Field Insights and Analysis of the 2018 Mw 7.5 Palu, Indonesia Earthquake, Tsunami and Landslides

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Abstract—A devastating Mw 7.5 earthquake and tsunami struck northwestern Sulawesi, Indonesia on 28 September 2018, causing over 4000 fatalities and severe damage to several areas in and around Palu City. Severe earthquake-induced soil liquefaction and landslides claimed hundreds of lives in three villages within Palu. The mainshock occurred at 18:03 local time at a depth of 10 km on a left-lateral strike-slip fault. The hypocenter was located 70 km north of Palu City and the rupture propagated south, under Palu Bay, passing on land on the west side of Palu City. The surface rupture of the earthquake has been mapped onshore along a 30 km stretch of the Palu-Koro fault. We present results of field surveys on the effects of the earthquake, tsunami and liquefaction conducted between 1–3 and 12–19 of October 2018. Seismic intensities on the Modified Mercalli Intensity (MMI) scale are reported for 375 sites and reach a maximum value of 10. We consolidate published tsunami runup heights from several field studies and discuss three possible interrelated tsunami sources to explain the variation in observed tsunami runup heights. Due to limited instrumentation, PGA and PGV values were recorded at only one of our field sites. To compensate, we use our seismic intensities and Ground Motion to Intensity Conversion Equations (GMICES) and Ground Motion Prediction Equations (GMPEs) developed for similar tectonic regions. Our results indicate that the maximum predicted PGAs for Palu range from 1.1 g for GMICES to 0.6 g for GMPEs.

Keywords: Field survey, modified Mercalli intensity (MMI), tsunami, soil liquefaction, ground motion.

1. Introduction

Indonesia is one of the most seismically active regions in the world, and is subject to frequent destructive earthquakes > Mw 6 (Cardwell et al.,

1980; Henry and Das, 2002; Saroso et al., 2008; McCaffrey, 2009; Okal, 2012). The island of Sulawesi is located within a broader convergent zone where the Pacific-Philippine plate and the India–Australia plate subduct underneath the Sunda plate at rates of 90 mm and 75 mm/yr, respectively (Fig. 1; Socquet et al., 2006; Spencer, 2011). Sulawesi and the surrounding region have a complex tectonic history of continuous terrane accretion and rifting, opening and subsequent closing of basins, subduction, and extension (Hall, 1987; Hall, 1996; Hall & Spakman, 2002; Nugraha and Hall, 2018). A prominent strike-slip fault in Sulawesi, the Palu-Koro fault (Fig. 1) passes directly through north-central Sulawesi and presents a high seismic hazard (Bellier et al., 2001; Socquet et al., 2006; Cipta et al., 2017; Watkinson and Hall, 2017). Furthermore, the numerous elongate narrow bays that form Sulawesi’s coastal morphology compounds risk for damaging tsunami waves (Metzner, 1981; Pelinovsky et al., 1997; Sutapa and Galib, 2016).

A devastating Mw 7.5 earthquake struck Sulawesi Island on 28 September 2018 at 18:03 local time (10:03 UTC), with an epicentre located 70 km north of Palu City (Fig. 2). Interferometric Synthetic Aperture Radar (InSAR) observations depict an approximately 170-km-long left-lateral strike-slip rupture that passed through the west side of Palu City (Fang et al., 2019). The surface rupture of the earthquake has been mapped onshore along a 30 km stretch of the Palu-Koro fault (Fig. 2). The earthquake triggered multiple local tsunamis as well as soil liquefaction and landslides that resulted in direct damage, economic loss, and a death toll of 4340 (Sangadji, 2019). The earthquake and tsunami destroyed large residential areas, damaging more than

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00024-021-02852-6>.

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Figure 1

Map of Indonesia showing the major tectonic structures. Fault traces taken from Hinschberger et al. (2005). The motions of the Australia (AUS) and Pacific (PAC)-Caroline (CAR)-Philippine Sea (PSP) plates are from the Nuvel 1 model (DeMets et al., 1990). The motion of the Sunda plate has been derived from GPS data (Wilson et al., 1998; Rangin et al., 1999). Plate motions are indicated with respect to Eurasia. AT Alor back-arc thrust, BS Banggai-Sula, CT Cotabato Trench, HS Halmahera subduction, LFF lowland fault zone, MF Matano Fault, NGTB New Guinea thrust belt, NST North Sulawesi Trench, NT Negros Trench, PFZ Philippine Fault Zone, PKF Palu Koro Fault, SFZ Sorong Fault zone, ST Sulu Trench, TAFZ Tarera Aiduna Fault zone, TS Tolo subduction, WT Wetar back-arc thrust

70,000 houses and numerous schools (Maidiawati et al., 2020).

Two field surveys were conducted between October 1–3 and 12–19, 2018. The goals of our field survey were three-fold: (1) to document structural damage caused by shaking and quantify these observations using the Modified Mercalli Intensity (MMI) scale; (2) to document the characteristics of the tsunami, including the wave height, inundation distances, and runup heights; and (3) to evaluate the effects of landslides and liquefaction. This study adds to previous studies by presenting a more comprehensive quantitative assessment of the distribution of damage associated with earthquake ground motions in Palu and its surrounding areas. We present for the first time a macroseismic intensity map for the Palu

event with seismic intensity (MMI) values documented for 375 site locations based on observed exterior and interior damage to buildings. None of the 375 sites were affected by tsunami inundation.

The origin of the 2018 Palu tsunamis has been the subject of debate, as the Palu earthquake occurred principally on land and exhibited a strike-slip mechanism that is usually not associated with the generation of large tsunamis (Muhari et al., 2018; Mikami et al., 2019; Omira et al., 2019; Putra et al., 2019; Sepulveda et al., 2020). We present a summary of tsunami runup heights around the perimeter of Palu Bay from those published tsunami surveys and summarize three possible sources for the generation of the tsunami: (1) submarine landslides; (2) a submarine fault step-over (to the east) accompanied by

Figure 2

Map of significant tsunamigenic earthquakes in northern Sulawesi since 1968, with Palu as the most recent. Each letter (A–E) corresponds with a previous major event, each labelled by date (day/month/year). Stars represent the epicenters for each event, with the red star indicating 2018 Palu mainshock. Focal mechanisms were obtained from the USGS earthquake catalogue and are shown in black and white

thrust faulting; and (3) horizontal motion of the topography beneath the bay.

Ground motion data such as Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) are commonly used when assessing the seismic response of structures. However, few instrumental recordings are available for the Palu

event. We address this gap by using published ground motion prediction equations to estimate the levels of ground shaking at our 375 MMI site locations. We also estimate the ground motions at the sites that experienced severe ground failure and soil liquefaction.

2. Previous Work

There are several post-event field surveys of the 2018 Palu earthquake and tsunami. Table 1 summarizes the main results of studies based on data collected up to seven weeks after the earthquake. The term ‘submarine landslide’ refers to a mass movement of soil underwater due to slope failure, often triggered by earthquake ground shaking (Mikami et al., 2019). The ‘watermark’ measured in the field surveys refers to the maximum flow depth above ground level at a specific site (Paulik et al., 2019). ‘Tsunami runup’ is the elevation above mean sea level at the location of furthest inundation by the tsunami wave (Satake et al., 2013). The observations presented in Table 1 include: (1) damage from the earthquake, and (2) tsunami measurements, including runup heights and inundation distances. Some of these studies also infer the source of the tsunami based on field observations, together with the arrival time of the first tsunami inundation. Table 2 summarizes numerical models used to quantify the source mechanism(s) of the tsunami and/or simulate the tsunami arrival times for one or more waves. Table 3 shows the studies that are based on secondary (i.e., non-field) data. These studies use various imaging techniques and geospatial tools to quantify changes in the physical landscape and analyse the role that irrigation systems and local fluctuations in the water table could have played in contributing to slope failures and/or the generation of the tsunami.

We consider many published tsunami source models to date and provide a synthesis of these results, as well as develop ideas on three possible interrelated tsunami source mechanisms. We also study areas that experienced extreme soil liquefaction and landslides, then estimate expected PGA and PGV values at these sites based on existing GMICEs and GMPEs developed for tectonic regions similar to Central Sulawesi.

2.1. Previous Tsunamiogenic Earthquakes in Sulawesi

A Mw 7.6 earthquake generated a tsunami on 14 August 1968 in the region of Manimbaja Bay north (Fig. 2, label A), approximately 40 km northwest of the 28 September 2018 epicenter. The earthquake had

a normal faulting mechanism (Fitch, 1970). The tsunami measured 10 m in height and inundated up to 500 m inland (Pelinovsky et al., 1997), killing 200 people, destroying 800 coastal homes, and inundating coconut plantations (BNPB, 2010).

Another notable tsunamigenic Mw 7.9 earthquake occurred on 1 January 1996 on a shallow thrust fault (Fig. 2, label B) causing a 3.4 m high tsunami that carried seawater 300 m inland (Widiyanto et al., 2019). Nine people were killed, 53 injured and more than 400 homes were destroyed (Pelinovsky et al., 1997). This event was followed by two significant aftershocks, including a Mw 6.6 earthquake on 16 July 1996 (Fig. 2, label C) and a Mw 7.0 earthquake on 22 July 1996 (Fig. 2, label D) (Gomez et al., 2000). Neither of these aftershocks generated a tsunami.

The most recent large earthquake in Sulawesi prior to 2018 was the 16 November 2008 Mw 7.3 earthquake (Fig. 2, label E), which was located farther north of the island near Gorontalo, at a depth of 30 km on a south-dipping megathrust (De et al., 2011). Although tsunami warnings were issued for the region, these were later cancelled; the earthquake caused few casualties (Widiyanto et al., 2019).

2.2. The 2018 Palu Earthquake

2.2.1 Mainshock

The 2018 Palu earthquake initiated on an onshore fault located north of the mapped Palu–Koro fault (Fig. 3A). The epicentral location has been derived from the USGS earthquake catalogue and is in agreement with various studies (Fang et al., 2019; Socquet et al., 2019; Song et al., 2019; Ulrich et al., 2019). The rupture propagated predominantly towards the south through one or more transpressional step-overs before it reached the more active Palu–Koro fault (Mason et al., 2019). The rupture expanded rapidly from the hypocenter towards the north and south along the strike direction during the first 8 s, and then to the south, sustaining an average rupture speed of 4.1 km/s (Fig. 3B; Bao et al., 2019; Fang et al., 2019). This high average rupture speed indicates unusual earthquake behaviour, differing from more common supershear events that typically

Table 1

Summary of post-earthquake and tsunami field surveys

Published field surveys		
Author(s) and date	Method(s)	Observations and interpretation(s)
Sassa and Takagawa (2018)	Documented observations of submarine landslides along the coast	<p>Ground shaking</p> <p>Evidence of much localised liquefaction-induced landslides. The majority of the Sulawesi tsunami height was caused by submarine landslides, as characterised by liquefied sediment flows</p> <p>Tsunami</p> <p>Estimated that less than 20% of the Sulawesi tsunami height was related to tectonic processes</p>
Arikawa et al., (2018)	Documented observations of submarine landslides along the coast	<p>Ground shaking</p> <p>Subsidence observed at a minimum of seven points along the coast. This is consistent with eyewitness reports and is suggested to be the source of the tsunami generation</p> <p>Tsunami</p> <p>Tsunami runup heights ranged from 2 to 6 m in Palu Bay. Low tsunami height measurements at the mouth of the bay suggest it is extremely likely that major tsunamis occurred primarily within the bay</p>
Muhari et al., (2018)	Tsunami runup heights measured, analysis of tsunami waveforms, documented tsunami observations from eyewitness accounts	<p>Ground shaking</p> <p>Tsunami hypothesized to be generated by an underwater landslide occurring inside Palu Bay, which was triggered by earthquake induced ground shaking</p> <p>Tsunami</p> <p>The tsunami had a relatively short period (the first tsunami wave arrived a few minutes after the mainshock) and caused devastation as far as 300 m inland. Water-marks up to 8 m high were observed near the coast, which decreased rapidly when the tsunami reached dense development 150 m inland. Eyewitness accounts indicate that the tsunami did not enter the bay through the opening to the north but obliquely from an area inside Palu Bay</p>
Mulchandani et al. (2019)	Structural engineering and earthquake reconnaissance report documented observations of submarine landslides and structural damage	<p>Ground shaking</p> <p>Ground shaking did not damage or only slightly damaged low-rise reinforced concrete structures with unreinforced masonry fills. A total of 13 locations showed evidence of landslides along Palu Bay</p> <p>Tsunami</p> <p>Tsunami waves were caused by a series of submarine landslides</p>
Syamsidik et al., (2019)	Documented observations of submarine landslides along the coast	<p>Ground shaking</p> <p>Sporadic distribution of submarine landslides observed in several locations around Palu Bay</p> <p>Tsunami</p> <p>Greatest flow depths were found at Talise Beach, with the greatest flow depth found in Tondo village, on the northeastern edge of the bay. Evidence of submarine landslides thought to have generated the tsunami, and were also implicated by the direction of the tsunami waves</p>

Table 1 *continued*

Published field surveys		
Author(s) and date	Method(s)	Observations and interpretation(s)
Paulik et al., (2019)	Documented structural damage of buildings (based on tsunami flow depths), and damage to roads and electrical infrastructure from ground shaking in Palu City	Ground shaking 32 light-timber buildings were surveyed, with 20 in Damage Level (DL3) condition (complete damage/collapse). Irreparable building damage (DL2) was observed when flow depths exceeded 0.4 m above first finished floor levels and complete damage when depths exceed 1.2 m Tsunami Tsunami flow depths measured at 371 building sites ranged from 0.1 to 3.65 m
Putra et al., (2019)	Collection of sediment deposits along six coastal sites	Ground failure Earthquake induced submarine landslides to have contributed to tsunami generation Tsunami Tsunami runup height was less than 8 m with a maximum inundation distance of 310 m. Deposits show simple fining upward sequences, consistent with typical tsunami deposits elsewhere in the world
Widiyanto et al., (2019)	Tsunami runup height and tsunami inundation measurements	Tsunami Measurements of runup tsunami waves and inundation taken in 18 sites, mostly in Palu Bay, with runup heights ranging from 2 to 10 m and inundation distances ranging between 80 and 510 m. Short wave tsunami wave arrival times estimated at 3–8 min from the time of the main shock
Omira et al., (2019)	Tsunami runup height and tsunami inundation measurements	Ground failure Ten large coastal sectors that collapsed into the sea of Palu Bay were identified Tsunami 78 tsunami runup and inundation height measurements, with measured values reaching 9.1 m for the runup height and 8.7 m for the inundation height
UNESCO and IOC (2019)	Ground and air reconnaissance, 3D LIDAR, drones, and video footage of landslides	Ground failure Evidence of submarine landslides observed along the east and west coast Tsunami Submarine landslides acted as secondary contributions to the tsunami
Mikami et al., (2019)	Tsunami runup height measurements, structural damage observations documented using an Unmanned Aerial Vehicle (UAV)	Ground shaking Partial to complete collapse of low-lying coastal planes within 200 m from the shoreline Tsunami In the southern shores of Palu Bay, tsunami runup heights of more than 4 m were measured (maximum 6.8 m). In the north and close to the mouth of the bay tsunami runup heights were less than 3 m
Maidiawati et al., (2020)	Observations of structural damage to buildings documented	Ground shaking Several types of damage sustained in reinforced concrete (RC) buildings such as collapse due to soft story construction, damage to beam-column-joint, failure of short column, shear failure of the column, and masonry infills. Results show that RC buildings could have survived during the earthquake if they had a high strength capacity in large plastic deformation

Table 1 *continued*

Published field surveys		
Author(s) and date	Method(s)	Observations and interpretation(s)
Gallant et al. (2020)	Field mapping of the local morphology using unmanned aerial vehicle (UAV) flights, documented observations from eyewitness interviews	Ground failure Observed morphological features and eyewitness accounts show the Sibalaya landslide (30 km south of Palu) initiated near a change from steep to shallow terrain. Progressive liquefaction and/or void distribution are speculated to have contributed to the timing and delay of initiation
Mas et al., (2020)	Damage from tsunami loading was documented using optical satellite imagery, machine learning and remote sensing utilised on multi-sensor and multi-temporal satellite images (MLRS)	Tsunami The characteristics of Palu structures exhibited higher fragility in response to tsunamis than fragility functions developed after the 2004 Indian Ocean tsunami in Banda Aceh Results from tsunami fragility functions, (cumulative distribution functions that express the probability of a structure reaching or exceeding a particular damage state in response to a specific value of tsunami intensity measure or another engineering demand parameter), show that the tsunami damage observed from the Donggala tsunami had a slightly lower damage probability (0–5 m inundation depths) than the 1993 Hokkaido Nanseioki tsunami
Stolle et al., (2020)	Structural damage documented for local infrastructure and buildings	Ground shaking Damage to timber buildings along the coast was widespread, though reinforced concrete structures for the most part survived

show an initially lower subshear rupture speed (Fang et al., 2019).

Many studies have investigated the source geometry and rupture kinematics of the 2018 Palu earthquake (Yolsal-Cevikbilen and Taymaz, 2019; Fang et al., 2019; Bao et al., 2019; Socquet et al., 2019; Liu et al., 2020; Bacques et al., 2020). Here, we consider the rupture model of Fang et al. (2019) as the preferred model (Fig. B) due to the combined data sets used and the extensive data analysis undertaken. The model of Fang et al. (2019) combines data from Advanced Land Observing Satellite-2 (ALOS-2) and InSAR, together with broadband regional seismograms to illustrate the total slip distribution across four visible asperities (identified as areas of large slip) that formed during the slip pulse propagation.

In Fang et al. (2019), Asperity III, is associated with the region of greatest slip, and is located approximately 3 km west of Palu City, and extends south along the Palu–Koro fault and through the village of Balaroa (Fig. 3). A maximum slip of 6.5 m was calculated on a shallow part of the crust in the

same region as Asperity III, and is consistent with the greatest seismic moment released along this segment as modeled by Bao et al. (2019) and Socquet et al. (2019).

2.2.2 Foreshocks and Aftershocks of the 2018 Palu Earthquake

From 28 August 2018 until the Mw 7.5 mainshock on 28 September 2018, fifty-three earthquakes were recorded with magnitudes ranging from Mw 4 to Mw 6.1 (Fig. 3). Data derived from the USGS earthquake catalogue show that twelve foreshocks ($\geq$ Mw 4) were generated on the morning of the mainshock, including a Mw 6.1 foreshock at 14:59 local time (04:59 UTC). The Mw 6.1 foreshock was located approximately 40 km southwest of the mainshock (Fig. 3). Cross-correlation of regional seismograms for the foreshock sequence three hours prior to the mainshock indicate that the foreshocks were not repeated ruptures of the same patch by fault creep; the Palu mainshock was triggered by a cascade of

Table 2

Summary of studies that used numerical modelling to identify the tsunami source(s)

Additional studies		
Tsunami source modelling		
Author and date	Method	Observations and interpretation(s)
Carvajal et al., (2019)	Analysis of satellite imagery from Google Earth and a collection of 38 amateur and closed-circuit television videos from nearby locations. Spectral analysis and ray-tracing analysis of tide gauge records	Video footage shows tsunami inundation within 1–2 min after the main shock with periods shorter than those recorded by the local tide gauge, which cannot be explained by the earthquake fault slip alone Tsunami source Post-tsunami coastline surveys combined with video evidence and modelled tsunami travel times suggest that submarine landslides contributed to tsunami generation
Heidarzadeh et al., (2019)	Spectral analysis and backward ray-tracing analysis of tide gauge records and tsunami waveform data	Maximum tsunami wave height at tide gauge stations at Pantaloan (within Palu Bay) and Mamuju (outside the bay) were 380 and 24 cm, respectively. Results from backward tsunami ray tracing analysis shows the southern part of Palu Bay, around the latitude of 0.82° S, as the most likely location of a potential landslide Tsunami source A large submarine landslide contributed to and intensified the Sulawesi tsunami
Gusman et al., (2019)	Tsunami source model using a combination of landslide and coseismic sources Seafloor vertical displacement was estimated using tsunami wave heights and land SAR data	Ground subsidence (the earthquake lowered the ground level) of up to 1 m and a tide level of 1 m during the event enhanced the tsunami impact in Palu City Tsunami source The series of tsunami waves were caused by a combination of seafloor uplift and multiple landslides. Seafloor vertical displacement was evaluated to be the source of the largest tsunami
Takagi et al., (2019)	Bathymetric survey and analysis of tsunami waveforms	Simplified numerical modelling suggests that the landslide tsunami propagated as an edge wave and split into two separate waves due to the presence of an underwater shallow area just north of Palu City Tsunami source The two initial tide gauge waveforms were most likely generated by a landslide at the southwestern shore of Palu Bay
Ulrich et al., (2019)	Coseismic deformation modelling	Landsliding may not have been the primary source of the tsunami Tsunami source A tsunami source related to earthquake displacement in the strike-slip system is probable
Sepulveda et al., (2020)	Earthquake source modelling using InSAR data, tsunami inversions using video-derived time histories and tide gauge records	Coseismic deformation played only a minor role in generating the Palu tsunamis. Several landslides in Palu Bay were the major contributors to the tsunamis Tsunami source A combination of coseismic deformation and landslides
Williamson et al., (2020)	Static offsets from geodetic observations used to constrain coseismic slip and are compared with tsunami observations from tide gauge and survey data	Overall, the model fits to some localized runup measurements but overall fails to reproduce both the timing and scale of the tsunami Tsunami source The leading cause of the Palu tsunami is a complex combination of coseismic deformation and shaking induced landsliding

Table 2 *continued*

Additional studies		
Tsunami source modelling		
Author and date	Method	Observations and interpretation(s)
Natawidjaja et al., (2021)	Combined four data types—LiDAR, multi-beam bathymetry mapping, field surveys and seismic reflection—to map the fault ruptures from the Palu earthquake and improve the accuracy of measured offsets. These results form an important component of tsunami modelling	

Table 3*Summary of landslide and liquefaction studies using secondary data*

Additional studies		
Landslide and liquefaction analyses		
Author and date	Method	Observations and interpretation(s)
Bradley et al., (2019)	Quantitative mapping of deformation within landslide areas using sub-pixel correlation of 3 m resolution Planet satellite imagery	Major alluvial landslides were a direct consequence of irrigation that activated a previously non-existent liquefaction hazard. Wet rice cultivation raised the water table to near ground level, saturating sandy alluvial soils and enabling extensive and large-displacement lateral spreads on slopes less than 1.5°
Watkinson and Hall (2019)	Analysis of satellite imagery to identify the role of communal irrigation systems in contributing to coseismic landslides	Landslide activity was limited to irrigated terrain mostly sloping $\geq 1.5^\circ$. Slopes above the irrigation network did not fail, despite being steeper, indicating that irrigation water was a more important control on landslides than slope alone. Results from correlation coefficient and principal component analysis shows that irrigation parameters (distance to canal, nodes and other channels) correlate strongly with ground displacement
Mason et al., (2021)	Post-earthquake reconnaissance to investigate three large landslides along the east of Palu Bay	The flowslides were not coseismic but instead occurred several minutes after earthquake shaking ended. An adjacent unlined agricultural canal played a critical role in the failure sequence by artificially raising the groundwater level, thereby increasing the susceptibility to liquefaction and loss of soil strength

foreshocks, not by a slow-transient slip (Sianipar, 2020). We define an aftershock as any earthquake that occurred after the mainshock and has a location within one fault length of the mainshock's rupture plane. The aftershock pattern exhibits a N–S trend that is ~ 200 km in length and ~ 50 km in width (Supendi et al., 2019). Approximately 90% of the aftershocks are located to the east of the causative fault line (Fig. 3).

3. Methodology

3.1. Seismic Intensity Surveys

The first survey was undertaken in Palu by the local Badan Meteorologi, Klimatologi, dan Geofisika (BMKG 2018) office by two teams led by the third author of this report between 1 and 3 October 2018 as an immediate response to the earthquake. The overall purpose of the survey was to document the structural

Figure 3

a Map showing the distribution and magnitude of the foreshocks and aftershocks that occurred between 28/09/18 and the end of 28/10/2018. The red star represents the epicenter of the Mw 7.5 Palu mainshock. Symbol size is proportional to the earthquake magnitude, **b** coseismic slip distribution of the Mw 7.5 mainshock from the joint inversion of InSAR and broadband regional seismograms, taken from Fang et al. (2019). Gray arrows indicate the slip directions of each fault patch. Gray dashed lines are slip contours derived from Socquet et al. (2019) with a slip magnitude > 1 m and a step size of 0.5 m

damage caused by ground shaking, take in-field measurements of tsunami runup heights and tsunami inundation distances, and identify areas impacted by extreme soil liquefaction. The second survey was completed by the first author of this report between 12 and 19 October 2018 to further assess and document the extent of damage caused by ground shaking, tsunamis, and soil liquefaction. The total area covered for both surveys was 150 km north-to-south and 50 km east-to-west, both of which started in Palu City. A total of 375 sites were visited for both surveys. Approximately 3–5 digital photos were taken within a couple of hundred meters of each site, and all site locations were documented using a handheld GPS receiver. All major locations, including Palu City, towns and villages are presented in Fig. 4.

Both surveys determined seismic intensities using the procedures employed by Cilia et al. (2017) and Smith and Mooney (2021). We assigned a seismic intensity value based on the MMI scale as described by Dewey et al. (1995) to each site that was not inundated by the Palu tsunamis (Widiyanto et al.,

2019; Omira et al., 2019 and Mas et al., 2020). At each site, inspections were made over several blocks with structural and non-structural effects photographed and documented, as well as descriptions of different building types. Cracks found in walls were closely examined and measured diagonally with a measuring tape which were documented in field notes. We note that areas inundated by a tsunami cannot be assigned an MMI value since ground shaking damage will have been replaced by tsunami damage; thus, any data points inside of this tsunami boundary were omitted. The highest possible MMI based on this scale is 12, and the maximum MMI assigned to our field observations is MMI 10. The definition of each MMI value is provided in Table 4. Soil liquefaction and landslides were studied using field investigations and aerial imagery. Sites that experienced damage primarily from ground failure have not been included in our MMI assignments. A list of each site visited and its corresponding MMI value can be found in Table 1 of the Supplemental Material. The combined datasets from the two surveys includes over 8000 geotagged photos, ground

Figure 4

Map of northwest Sulawesi (see 'study area' in Fig. 1). Black dots are the towns and villages visited between 1–3 October and 12–19 October 2018. The black dotted line represents the fault trace estimated by the BMKG Palu office. The orange dotted lines correspond to Asperity III, a coseismic slip distribution area, modelled by Fang et al. (2019) (see Fig. 3 for reference). Green dots are the main villages visited to record tsunami data, including runup heights/runups and inundation distances

co-ordinates, measured offsets, elevation data, and other field measurements and observations.

Four detailed interviews were also conducted with local eyewitnesses in the affected areas. The questions were prepared in English, asking each person to describe what they felt and observed during the earthquake and tsunami. Residents were interviewed by BMKG in Bahasa Indonesian with English translations provided. Two interview participants were survivors of a landslide, and one participant was a survivor of the tsunami. Questions included where each participant was located at the time of the mainshock, what they were doing at the time, whether they could describe their surroundings as the ground shaking began, and what they were thinking and feeling. In addition, the tsunami survivor was asked about the arrival time of the tsunami waves

and inundation distances of the waves onshore. The translated transcripts from the interviews are included in the Supplemental Material.

3.2. Tsunami Survey

The local BMKG office deployed two field teams who worked on a post-tsunami survey. They systematically documented in-field measurements of tsunami heights, runups and tsunami inundation distances along the eastern and western coasts of Palu Bay. Tsunami heights and runups were measured depending on the situation at each site, with a summary definition of each measurement shown in Borrero et al. (2020). Inundation limits were estimated from swept up debris and personal belongings onshore, video and photographic evidence taken by

Table 4

Descriptions of MMI values assigned in the field

MMI	Description
10	Only few masonry structures remained standing, broad fissures were found in the ground, and significant earth slumps were identified in soft ground. For a MMI 10 to be assigned, the majority of masonry and frame structures were destroyed along with foundations, and the ground was severely cracked and transport rails were bent
9	Considerable damage was observed in well-engineered structures. This includes when well-designed frame structures were thrown out of plumb, when substantial masonry buildings suffered extensive damage, and when buildings were completely shifted off their foundations
8	Slight to moderate damage in well-engineered structures, such as reinforced concrete buildings, or a significant amount of damage in poorly- constructed structures
7	Considerable amount of damage, such as partial to total collapse, in informally constructed (i.e., non-engineered) buildings and low-rise homes, or if there was minimal damage to reinforced concrete and well-constructed structures
6	Poorly built or old masonry structures with no concrete or structural reinforcements. An MMI of 6 was also assigned to regions with slight damage such as cracked or displaced paving stones or collapsed masonry walls
5	Sites with cosmetic damage, such as minor cracks in the plasterwork or small cracks in masonry buildings. Other structural and non-structural witness information obtained from interviewing locals was also used to assign MMI values of 5. Interviews also included information about what they saw and experienced during the earthquake ground shaking

local residents, and through local interviews. The tsunami survey equipment included a laser pointer, a 3 m ruler and rolling distance-measurement device, a GPS receiver and camera. Measurements of tsunami runup heights and inundation distances were taken at 26 site locations (see Table 2 in Supplemental Material). These results can be used for the calibration and validation of hydrodynamic models for the Palu tsunami.

3.3. Microzonation Survey

The fifth field team from the local BMKG office conducted a shallow seismic shear-wave velocity survey, also known as a microzonation survey. The purpose of the survey was to document the soil

properties in the zones of liquefaction and determine the average shear wave velocity for three villages impacted by extreme liquefaction—Balaroa, Petobo, and Jonooe-Sidera (Fig. 4). This microzonation survey was conducted between June and August 2018 was provided to the central government in November 2018. Part of this work also involved mapping approximately 30 km of the on-land surface rupture along the Palu–Koro fault (Fig. 3).

Microzonation surveys were conducted using two methods. The multi-channel surface wave analysis (MASW) method was employed at 206 sites using a hammer source and 24-channel geophone array. These data provided a measurement of the shear-wave velocity in the upper 30 m. The spatial autocorrelation method (SPAC) was employed at 23 sites using seven geophones in two concentric arrays that recorded ambient noise. This passive-source method provided the shear-wave velocity to a depth of about 500 m.

3.4. Local Building Construction Techniques

A summary of the construction practices within Central Sulawesi is relevant to an understanding of types of structural damage observed and the assignment of MMI values. The construction of low-rise houses in Palu and neighbouring areas can be categorised into three main types: timber ‘stilt’ houses, timber framed houses with infills and confined masonry (clay brick and concrete block) (EEFIT, 2019). Each category represents a different era of non-engineering building practices in the region. Stilt houses are commonly found in Palu Bay and include diagonal struts on the ground floor frame in order to improve stability under lateral loads (EEFIT, 2019). The oldest construction practice of the three categories is timber framed houses with infills, which was built in colonial times, and includes infills made either from mortar reinforced with barbed wire or barbed mesh or are masonry (red clay brick or concrete block) (Mansur, 2006). Confined masonry is the most commonly used in Palu and is a load bearing type of construction in which the brick masonry walls are confined with reinforced concrete elements, called tie-elements (EEFIT, 2019). Multi-story buildings are predominantly

constructed using reinforced concrete and moment frames with unreinforced masonry infill walls (STEER, 2019). Moment frames are designed to resist strong earthquake ground shaking without a significant loss of strength or stiffness (Moehle and Hooper, 2008).

The Indonesian code for reinforced concrete construction is modelled on the American Concrete Institute ACI-318 Build Code and contains various design requirements for reinforced concrete buildings (STEER, 2019). This would include:

- Requirements to ensure “strong-column, weak-beam” performance for moment resisting frames.
- Requirements for joint confinement at beam-column connections.
- Requirements for enhanced confinement of column members supporting walls that do not continue to the foundation.
- Requirements for shear design of beams and columns to avoid shear failure prior to formation of flexural hinges.

4. Results

4.1. Earthquake Ground Shaking Effects

The southern portion of the earthquake surface rupture passed through the west side of Palu City (Fig. 3), along the Palu–Koro fault, and generated up to 4 m of left-lateral slip at a location 2 km south of Palu Bay (Fig. 5A). The ground surface motions caused severe structural damage in Palu City, including partial or complete collapse of several one- and two-story structures (Fig. 5B). These sites were assigned an MMI value of 7. Moreover, moderate to heavy damage was evident in well-designed structures within Palu City, such as three and four-story hotels and shopping centres, constructed with reinforced concrete foundations and walls (Fig. 5C). An MMI value of 8 was assigned at these sites. Damage to these reinforced concrete structures included damage to beam-column joints, shear failure of short columns, and collapse of masonry infills (Paulik et al., 2019; Mulchandani et al., 2019 and Maidiawati et al., 2020). Although

reinforced concrete frame structures often performed well, several multi-story buildings experienced serious damage with shear failure of walls. Moderate damage such as cracking and occasional wall collapses were sustained by two and three-story unreinforced concrete structures (STEER, 2019). Clay-brick masonry walls between 5 and 6 cm thick and infilled columns were also highly susceptible to shear failure from tsunami loading greater than 1 m in depth (Paulik et al., 2019).

Large civil structures such as the Palu IV bridge suffered severe structural damage (Fig. 5D), and was assigned an MMI value of 9. The bridge was constructed in 2006 from steel and composite steel girders. Eyewitness reports suggest that failure of the supporting pillars caused the collapse of the bridge.

Figure 6 presents a map with all 375 MMI values, ranging from MMI 5–10. The location of the fault rupture, as defined by surface offsets, is also depicted. MMI values are not assigned: (1) in regions affected by the tsunami, and (2) in regions with liquefaction. Hence, our MMI map indicates only effects due to ground shaking. Whereas MMI values of 7 and 8 are the most common in Fig. 6, the MMI values range from 5 to 10, with some adjacent sites showing variability of 3–4 units of seismic intensity. A peak intensity was estimated between 7 and 8 for the Palu event by the USGS Shakemap (Wald et al., 2005) and the BMKG Shakemap.

4.2. Tsunami Effects

The Palu earthquake unexpectedly generated multiple tsunamis (Williamson et al., 2020) that caused severe damage and, in some cases, complete coastal inundation to low-lying settlements along Palu Bay (Fig. 7A and B). Other evidence of tsunami inundation included debris deposited along the shore, mudlines marked on buildings, and local reports from eyewitnesses. The maximum tsunami run up height measured 11.6 m in southeast of Palu Bay, and the maximum tsunami inundation was 468 m on Lere Beach, west Palu. Two locals interviewed in Palu City noted the arrival time of two tsunami waves, the first arriving approximately ten minutes after the earthquake ground shaking, and the second wave three minutes later. Tsunamis generated by

Figure 5

a Field photos of structural damage caused by strong ground shaking from the 2018 Palu earthquake (see Fig. 4 for locations)—Palu City. Evidence of a 4.7 m offset on a major road (See Table 3 in Supplemental Material for coseismic displacement values as well as a summary map of measured offset locations). View is approximately West 20° South. **b** Palu City. Structural damage includes the complete collapse of some one- and two-story structures made from timber. Broken sewage pipes have created puddles of polluted water on major roads and caused disruptions in traffic flow. **c** Ramayana shopping centre; a 3-storey structure located in Palu City made with reinforced concrete foundations and walls. Red circles highlight evidence of structural damage to beam-column joints and shear failure of short columns and masonry infill. **d** Palu IV bridge, located along Talise beach which has collapsed due to very strong ground shaking. Prior to collapse, the bridge was upheld by three pillars, each approximately 4 m high. Seafloor displacement, possibly triggered by under-thrusting beneath Palu Bay, likely caused the middle pillar to collapse, creating an inward ‘pancake’ collapse of the rest of the bridge

submarine landslides often have exceptionally large runup heights close to the source area but have more limited far-field effects than tsunamis caused by thrust faults (Harbitz et al., 2006). We present a summary map of primary field observations of runup heights taken during the BMKG field survey. In total, 26 values were recorded. These values are in good agreement with previously published tsunami surveys (Fig. 8). The distribution of runup heights range from 3.9 to 11.3 m compared to 1.0 to 12.2 m in other published studies. The highest runup values of 11.3 m and 12.2 m were recorded on the southeast

of Palu Bay at 0.52° S. The runup values decrease further north along Palu Bay between 0.40° S and 0.45° S, with an average value of 8.9 m for BMKG and 3.5 m for other tsunami surveys.

4.3. Soil Liquefaction and Landslide Effects

The landslides in Palu were initiated by strong earthquake ground shaking, with extensive landslides and soil liquefaction striking the villages of Balaroa, Petobo and Jonooge-Sidera (Fig. 9). We note that we define ‘soil liquefaction’ as a partially or fully

Figure 6

Seismic intensity map of the 375 sites surveyed in north Sulawesi. The black rectangle in the inset map denotes the full extent of our study area. Each coloured data point corresponds with an assigned value according to the Modified Mercalli Intensity scale (Dewey et al., 1995). The blue dotted lines represent an area of high slip (Asperity III) (see Fig. 3 for reference) that has been derived from Fang et al. (2019)

saturated soil substantially losing strength as a result of strong coseismic ground motion; this may lead to 'extensive landslides', which we consider here as large, disruptive mass movements over a larger area (Sassa and Takagawa, 2018; Bradley et al., 2019; Watkinson and Hall., 2019; Gallant et al., 2020; Mason et al., 2021). Optical satellite imagery taken on 1 October 2018 was used to identify regions of extreme soil liquefaction in the same three villages, with maximum landslide inundation areas outlined (Fig. 9). These major landslides have also been identified in various studies (Bradley et al., 2019; Watkinson and Hall, 2019; Mason et al., 2021).

Soil conditions are also hazardous; results from a microzonation survey conducted by BMKG within three days of the mainshock indicate that liquefaction sites consisted of soft soil. The results from the

microzonation survey show that the maximum average shear wave velocity (V_{s30}) values were 552.57 m/s for Balaroa, 464.06 m/s for Petobo, and 350 m/s for Jonooge–Sidera. Specific field observations of sand (dominant) and loose silt were documented as part of the soil profile at Jonooge–Sidera (see Figs. 4 and 6 for location).

Aerial imagery from Google Earth Pro suggests the average slope angle measured within Balaroa was 2.6° , compared to 2.4° within Petobo. This is in agreement with Watkinson and Hall (2019) who concluded that landslide activity was limited to irrigated terrain mostly sloping $\geq 1.5^\circ$. The total area of the Petobo landslide was approximately four times larger than Balaroa, with an estimated landslide inundation area of 1.7 km^2 ; Jonooge–Sidera village experienced the largest inundation across an

Figure 7

a Field photos of devastation caused by localized tsunamis from the 2018 Palu earthquake (see Fig. 4 for locations) Approximately 200 m inland of Talise beach. Evidence of tsunami inundation that has saturated land. Single story houses made from timber have also been demolished all along the coast. View is approximately North 30° East. **b** Momboro. Evidence of a tsunami wave that has washed away vegetation. The palm trees stand at 4 m tall and are still intact, suggesting the height of the localized tsunami wave was below this point. View is approximately North 45° East

estimated area of 1.965 km² (Fig. 9). Landslides in Balaroa moved in an eastward direction, compared to the westward direction of the Petobo and Jonooge–Sidera flows.

Large volumes of mud flowed through these villages within minutes, resulting in the mass inundation of the region, with some houses completely detached from their foundations (Fig. 10A). Eyewitnesses interviewed stated that churning and mass flows of soil and mud were observed after the ground shaking had stopped. Planks of brittle wood and personal belongings remained sprawled across the inundated areas (Fig. 10B). Although electrical poles had collapsed in both Balaroa and Petobo, local outbreaks of fire were only reported in Petobo. Extensive lateral spreading caused widespread road damage (Fig. 10C). This also resulted in broken sewage pipes that protruded from the ground (Fig. 10D). Major landslides (debris flows) were surrounded by regions with extensive lateral spreading that was most easily observed at disrupted roads and bridges. This hindered transportation, in particular critical emergency relief. Some vertical or horizontal offsets of roadways exceeded a meter (Fig. 10E).

4.4. Intensity Prediction Equations (IPEs)

Equations that predict seismic intensity as a function of magnitude and distance (Intensity Prediction Equations, or IPEs) are useful tools for seismic hazard and risk assessments. We compare our intensity data with various IPEs derived for western North America (Atkinson et al., 2014) and Central Asia (Bindi et al., 2011) (Fig. 11). The equations presented in Atkinson et al. (2014) are based on the database of USGS ‘Did You Feel It’ (Wald et al., 1999) MMI values from 2000 to 2013. The log equation we used to compute the IPE is:

$$\text{MMI} = c_1 + c_2M + c_3\log R + c_4R + c_5B + c_6M \log R.$$

where M is the moment magnitude, R is an effective distance measure that builds in near-distance saturation at close hypocentral distances, and the determined coefficients are $c_1 = 0.309$, $c_2 = 1.864$, $c_3 = -1.672$, $c_4 = -0.00219$, $c_5 = 1.77$ and $c_6 = -0.383$.

The equations developed in Bindi et al. (2011) consider 6000 intensity data points from 66 earthquakes encompassing the surface-wave magnitude range of 4.6–8.3. The work of the authors follows a

Figure 8

a Summary map of published primary field observations used in tsunami models (Sepulveda et al., 2020; Williamson et al., 2020). Uncorrected field data have been obtained from Omira et al. (2019), Mikami et al. (2019) and Widiyanto et al. (2019). The size of each bar corresponds with the measured tsunami runup height (m) in each study **b** Summary map of 26 tsunami heights/runups measured along Palu Bay by BMKG

standard regression approach where the parameters of the considered model are determined by evaluating the best least-squares fit to the set of observed intensities. The equation we use to compute the IPE uses a parametric regression and considers a model linear in magnitude and log-distance:

$$I = a_1 M + a_2 - a_3 \log_{10}(R_H/10) - a_4 (R_H - 10)$$

where I is intensity, M is the moment magnitude, R_H is the hypocentral distance, and the determined source coefficient terms are $a_1 = 1.071$, $a_2 = 1.003$, $a_3 = 2.621$, and $a_4 = 5.567 \times 10^{-4}$. We assume that the I value of Bindi et al. (2011) is comparable to an MMI.

Our results are consistent with all prediction equations within 0–30 km of observed intensities for a MMI range of 5 to 10. Asperity III is the region of greatest slip (max 6.5 m) located directly within Palu

basin, just south of Palu Bay, and is shown in Fang et al. (2019). Between 30 and 60 km, our results are in agreement with the prediction equations of Bindi et al. (2011) and Atkinson et al. (2014). Overall, our results are most consistent with the prediction equations of Atkinson et al. (2014).

4.5. Inverse Ground Motion to Intensity Conversion Equations (GMICES)

There are only two local instrumental ground motion recordings available for the Palu earthquake from seismic stations. One is located at Donggala, approximately 45 km north of the Mw 7.5 epicenter (Sunardi et al., 2019) and another in Palu, approximately 3 km west of the Palu–Koro fault (Kiyota et al., 2020). The recorded horizontal PGA values are

0.14 g for Donggala, (Sundari et al., 2019) and 0.33 g for Palu (Kiyota et al., 2020). We estimate predicted PGA values based on inverse ground motion to intensity conversion equations (GMICEs). Inverse GMICEs describe the relationships between the MMI determined at a site and the estimated PGA and PGV values at the same site (Moratalla et al., 2020; Worden et al., 2012). For comparison, we select regions with a similar tectonic setting to that of northwestern Sulawesi.

The GMICE equations in Worden et al. (2012) have been developed using $\sim 200,000$ MMI observations collected from the USGS Shakemap database (Wald et al., 1999). The earthquake magnitudes ranged from 3.0 to 7.3, and the distances ranged from > 1 km to approximately 400 m from the source. The equations used for calculating PGM from MMI are:

Figure 10

a Field photos of devastation caused by soil liquefaction during the 2018 Palu earthquake (see Figs. 4 and 5 for locations)—Petobo village. Evidence of extreme soil liquefaction that caused the destruction of roads and hundreds of houses is shown. Entire two-storey structures have been buried under large volumes of liquified soil. Strong ground shaking caused sewage pipes to burst, creating puddles of a pungent smelling water. View is approximately North 40° West. **b** Balaroa village. Locals are standing in shock at extreme soil liquefaction that has broken off part of a major road and completely inundated all houses in the way. View is approximately North 60° East. **c** 10 km south of Palu City. Very strong ground shaking has caused extensive lateral spreading on a major road, with up to 1 m of offset evident. An MMI value of 8 has been assigned to this site. View is approximately North 35° West. **d** Petobo village. Earthquake-induced soil liquefaction has caused one- and two-storey houses to be detached from their foundations. Some electricity poles have completely collapsed, with local reports of a fire outbreak. **e** A major road called Jalan Gawalise, located approximately 1.75 km south of Balaroa. There is clear evidence of extreme and extensive soil liquefaction, with large vertical offsets measured up to 2.25 m high. View is approximately North 40° West

Figure 9

a Zoomed in map showing the location of the three villages impacted by extreme soil liquefaction and landslides. A satellite image taken on 1st October 2018 of the landslide inundation is identified in three villages **b** Balaroa. **c** Petobo. **d** Jonooge–Sidera. Red lines indicate the area of landslide inundation. Accessed from Google Earth

Figure 11

MMI values as a function of distance from Asperity III (the region of greatest slip (~ 6.5 m) located directly within Balaroa and south of Palu Bay that is shown in Fang et al. (2019). Black circles represent our 375 MMI field observations. Each coloured curve corresponds with a comparative study. The red line is the Atkinson et al. (2014) model developed for western North America. The blue line is the Bindi et al. (2011) model developed for moderate to large events (M 4.6–8.3) in Central Asia

$$\log(Y) = (MMI - c_1)/c_2 \quad \text{for } MMI \leq t_2$$

$$\log(Y) = (MMI - c_3)/c_4 \quad \text{for } MMI > t_2$$

where t_2 is the MMI intersection at 4.22. Given this is lower than our lowest MMI value of 5, we only compute the equations for the upper curves of PGA and PGV. The determined coefficients for PGA are $c_3 = -1.60$ and $c_4 = 3.70$, and for PGV, $c_3 = 2.89$ and $c_4 = 3.16$.

The intensity database used to derive GMICE in Moratalla et al. (2020) is comprised of 67,575 felt reports from 917 earthquakes, with magnitudes ranging 3.5–8.1, and 1797 recordings from 247 strong motion stations. The hypocentral distances vary from 5 to 345 km. Total least squares regression was chosen for the reversibility of the equations. The equations used for calculating PGM from MMI are:

$$\log_{\text{PGM}} = (MMI - a_1)/b_1 \quad \text{if } MMI < t_{\text{MMI}},$$

$$\log_{\text{PGM}} = (MMI - a_2)/b_2 \quad \text{if } MMI \geq t_{\text{MMI}}.$$

As each equation line for PGA and PGV intersect at t_{MMI} 5.5277 (PGA) and 5.7433 (PGV) respectively, which is just above our lowest MMI value of 5, only the upper curve of both equations has been computed. The determined coefficients for PGA are

$a_2 = -1.9095$ and $b_2 = 3.9322$, and for PGV, $a_2 = 1.8970$ and $b_2 = 3.837$.

For a GMICE to be valid as an inverse GMICE—that is, reversible—the regression must be performed in both dimensions (PGM and MMI) simultaneously. Worden et al. (2012) and Moratalla et al. (2020) have both developed valid direct and inverse GMICES for MMI, PGA and PGV.

Figure 12A shows predicted PGA based on inverse GMICES developed by Worden et al. (2012) for California and Moratalla et al. (2020) for New Zealand. The equations in Worden et al. (2012) saturate at MMI 8.6, which corresponds to a predicted PGA of 0.57 g. For the equations of Moratalla et al. (2020), the maximum predicted PGA for sites assigned the highest MMI value of 10 is 1.1 g. The measured PGA value for the horizontal vector at the Palu station is 0.33 g and corresponds to an MMI value of 8, which is in agreement with our MMI determinations in the field. The predicted PGA and PGV values are approximately 0.2–0.3 g higher than predicted by the Indonesian Seismic Codes presented in Irsyam et al. (2020). Sites assigned an MMI value of 5 (our lowest MMI field observation) have a predicted PGA of 0.06 g.

Figure 12

a Predicted peak ground acceleration (PGA) and **b** predicted peak ground velocity (PGV) as a function of Modified Mercalli Intensity (MMI) based on inverse ground motion to intensity conversion equations (GMICEs) developed for California (Worden et al., 2012) and for New Zealand (Moratalla et al., 2020). Y-axis is log-scaled

Figure 12B shows predicted PGV based on GMICEs developed by Worden et al. (2012) for California and Moratalla et al. (2020) for New Zealand. Both equations are in excellent agreement and intersect at MMI 7.5 with a predicted PGV of 0.29 cm/s. For near distances (between 1 and 3 km from the fault), the predicted PGV is 85 cm/s, which corresponds to an MMI 9. Overall, the estimated ground motions developed for California and New Zealand for both PGA and PGV are consistent with each other and our field data.

4.6. Predicted Ground Motions

Another method used to estimate levels of ground shaking at a particular site are Ground Motion Prediction Equations (GMPEs), also referred to as Ground Motion Models (GMMs). GMPEs relate ground motion intensity measures (PGA and PGV) to predictor variables describing an earthquake source, path (site-to-source distance), and site effects (Stewart et al., 2015). Estimates of ground shaking at specific sites of damage or ground failure are useful to relate ground motion intensity measures responsible for such failures when developing fragility functions.

There are no published GMPEs for Sulawesi, so we therefore consider a GMPE model developed by Boore et al., (2014; referred to hereafter as BSSA14), which is based on recordings from shallow crustal earthquakes in western North America. We adopted the appropriate source parameters for the Palu event when running the BSSA14 model. These include a surface shear wave velocity of 400 m/s within a sedimentary basin calculated by the average of the minimum and maximum Vs30 values from the BMKG microzonation survey results, and PGA and PGV sites situated at 90° to the fault. The BSSA14 model predicts a maximum PGA of 0.6 g at a location nearest the fault, and a maximum PGA value of 0.017 g at 200 km from the same source (Fig. 13). The BSSA14 model predicts a maximum PGV value of 85–70 cm/s between 1 and 3 km of the closest points to the fault, and a maximum PGV prediction of approximately 6 cm/s up to 200 km from the fault (Fig. 14). Overall, the observed ground motion levels in Palu appear to be lower than ground motion models developed for similar tectonic regions. This result was also found in Goda et al. (2019), where the authors concluded that the expected PGA for the Palu event using BSSA14 was close to 0.5 g, which is approximately twice as large as the geometric mean

Figure 13

a Predicted peak ground acceleration (PGA) and as a function of Joyner–Boore distance (R_{jb}) (the closest distance from a data point to the projected fault surface) for the Palu earthquake based on the Boore et al. (2014) model developed for moderate to large earthquakes in eastern and western North America. Dotted lines represent $+1$ and -1 Σ . X-axis and Y-axis are log-scaled. **b** Strong ground motion record for Palu showing two vertical components and one horizontal component

of the two horizontal components of the observed ground motion record (0.24 g).

5. Discussion

5.1. Seismic Intensity Map

The observed seismic intensities are a product of the rupture characteristics of the Palu earthquake as made evident in kinematic rupture models (Fig. 3B) (Fang et al., 2019; Socquet et al., 2019; Liu et al.,

2020). All of our MMI values are within or adjacent to the region of highest slip (Asperity III in Fang et al., 2019, with the highest MMIs recorded of 8 + along the Palu–Koro fault. An average MMI value of 7 was found in Palu City. The spatial variability of our MMI values indicates that local site effects were a major contributor in the distribution of damage. Overall, most of the damage was concentrated > 70 km south of the mainshock. The maximum MMI value observed in our study is similar to studies conducted for other large earthquakes such as the 2014 Mw 8.2 Iquique, Chile (Cilia

Figure 14

Predicted peak ground velocity (PGV) and as a function of Joyner-Boore distance (Rjb) (the closest distance from a data point to the projected fault surface) for the Palu earthquake based on the Boore et al. (2014) model developed for moderate to large earthquakes western North America. Dotted lines represent $+1$ and -1 Σ . X-axis and Y-axis are log-scaled

et al., 2017) and 2016 Mw 7.8 Pedernales, Ecuador (Smith and Mooney, 2021) events. The Chile and Ecuador earthquakes were both subduction zone events with maximum MMI values of 6 and 8, and are in agreement with our average MMI value of 7.

5.2. The Origin of the Palu Tsunami

The origin of the Palu tsunami has been widely debated because the earthquake occurred predominantly on a strike-slip fault. The question considered was whether the Palu tsunami was triggered primarily by coseismic deformation beneath Palu Bay or shaking-induced landslides. Several studies (Sepulveda et al., 2020; Williamson et al., 2020; Liu et al., 2020; Carjaval et al., 2019; Gusman et al., 2019; Ulrich et al., 2019) have suggested the answer may be a combination of the two processes.

The tsunami source models for the Palu event rely predominantly on three key variables: (1) the tide gauge records (2) field survey data of runup heights; and (3) an accurate rupture model of the mainshock. Many models have demonstrated success in fitting one or more of these key observations (Carvajal et al., 2019; Heidarzadeh et al., 2019; Gusman et al., 2019;

Takagi et al., 2019; Ulrich et al., 2019; Williamson et al., 2020).

Two tide gauge records are available for the Palu tsunamis, one located at Pantoloan (on the northern east coast of Palu Bay) and the other at Mamuju (on the southwestern edge of Central Sulawesi). Several field surveys documented observations of coastal collapses along the east and west coast of Palu Bay (Sassa and Takagawa, 2018; Arikawa et al., 2018; Syamsidik et al., 2019; Putra et al., 2019; Omira et al., 2019; UNESCO and IOC, 2019; Liu et al., 2020), which have been attributed as sources of the Palu tsunamis. A consistent theme in most tsunami source models for the Palu event to date is that runup simulations based solely on either submarine fault motion or on coastal landslides consistently underpredict observed runup values. This may indicate that both source types could have contributed to the tsunamis.

The offshore fault geometry in Palu Bay and along the “neck” of Sulawesi has proven to be uncertain and complex. Natawidjaja et al. (2021) address this by combining LiDAR, multi-beam bathymetry mapping, field surveys of the surface rupture, and seismic reflection surveys to map the

Figure 15

Summary sketch of tsunami source mechanisms: (1) submarine landslides, (2) a fault step-over (to the east) accompanied by submarine thrust faulting. Green dots are 15 landslide zones presented in Sepulveda et al. (2020)

fault ruptures from the Palu earthquake and improve the accuracy of measured offsets. These authors conclude that the Palu earthquake occurred on a mappable, mature, offshore fault line. This is contrary to previous studies that have assumed an immature, hidden-unknown fault inland of where the Palu earthquake occurred (Bellier et al., 2001; Socquet et al., 2006; Walpersdorf et al., 1998; Watkinson et al., 2012; Watkinson and Hall, 2017).

The tsunami source may also be related to fault displacement (Fig. 15). If fault displacement were the main source, a significant component of horizontal motion of steep topography or dip slip motion within the fault structure hidden beneath the bay would be required to produce the vertical seafloor displacement necessary to generate the tsunami. However, analysis

of the Pantoloan tide gauge record used in various tsunami models as well as integrated field surveys proves that the fault displacement alone was insufficient to generate a large tsunami (Sassa and Takagawa, 2018; Gusman et al., 2019; Takagi et al., 2019; Heidarzadeh et al., 2019; Carvajal et al., 2019; Omira et al., 2019; Sepulveda et al., 2020; Williamson et al., 2020).

5.3. Intensity Prediction Equations vs Ground Motion Models vs Ground Motion Intensity Conversion Equations

Empirically derived relationships, such as IPE, GMMs and GMICEs, can be useful for predicting levels of earthquake-induced ground shaking and the

associated structural damage. The high levels of earthquake damage from our field observations, when considered in conjunction with the rupture kinematics of the Palu earthquake, could imply that liquefaction sites in particular experienced moderate to high levels of high frequency energy radiated during the 2018 Palu event. This is proved true in the case of Balaroa as the recorded PGA value of 0.33 g is located on the edge of Palu basin (possibly on a hard rock site), approximately 1 km west of Balaroa and 3 km west of the Palu-Koro fault (Kiyota et al., 2020). The response spectral values at the Palu station were reported to be less than those proposed by the Indonesian seismic design code, except for the period range of 2.5–3.5 s (Goda et al., 2019). This could explain MMI values as low as 5 assigned at the same site, which increase by a factor of 2 less than a km south of this at the starting point of the Balaroa landslide. The vertical ground motion was larger (0.34 g for the U–D component) than the respective PGA values (0.29 g for the E–W and 0.21 g for the N–S components), and is consistent with the large slip concentration at shallow depth underneath Palu Bay (Goda et al., 2019).

The scatter in MMI values shown in Fig. 12 between 0–60 and 90–120 strongly suggests the influence of local geological site effects. Moreover, there are noticeable differences in distance measurements used for each equation and our own calculated distances (fault distance compared to hypocentral and epicentral distances). Another possible factor contributing to the scatter in MMI values is the variability in building vulnerability that was not accounted for during the field survey.

6. Conclusions

Our highest observed MMI are adjacent to the region of greatest slip (max. 6.5 m) for the earthquake, referred to as Asperity III (Fig. 3B) by Fang et al. (2019). Hence, the largest concentration of damage was observed > 70 km south of the epicenter. Several multi-story buildings experienced serious damage with shear failure of walls, and moderate damage was sustained by two and three-story

unreinforced concrete structures. Reinforced concrete frame structures often performed well.

Large fluctuations of maximum tsunami runup heights extended from 20 km north of Palu Bay to much further south towards the south-eastern edge of Palu Bay. This is indicative of a secondary controlling factor which triggered multiple tsunamis within the region. Many field studies and tsunami models to date (Table 2) suggest this is due to a complex combination of coseismic deformation and submarine landslides. Accurately constraining the fault geometry beneath Palu Bay has been difficult due to the limited and low resolution of bathymetry data covering the entire bay, but this has been addressed and discussed extensively by Natawidjaja et al. (2021) and provides further evidence of fault-related seafloor deformation patterns beneath Palu Bay.

Highly localized earthquake-induced soil liquefaction was very damaging and a major cause of casualties up to 12 km southeast of Palu City. The relationship between PGA and the likelihood of liquefaction can be closely inspected from the recorded ground motions in Donggala and Palu (Kiyota et al., 2020; Sunardi et al., 2019). Both ground motion recordings (0.14 g for Donggala and 0.33 g for Palu) are in very good agreement with predicted ground motions equations (Boore et al., 2014) and are consistent with our MMI field observations. The profound liquefaction observed in Balaroa, Petobo and Jonooge-Sidera was likely due to a combination of factors: soil type, slope geometry (slope height and inclination), the relative position of the groundwater table, high slip along the earthquake fault, and a long duration of earthquake ground shaking. The similar directions of the landslide flows, as indicated in Fig. 9, could highlight the presence of a prominent structural feature along the mapped Palu–Koro fault. This appears to have a major effect in the topography and could heavily influence the orientation of landslide flows.

The results from Intensity Prediction Equations (IPEs), Ground Motion Models (GMMs) and Ground Motion Intensity Conversion Equations (GMICEs) are consistent with each other and our field data. The ground motion predictions are in good agreement with the recorded ground motion data in Palu and Donggala, as well as with

expectations of the Indonesian Seismic Codes (Irsyam et al., 2020). Updates to the national seismic hazard maps of Indonesia presented by Irsyam et al. (2020) estimate PGA values of 0.8–0.9 g for Palu. The updated seismic hazard map has led to new seismic design criteria in the most updated seismic building codes (Sengara et al., 2020). The results from our study will lead to a further improvement to the seismic hazards maps of Indonesia and can provide critical engineering parameters such as peak ground acceleration (PGA) or peak ground velocity (PGV) where limited instrumental ground motion recordings are available, such as in Palu.

6.1. Data and Resources

Seismic intensity data were collected by the Palu Regional Office of the BMKG and Marcella Cilia (USGS 2019). Supplemental material comprises of the following: (1) table of GPS co-ordinates of visited locations, and the corresponding MMI value, (2) transcripts of local interviews translated into English (3) table of BMKG measured runup values, (4) map of coseismic displacement measurements, (5) table of coseismic displacement measurements.

Acknowledgements

Support from the Indonesian Foreign Affairs office during field work is gratefully acknowledged, as well as all members of the local communities that allowed us to take pictures inside their homes and interview their family members. We thank the reviewers that have greatly helped to improve the clarity and scientific impact of this manuscript, including Anna Baker, Carol Barrera-Lopez, Sean Hutchings, Ellen Smith, Daniela Munoz-Granados, David Wald and Francesco Civilini. M. Cilia is grateful to the staff of Hotel Rajawali in Palu for providing logistical support in the Palu region. Comments from two anonymous reviewers greatly improved the paper.

Author contributions All authors contributed to the study conception and design. Material preparation, data and analysis were performed by MC, WDM and CN. The first draft of the manuscript was written by MC and all authors commented on

previous versions of the manuscript. All authors have read and approved of the final manuscript.

Funding

All funding for the data collection and the write-up of this study has been provided by the US Geological Survey Earthquake Science Centre (Department of the Interior) and the Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) office.

Availability of data and material

All data and materials comply with field standards and are openly available in the Supplemental Material.

Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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(Received May 3, 2021, revised August 16, 2021, accepted August 19, 2021, Published online September 9, 2021)