on the Rapid Damage Assessment and Needs Analysis report conducted by the municipality of Leyte, there were about 434 residential houses and 26 public infrastructures, including schools and government buildings, affected by the earthquake [25]. The DOST-PHIVOLCS QRT documented damaged structures, which are summarized in Figure 2B. Our assessment revealed that most of the damages were located near the epicentral area and could be attributed to poor-quality or substandard construction materials, such as CHB and reinforcing bars (Figure 4D). Notably, most of the damaged structures were located in alluvial and recent deposits (Figure 2B).

This earthquake affected about 437 families or 1775 persons in 15 barangays. There were a total of 18 injuries and no reports of death. The estimated cost of damage to structures was about PHP 27.6 million, or USD 502 thousand [9].

7. Discussion

The documentation and analysis of the 2023 M_w 4.7 Leyte, Leyte Earthquake impacts are limited to the affected area visited by the DOST-PHIVOLCS QRT. Although the earthquake was moderate in size, we have documented significant geologic, structural, and socio-economic impacts. Geologic impacts include surface rupture, the first documented occurrence along the creeping segment of the Philippine Fault, liquefaction in marshland with recent and alluvial deposits, and two landslides in the mountainous area west of the fault. Severe structural damages were documented in areas with PEIS VI (very strong), equivalent to MMI VI.

It is rare that an earthquake with a magnitude <6 will have a surface rupture [24]. We documented an 8 km long discontinuous rupture, which is the first documented surface rupture along the Philippine Fault and is unusual compared to other surface-rupturing earthquakes in the world [24]. Manifestations of the surface rupture in this event includes continuous cracks with discernible left-lateral displacement and parallel *en-echelon* visible cracks identified as Riedel shear structures. The mapped surface rupture exceeded the expected length, while the observed maximum horizontal displacement agreed with its magnitude based on empirical relations [25]. Since the field survey was conducted two weeks after the event, the unusual surface rupture length may not only have been coseismic, but may also have included a postseismic slip after the mainshock. Moreover, it was established that this part of the Leyte segment is creeping [10,16–19] and did not rupture during the 2017 M_w 6.5 Leyte Earthquake [4]. Hence, analyzing and documenting this phenomenon may widen our knowledge regarding creeping faults and surface rupture during moderate earthquakes. A quick but detailed investigation of moderate-sized earthquakes along creeping faults may help us to characterize these types of faults.

The PGA value recorded in Brgy, Poblacion, Leyte (station code: LYLY) was relatively high (0.407 g), equivalent to PEIS VIII (MMI VIII) (Figure 2A and 3) [23]. This value seems to contradict the maximum earthquake intensity, PEIS VI (very strong), felt in areas along the trace of the fault based on reports and intensity surveys (Figure 2A). In some cases, the recorded PGA value may be affected by local site amplification of the ground motion, which may have been influenced by the subsurface geology of the area. LYLY is located in an area that is mainly overlain by thick sediments, which is consistent with the geology (alluvial deposits) and geomorphology (marshland) (Figure 2) [13]. Thus, site amplification is the reason why there was a relatively high PGA value recorded in Brgy. Poblacion, Leyte. A PGA value of 0.052 g was recorded in Brgy. Poblacion, Kananga (station code: LYKN), which is located ~16 km southeast of the epicenter (Figures 2A and 3); this is equivalent to PEIS V (strong). This recorded PGA corresponded to the observed earthquake intensity felt in the area based on the intensity survey we conducted (Table 1 and Figure 2A).

The limited liquefaction occurrence can be attributed to several factors. First, the low magnitude of the earthquake (M_w 4.7) suggests that liquefaction was constrained to around 13 km from the epicenter, as discussed by Castilla and Audemard [29]. The documented liquefaction in Palaypay District (Figures 2 and 4B) was around 8 km from the epicenter, which is within the estimated maximum distance of liquefaction impacts. Another factor is the relatively short duration of ground shaking from the earthquake. According to the locals interviewed, ground shaking lasted for less than 10 **s**, which is consistent with the duration inferred by the PSMNet (Figure 3). The low-magnitude earthquake coupled with the short ground shaking duration corresponded to a lesser load required for the soil to lose its shear strength and liquefy. This is also the case with the distribution of landslides. Using the magnitude–distance relations of occurrences of earthquake-induced landslides in Greece [30], the maximum distance that landslides can occur from a M_w 4.7 earthquake is around 10 km from the epicenter. The landslides in Brgys. Calaguise and Palid Uno occurred 6 km and 9 km from the epicenters, respectively, both within the expected maximum distance of earthquake-induced landslides [30]. We should take note that the magnitude–distance relations used may be applicable on a regional scale or in specific tectonic and geologic settings; thus, the maximum distance of landslide potential may vary. Our information about the occurrence of liquefaction and landslides in a moderate-sized earthquake may add to the global database. It is also important to mention that the occurrence of liquefaction and earthquake-induced landslides for this moderate-sized earthquake coincided with the hazard zones reflected in the DOST-PHIVOLCS regional-scale earthquake-related hazard maps [31,32].

Significant damage to structures was concentrated around the epicentral area and can be attributed to poor construction practices, substandard construction materials, and improper building design. These observations were also identified in past damaging earthquakes [1–8], but our investigation also revealed that, even for a moderate-size earthquake, structural damages may also be expected. Despite the existence of the National Building Code in the Philippines and the National Structural Code of the Philippines [33], their non-implementation and poor regulation have contributed to the severe impacts after an earthquake. Thus, strict implementation of the building codes should be considered in rehabilitation and future development. Moreover, post-earthquake investigation and assessment can allow us to revisit and analyze the earthquake's impacts; validate and improve the seismic building codes and seismic hazard assessment; update the existing earthquake contingency and business continuity plans; and educate the different stakeholders by explaining the causes of the earthquake's impacts and damages.

Despite the low magnitude of this earthquake, significant impacts, including the occurrence of surface ruptures, liquefaction, mass wasting, and severe damage to structures, were documented. The peculiarity of this event may be attributed to the shallowness of the earthquake source. Moreover, site conditions, such as the geology, geomorphology, and soil properties, cause local amplification of ground motion that contributes to the severity of the impacts. Documentation and analyses of the impacts of these moderate-sized earthquakes should be conducted in the future, such as soil and water content analyses for liquefaction and hazard modeling.

This event may not be comparable with the impacts of the 2017 M_w 6.5 Leyte Earthquake [4], but the impacts of the 2023 M_w 4.7 Leyte, Leyte Earthquake remind us of the importance of earthquake preparedness. It is important to re-examine efforts related to earthquake preparedness and contingency planning made by the national and local government units as well as the community. While there are assumptions regarding seismic hazard assessment, efforts must be enhanced to develop resilience to earthquakes.

8. Summary and Conclusions

The 2023 M_w 4.7 Leyte, Leyte Earthquake is considered a moderate-sized earthquake, but in terms of its geologic, structural, and socio-economic impact, this earthquake is worthy of being discussed and analyzed in the scientific and disaster risk reduction and management fields. This paper emphasizes the importance of documenting earthquake impacts as a tool and guide for medium- and long-term earthquake risk assessment and resiliency, even for low-magnitude earthquakes. The significant geologic, structural, and economic impacts were documented for this event. The 8 km long surface rupture was the first documented surface rupture along the Philippine Fault with a magnitude <6. Liquefaction and mass wasting impacts occurred near the epicentral area, and its distribution coincides with previous studies. Based on the analysis of earthquake and field data, we suggest that the shallow hypocenter and the site conditions explain the significant impacts associated with this moderate-sized earthquake. We also reiterate the need for earthquake preparedness and proper adherence to the National Building Code of the Philippines in order to lessen earthquake impacts.

Author Contributions: Conceptualization, J.S.P.; field investigation and validation: J.S.P., D.C.E.L., D.J.L.B., R.C.C.C., C.J.M.L., R.N.G. and M.M.Y.Q.; formal analysis: J.S.P., D.C.E.L., D.J.L.B., R.C.C.C., C.J.M.L., K.D.B.L., R.N.G. and M.M.Y.Q.; writing—original draft preparation, J.S.P., D.C.E.L., D.J.L.B., R.C.C.C., C.J.M.L., R.N.G. and M.M.Y.Q.; writing—review and editing, J.S.P., D.C.E.L., D.J.L.B., R.C.C.C., C.J.M.L. and K.D.B.L.; figures and visualization, J.S.P., K.D.B.L., D.C.E.L., D.J.L.B., R.C.C.C., C.J.M.L. and M.M.Y.Q. All authors have read and agreed to the published version of the manuscript.

Funding: Funding for the DOST-PHIVOLCS QRT field activities and this research was provided by the DOST-PHIVOLCS Internal Funds based on the Philippine Government General Appropriations Act (GAA) of 2023.

Data Availability Statement: Data supporting this work, specifically the locations in the impact maps are available at DOST-PHIVOLCS upon request and are subject to agreements.

Acknowledgments: We acknowledge the members of the DOST-PHIVOLCS QRT who participated in the field investigation and the DOST-PHIVOLCS for logistical and office support. We would also like to thank the assistance of regional offices (Region VIII—Eastern Visayas) of the Office of Civil Defense and DOST and the municipality of Leyte for facilitating our investigation. This work was funded by the Philippine Government General Appropriations Act (GAA) of 2023.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Aurelio, M.A.; Dianala, J.D.B.; Taguibao, K.J.L.; Pastoriza, L.R.; Reyes, K.; Sarande, R.; Lucero, A., Jr. Seismotectonics of the 06 February 2012 Mw 6.7 Negros Earthquake. *J. Asian Earth Sci.* **2017**, *142*, 93–108. [CrossRef]
2. Lagmay, A.M.F.; Eco, R. Brief communication: On the source characteristics and impacts of the magnitude 7.2 Bohol earthquake. *Nat. Hazards Earth Syst. Sci.* **2014**, *14*, 2795–2801. [CrossRef]
3. DOST-PHIVOLCS Quick Response Team. 10 February 2017 Ms 6.7 Surigao del Norte Earthquake. PHIVOLCS Special Report. 2018. Available online: https://www.phivolcs.dost.gov.ph/index.php/publications/special-report (accessed on 15 December 2023).
4. DOST-PHIVOLCS Quick Response Team. 06 July 2017 Ms 6.5 Leyte Earthquake. PHIVOLCS Special Report. 2018. Available online: https://www.phivolcs.dost.gov.ph/index.php/publications/special-report (accessed on 15 December 2023).
5. DOST-PHIVOLCS Quick Response Team. 22 April 2019 Magnitude 6.1 Central Luzon Earthquake. PHIVOLCS Special Report. 2020. Available online: https://www.phivolcs.dost.gov.ph/index.php/publications/special-report (accessed on 15 December 2023).
6. PHIVOLCS. The 2019 Series of Earthquakes in Cotabato and Its Vicinity. Destructive Earthquakes in the Philippines. 2019. Available online: https://phivolcs.dost.gov.ph/index.php/earthquake/destructive-earthquake-of-the-philippines (accessed on 15 December 2023).
7. PHIVOLCS. The 2020 Magnitude 6.6 Masbate Earthquake. Destructive Earthquakes in the Philippines. 2020. Available online: https://phivolcs.dost.gov.ph/index.php/earthquake/destructive-earthquake-of-the-philippines (accessed on 15 December 2023).
8. Perez, J.S.; Llamas, D.C.E.; Dizon, M.P.; Buhay, D.J.L.; Legaspi, C.J.M.; Lagunsad, K.D.B.; Constantino, R.C.C.; De Leon, R.J.B.; Quimson, M.M.Y.; Grutas, R.N.; et al. Impacts and causative fault of the 2022 magnitude (Mw) 7.0 Northwestern Luzon earthquake, Philippines. *Front. Earth Sci.* **2023**, *11*, 1091595. [CrossRef]
9. National Disaster Risk Reduction and Management Council (NDRRMC). Progress Report No. 3 for Magnitude 5.3 Earthquake in Leyte, Leyte (Region VIII) 2023. Available online: https://monitoring-dashboard.ndrrmc.gov.ph/exports/export/incidents/2899 (accessed on 15 December 2022).
10. Tsutsumi, H.; Perez, J.S. Large-scale digital mapping of the Philippine fault zone based on aerial photograph interpretation. *Act. Faults Res.* **2013**, *39*, 29–37. [CrossRef]
11. Bautista, M.L.P.; Oike, K. Estimation of the magnitudes and epicenters of Philippine historical earthquakes. *Tectonophysics* **2000**, *317*, 137–169. [CrossRef]
12. PHIVOLCS. Earthquake Information. 2023. Available online: https://www.phivolcs.dost.gov.ph/2023_Earthquake_Information (accessed on 15 December 2023).
13. Aurelio, M.A.; Peña, R.E. (Eds.) *Geology of the Philippines*, 2nd ed.; Mines and Geosciences Bureau, Department of Environment and Natural Resources: Quezon City, Philippines, 2010; 532p.
14. Aurelio, M.A. Shear partitioning in the Philippines: Constraints from Philippine fault and global positioning system data. *Island Arc* **2000**, *9*, 584–597. [CrossRef]
15. Fitch, T.J. Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the western Pacific. *J. Geophys. Res.* **1972**, *77*, 4432–4460. [CrossRef]
16. Perez, J.S.; Cahulogan, M.T.; Abigania, M.I.T.; Daag, A.S.; Montes, A.G.; Canete, N.M.; Tsutsumi, H.; Solidum, R.S. The Philippine fault zone-Leyte segment: Site of catastrophic landslide and creeping movements. In Proceedings of the Abstracts of the 7th General Assembly of the Asian Seismological Commission and 2008 Seismological Society of Japan Fall Meeting 2008, Tsukuba, Japan, 24–27 November 2008; p. X4-084.

17. Tsutsumi, H.; Perez, J.S.; Lienkaemper, J.J. Variation of Surface Creep Rate along the Philippine Fault Based on Surveys of Alignment Arrays and Offset Cultural Features. In *AGU Fall Meeting Abstracts*; American Geophysical Union: Washington, DC, USA, 2016. Available online: https://ui.adsabs.harvard.edu/abs/2016AGUFM.T23A2907T/abstract (accessed on 15 December 2023).
18. Fukushima, Y.; Hashimoto, M.; Miyazawa, M.; Uchida, N.; Taira, T. Surface creep rate distribution along the Philippine fault, Leyte Island, and possible repeating of Mw ~ 6.5 earthquakes on an isolated locked patch. *Earth Planets Space* **2019**, *71*, 118. [CrossRef]
19. Dianala, J.D.B.; Jolivet, R.; Thomas, M.Y.; Fukushima, Y.; Parsons, B.; Walker, R. The Relationship Between Seismic and Aseismic Slip on the Philippine Fault on Leyte Island: Bayesian Modeling of Fault Slip and Geothermal Subsidence. *J. Geophys. Res. Solid Earth* **2020**, *125*, e2020JB020052. [CrossRef]
20. Nakano, M.; Kumagai, H.; Inoue, H. Waveform inversion in the frequency domain for the simultaneous determination of earthquake source mechanism and moment function. *Geophys. J. Int.* **2008**, *173*, 1000–1011. [CrossRef]
21. Bonita, J.D.; Kumagai, H.; Nakano, M. Regional moment tensor analysis in the Philippines: CMT solutions in 2012–2013. *J. Disaster Res.* **2015**, *10*, 18–24. [CrossRef]
22. Punongbayan, B.J.T.; Kumagai, H.; Pulido, N.; Bonita, J.D.; Nakano, M.; Yamashina, T.; Maeda, Y.; Inoue, H.; Melosantos, A.A.; Figueroa, M.F.; et al. Development and operation of a regional moment tensor analysis system in the Philippines: Contributions to the understanding of recent damaging earthquakes. *J. Disaster Res.* **2015**, *10*, 25–34. [CrossRef]
23. Lasala, M.; Inoue, H.; Tiglao, R.; Fan, Z.; Bautista, B.; Narag, I. Establishment of earthquake intensity meter network in the Philippines. *J. Disaster Res.* **2015**, *10*, 43–50. [CrossRef]
24. Bonilla, M.G. Minimum earthquake associated with coseismic surface faulting. *Environ. Eng. Geosci.* **1988**, *25*, 17–29. [CrossRef]
25. Wells, D.L.; Coppersmith, K.J. New empirical relationships among magnitudes, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seis. Soc. Am.* **1994**, *84*, 974–1002. [CrossRef]
26. Llamas, D.C.E.; Llamas, D.C.E.; Perez, J.S.; Constantino, R.C.C.; Buhay, D.J.L.; Legaspi, C.J.M. Surface rupture along the Leyte creeping segment of the Philippine Fault: The 2023 Mw 4.7 Leyte, Leyte earthquake. 2023; *in preparation*.
27. Tsuchida, H. Prediction and countermeasure against the liquefaction in sand deposits. In *Proceedings of the Abstract of the Seminar in the Port and Harbor Research Institute*; Ministry of Transport: Yokosuka, Japan, 1970; pp. 31–333.
28. Numata, A.; Mori, S. Limits in the gradation curves of liquefiable soils. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1–6 August 2004; p. 1190.
29. Castilla, R.A.; Audemard, F.A. Sand blows as a potential tool for magnitude estimation of pre-instrumental earthquakes. *J. Seismol.* **2007**, *11*, 473–487. [CrossRef]
30. Papadopoulos, G.A.; Plessa, A. Magnitude-distance relations for the earthquake-induced landslides in Greece. *Eng. Geol.* **2000**, *58*, 377–386. [CrossRef]
31. Department of Science and Technology—Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS). *Liquefaction Hazard Map of Leyte Province*; Department of Science and Technology—Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS): Quezon City, Philippines, 2009. Available online: https://www.phivolcs.dost.gov.ph/index.php/gisweb-hazard-maps (accessed on 15 December 2022).
32. Department of Science and Technology—Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS). *Earthquake-Induced Landslide Hazard Map of Leyte Province*; Department of Science and Technology—Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS): Quezon City, Philippines, 2009. Available online: https://www.phivolcs.dost.gov.ph/index.php/gisweb-hazard-maps (accessed on 15 December 2022).
33. Association of Structural Engineers of the Philippines. *National Structural Code of the Philippines*, 7th ed.; Association of Structural Engineers of the Philippines: Quezon City, Philippines, 2015.