EARTHQUAKE AND TSUNAMI RECONNAISSANCE REPORT

31 October 2018 - 8 November 2018, PALU - INDONESIA

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BUILD CHANGE

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EXCECUTIVE SUMMARY

On 28 September 2018 at 6:02 pm local time (10:02 UTC), a M 7.5 earthquake struck Central Sulawesi, with its epicenter approximately located 70 km (44 miles) north of Palu. The earthquake and its subsequent landslide, liquefaction and tsunami have caused 2,081 fatalities, with estimated 1,309 still missing or buried. Approximately 68,000 houses were damaged, and about 206,000 people displaced from their home. It is estimated that 94km^2 area of central Sulawesi was exposed to landslisde and 300km^2 to liquefcation, and the population exposed to landslide and liquefaction were 5,600 and 110,000, resepectivley.

A nine-day observation was conducted in Central Sulawesi provinces from 31 October 2018 to 8 November 2018. Four cities, 17 sub-districts, and 24 villages were visited with a total of 157 houses and 12 school buildings evaluated. Twenty-eight homeowners and eight builders were interviewed. Three liquefaction sites and tsunami affected areas were also visited. The observation result showed 6 houses (3.8%) experienced no damage, 53 houses (33.8%) were minorly damaged, 62 houses (39.5%) were moderately damaged and 36 houses (22.9%) were severely damaged or collapsed.

There were four main types of residential buildings encountered: confined masonry (CM) with concrete block or clay brick, reinforced concrete frame (RCF) with masonry infill, timber frame with heavy (clay brick, concrete blocks, low-strength concrete) infill (TFH) and timber frame with light wall panels (TFL). For school buildings, the buildings were of either of confined masonry or RCF with masonry infill. From the four types, CM and TFH houses suffered more severe and moderate damage compared to others. Except for houses located in the area where significant settlement happened, TFL houses only experienced minor or no damage, even though the house was non-engineered and used materials below specified standards.

The most common damage encountered in houses was: cracks on foundation, separation of structural elements, separation of frames and infill, dislocation of RCF/confining concrete/timber frame, diagonal/horizontal/splitting/corrosion/captive cracks on columns, OOP collapse on wall, diagonal/ flexural/vertical/stair-stepped/sliding/corner cracks on walls, toe crushing of wall, leaned walls, cracks on concrete floor and tilted/collapsed structure due to soft story mechanism.

Based on the observations, it is evident that none of the buildings observed fully meet the applicable standards. Deficiencies were always encountered, either of material quality, structural detailing, workmanship or the combination of all, showing the minimum (if not absent) involvement of technical support, such as engineers, technicians and authorized government body during the design and construction process.

I. INTRODUCTION

Central Sulawesi Province is located at 2°22'N and 3°48'S, 119°22'W and 124°22'E with a population of more than 2.6 million people and approximatly 620,000 households (Province BPBD, 2010). The population distribution is provided in Figure 1. Palu, the capital city, is the most dense area while Parigi Moutong is the most populated. This province consists of 11 districts, 154 sub-districts and 1,778 villages. Flood, landslide and earthquakes are the the most common natural disaster that occur in this area.

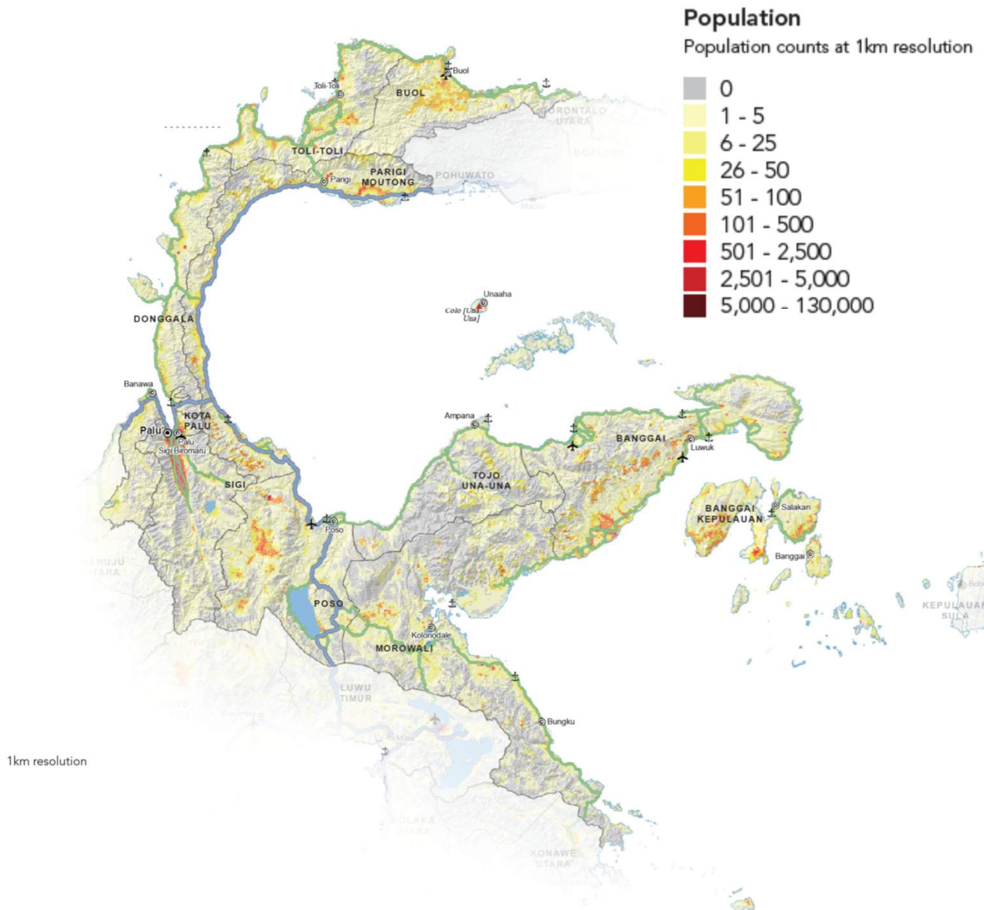


Figure 1. Population distribution of Central Sulawesi Area (Province BPBD, 2010)

A. Seismicity and Ground Motions of Central Sulawesi

Sulawesi, and most of Eastern Indonesia region, is located at the triple junction of three main plates, namely Pacific, Indo-Australia, and Eurasian and numerous micro-plates (USGS, 2018). The Island is also crossed by Palu-Koro Fault (PKF), Matano Fault (MF) and Nort Sulawesi Subduction (NSS) with the seismicity from 1900 to 2000 can be seen in Figure 2

(Bellier, et al., 2001). The area where the PKF (with long-term slip-rate of 40 mm – 50mm per year) and MF met has caused major active movements in Central Sulawesi area (Bellier, et al., 2001). So far, the capital city of Palu, that's crossed by the Palu-Koro fault, has been hit by destructive earthquakes (Rusydi, et al., 2018).

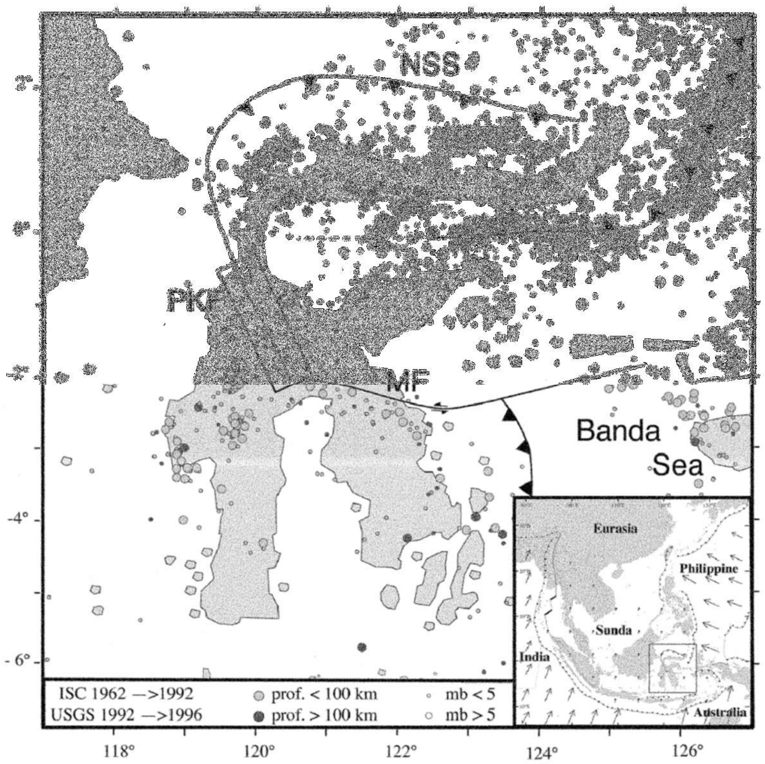


Figure 2. Seismicity of Sulawesi Region* *(Bellier, et al., 2001)*

* PKF, MF and NSS represent the Palu Koro fault zone, Matano Fault zone, North Sulawesi Subduction respectively

B. Geotechnical Aspects and Landslide/Liquefactions/Tsunami Hazard

Palu has various geological conditions and has a unique alluvial deposites with sandy layer on top (1-7m) and shallow ground water level (Fiantis & Minasny, 2018). The distribution of geological rocks in Palu is provided in Figure 3, where it is clear that it is dominated by alluvial deposit. Considering the type of soil, the shallow ground water level and high seismicity, Central Sulawesi is highly susceptible to landslide and liquefaction. The area with high potential of landslide and liquefaction are shown in Figure 4 and Figure 5.

Tsunami, that is usually caused by the abrupt motion of submarine earthquakes is expected to occur in any region in Indonesia (Wei-Haas, 2018), including Central Sulawesi. The areas that have high potential to inundation due to tsunami are provided in Figure 5.

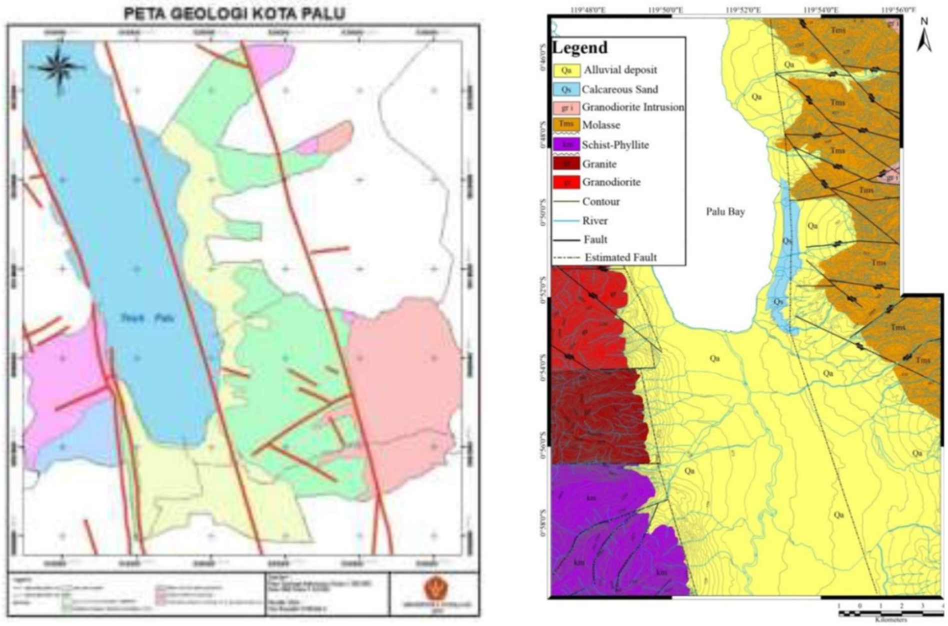


Figure 3. Geological condition of Palu city

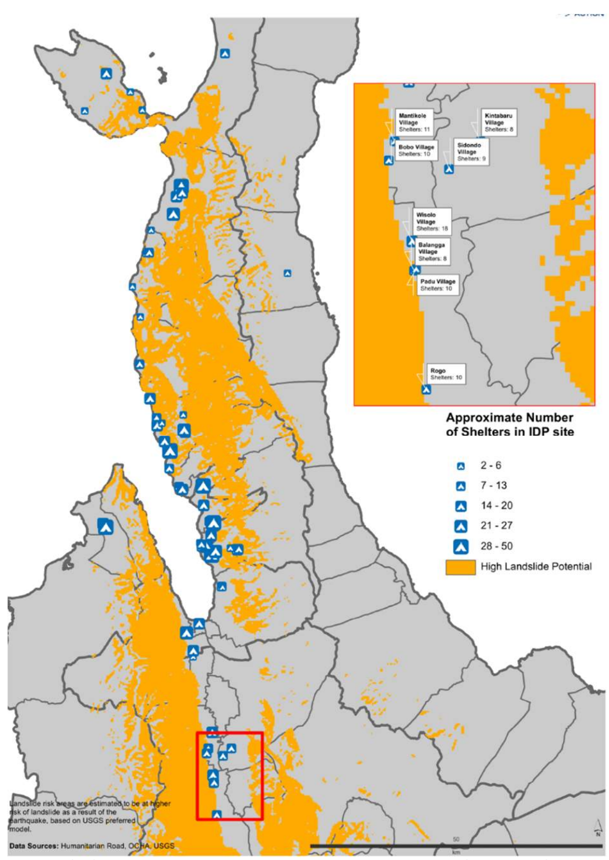


Figure 4. Sites with high potential landslide in Central Sulawesi

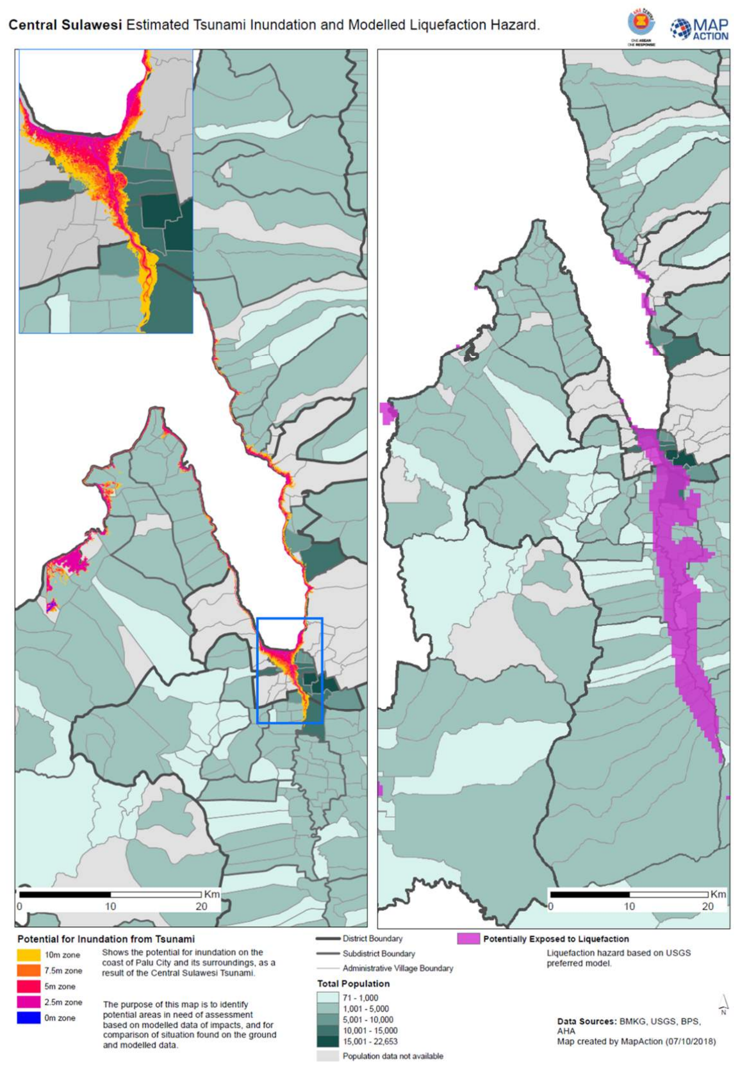


Figure 5. Central Sulawesi tsunami inundation and liquefaction hazard map *(MAP Action, 2018)*

C. Event Information

On 28 September 2018 at 6:02 pm local time (10:02 UTC), a M 7.5 earthquake struck Central Sulawesi, with its epicenter approximately located 70 km (44 miles) north of Palu (see Figure 6). The earthquake was caused by strike-slip fault movement at shallow depths within the interior of the Molucca Sea microplate. The earthquake rupture occurred either on a left-lateral north-south striking fault, or along a right-lateral east-west striking fault (see Figure 7).

The mainshock was preceded by four other foreshocks of M4.9 and larger in the epicentral region, the largest of which was a Mw 6.1 earthquake approximately three hours earlier. It was recorded that there were 748 aftershocks with > Mw3 that occurred after the main shock (see Figure 8).

Figure 6. Map of the September 28 earthquake near Palu *(USGS, 2018)*

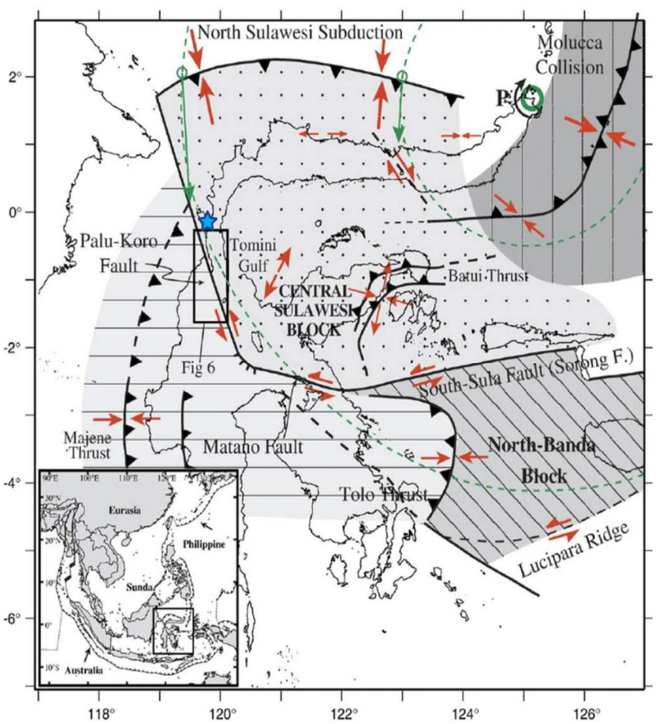


Figure 7. Faults of Sulawesi

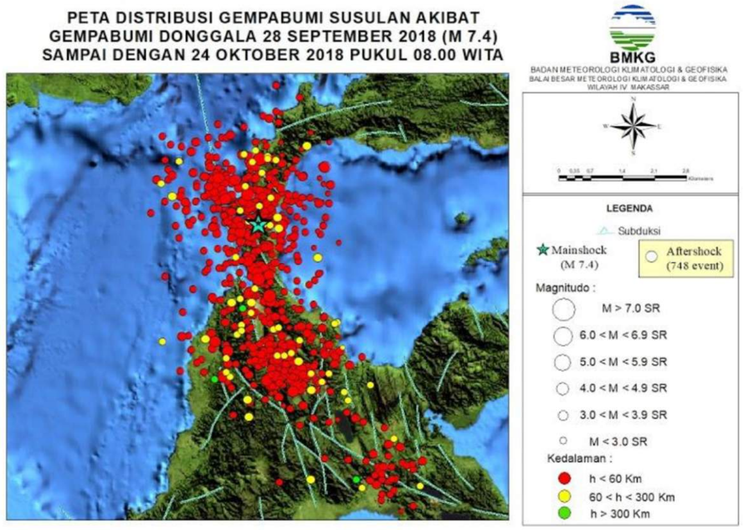


Figure 8. Aftershock distribution between 28 September 2018 and 24 October in Central Sulawesi
(The ASEAN Coordinating Center for Humanitarian Assitance on Disaster Management, 2018)

On 26 October 2018, the earthquake and its subsequent liquefaction and tsunami have caused 2,081 fatalities, with estimated 1,309 still missing or buried underneath the liquefaction. Approximately 68,000 houses were damaged, and about 206,000 people displaced from their home. The distribution of damaged buildings is provided in Figure 9.

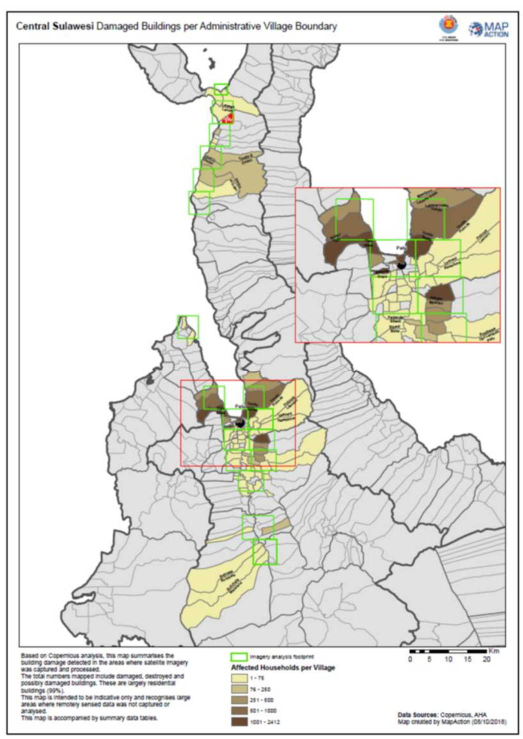


Figure 9. Damaged buildings per administrative village boundary
(The ASEAN Coordinating Center for Humanitarian Assitance on Disaster Management, 2018)

D. Buildings Observed

A nine-day observation was conducted in Central Sulawesi provinces from 31 October 2018 to 8 November 2018. Four cities, 17 sub-districts and 24 villages were visited with a total of 157 houses and 12 school buildings were evaluated. Twenty-eight homeowners and eight builders were interviewed. Three liquefaction sites and tsunami affected areas were also visited. Damage to lifeline such as road, bridges and airport were also observed (see details in Table 1 and the maps of areas visited are presented in Figure 10 and Figure 11).

Table 1. Summary of Areas Visited

City/Districts	Sub-Districts	Villages	Houses	Schools	Others
Palu	Tawaeli	Panawu	15	2	Mosque
	Palu Barat	Kamonji		3	
		Baru	7		
	Tatangga	Boyoage		1	
	Mantikulore	Lasoani	24	2	
		Talise Valanguni	9		
	Palu Tengah	Besusu Tengah		1	
	Palu Selatan	Petobo			Liquefaction sites, churches,
		Birobuli Utara			Airport
	Palu Timur				Tsunami affected sites, bridge
Donggala	Sirenja	Lende	7	1	
	Sindue	Labuan	1		
		Alindau	9		
	Banawa	Gunung Bale	11	1	
		Maleni	4		
Sigi	Kinovaro	Porame	6		
	Marawola	Baliase	5		
		Binangga	17		
		Tinggede	0	1	
	Gumbasa	Pakuli	7		
	Palolo	Bobo	10		
	Tanambulava	Sibalaya			Liquefaction sites
	Sigi biromaru	Bora	6		
	Sigi biromaru	Jono Oge			Liquefaction sites
Parigi Moutong	Parigi Tengah	Binangga	13		Bridge
	Parigi	Bantaya	6		
Total			157	12	

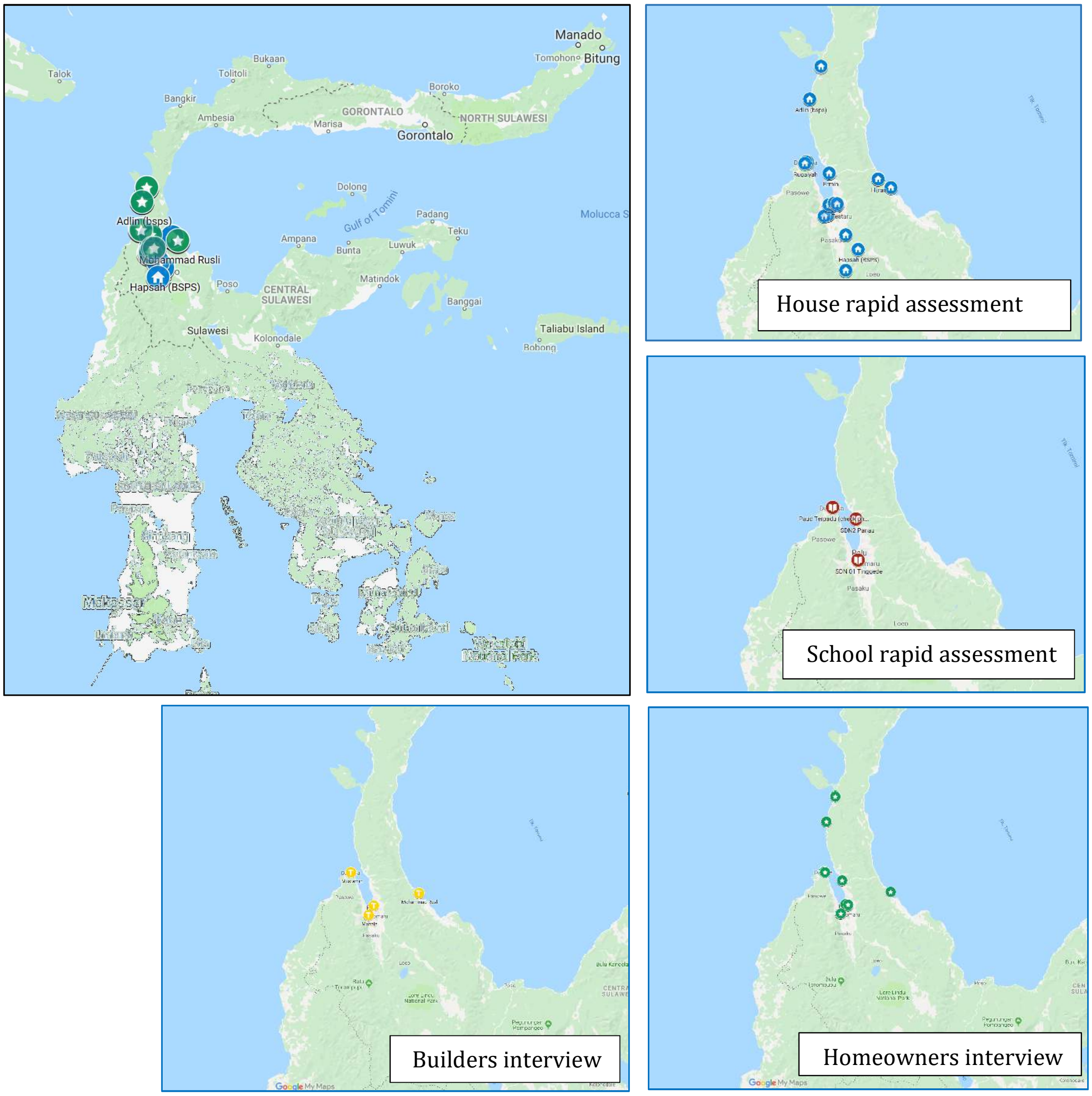


Figure 10. Maps of Areas Visited

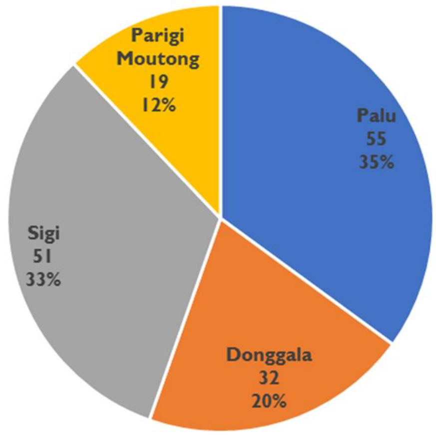


Figure 11. Total of residential buildings observed in each region

There were four main types of residential buildings encountered: confined masonry (CM) with concrete block or clay brick, reinforced concrete frame with masonry infill (RCF), timber frame with heavy (clay brick, concrete blocks, low-strength concrete) infill (TFH) and timber frame with lightweight wall panels (TFL). CM is the most common type for residential buildings (54%), followed by TFH (32%), TFL (8%) and RCF (6%) as shown in Figure 12. Some buildings could be easily categorized into one of the four main building types, but other buildings were the combination of the four main categories because some homeowners expanded their houses with different building type. The details of the number of each type of building and their variations can be seen in Table 2.

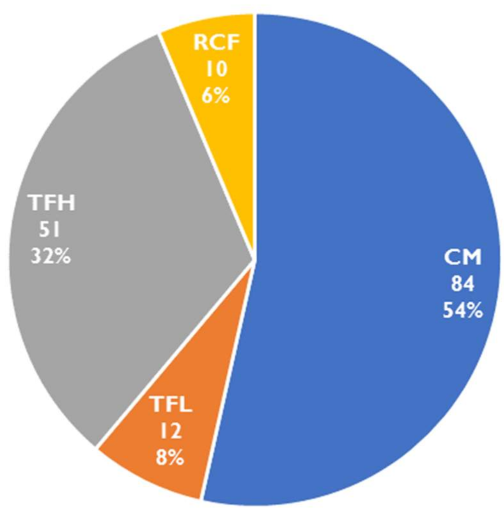


Figure 12. Types and total of residential buildings observed

Table 2. Types of residential buildings observed and their variations

Types	Variations	No	%
CM	Confined masonry (clay brick)	12	54%
CM	Confined masonry (concrete block)	49	
CM	Confined masonry (clay brick and concrete block)	10	
CM	Confined masonry and timber frame, with clay brick	2	
CM	Confined masonry and timber frame with concrete block	10	
CM	Confined masonry and timber frame with cast-in-situ concrete infill	1	
TFL	Timber frame with lightweight wall panels	5	8%
TFH	Timber frame with cast-in-situ concrete infill	12	32%
TFH	Timber frame with clay brick infill	10	
TFH	Timber frame with concrete block infill	14	
TFH	Timber frame with clay brick and concrete block infill	22	
RCF	Reinforced concrete frame with brick infill	3	6%
RCF	Reinforced concrete frame with concrete block infill	6	
RCF	Reinforced concrete frame with brick and concrete block infill	1	
	Total	157	100%

II. BUILDING AND INFRASTRUCTURE PERFORMANCE

The observation was done on residential buildings, school buildings, infrastructure and other structures. The discussion provided in this report is heavily focused on residential and school buildings only. The explanation of infrastructure and other structure performance is provided at a glance.

A. Residential Buildings

Most residential buildings were one-story with rectangular configuration, even though two-story or higher buildings were common in Donggala region. The average floor area is 70m^2 with the distribution of different type of buildings are provided in Figure 13. Most of CM and TFL buildings had relatively small floor area of 36m^2, compared to RCF and TFH with 100m^2.

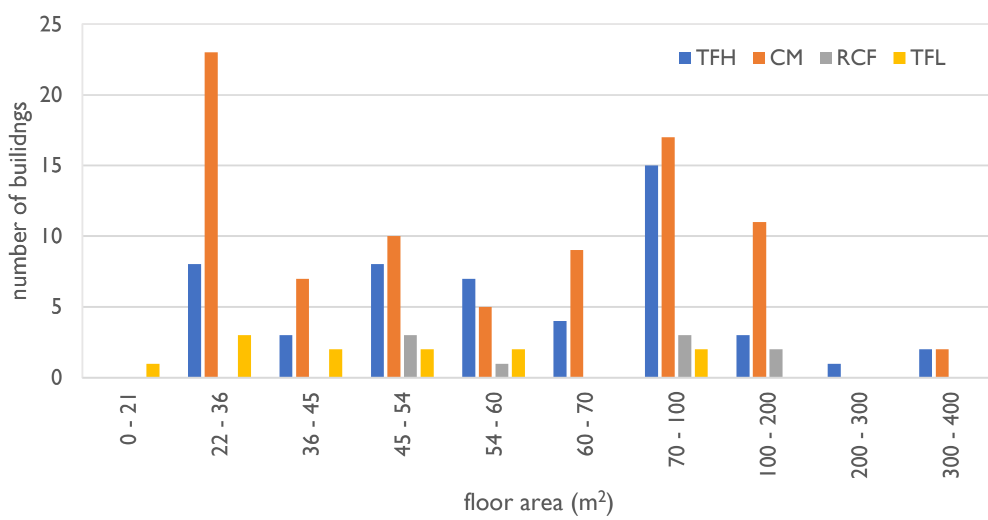


Figure 13. Distribution of floor area for different building types

The houses inspected were mostly constructed from 1920 to 2018, where 43% of houses were built before 2000 and the 57% were built in or after 2000. The distribution of construction period of each type of building is provided in Figure 14. The charts showed that TFL is the oldest building type in Central Sulawesi and might be the only building system used before up to the 1920s. The practice started to change in 1950s where light wall panel was replaced by heavy infill (TFH) and it was the most common building since then until early

2000s. People started to adopt confined masonry system in the 1970s and this building type is the most popular building type nowadays. RCF was only recognized since the 2000s.

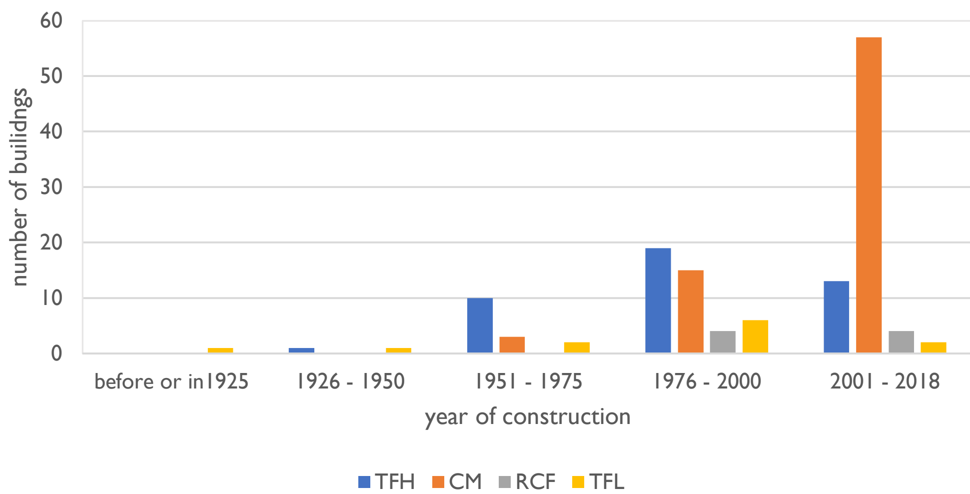


Figure 14. Distribution of construction period for different type of residential buildings

For overall residential building performance, the observation result showed that 6 houses (4%) experienced no damage, 53 houses (34%) were minorly damaged, 62 houses (39%) were moderately damaged, and 36 houses (23%) were severely damaged or collapsed (see Figure 15). For different type of buildings, the damage breakdown is provided in Figure 16. The detail explanation of damage for buildings and infrastructures are provided in the following discussion.

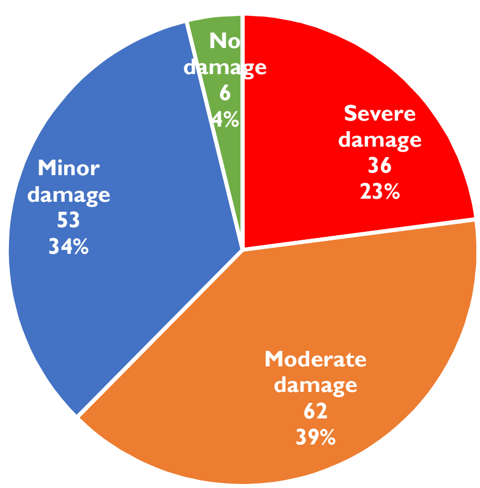


Figure 15. Damage of residential buildings observed

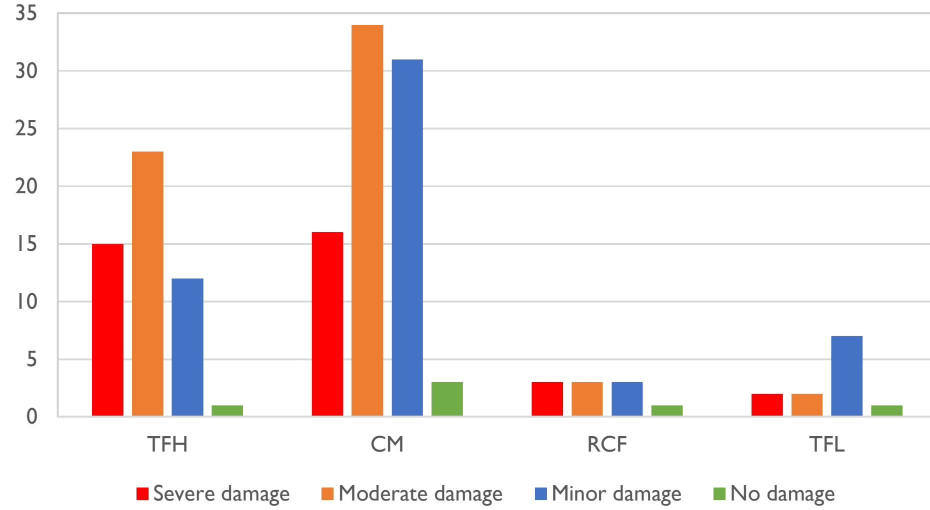


Figure 16. Damage of different type of residential buildings observed

65% of homeowners no longer resided in their building and only 35% still use their houses, but they avoid being in their house as much as they could as they were afraid that another major earthquake might occur. Most of the homeowners built a tent beside their houses and slept in it at night.

1. Confined Masonry

Confined masonry is the most common type of building encountered in Central Sulawesi region. Seventy (54%) of the total sample houses assessed are of this type, which can be categorized into concrete block (Figure 17) and clay brick (Figure 18). Buildings are generally one-story with floor area ranged from 24m^2 to 400m^2 (see the detail in Figure 19). The oldest house observed of this type was built in 1960 (see Figure 20).

Figure 17. Confined concrete block masonry house

Figure 18. Confined clay brick confined masonry house

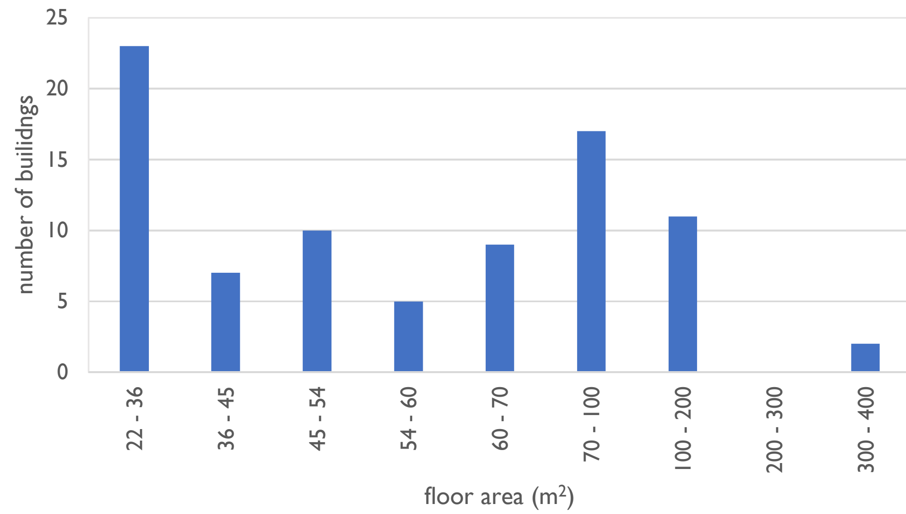


Figure 19. Distribution of plan area of CM residential buildings in Central Sulawesi

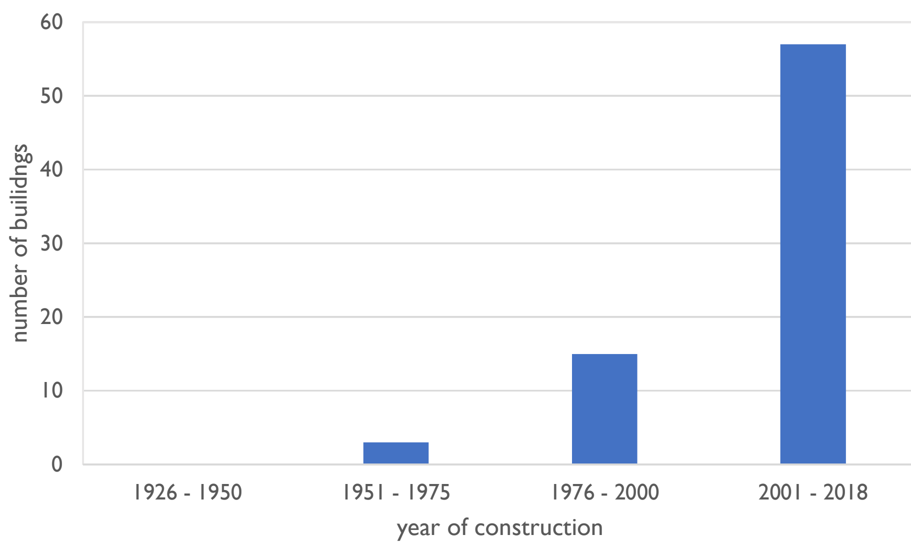


Figure 20. Distribution of construction period of CM residential buildings in Central Sulawesi

Moderate damage to the structure happened to 40% of total buildings observed, while 19% suffered severe damage. The rest of the buildings experienced minor or no damage (see Figure 21).

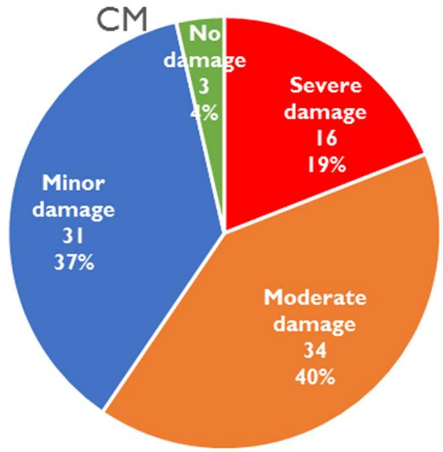


Figure 21. Breakdown of damage category for confined masonry residential buildings

Gable (see Figure 22) is the most common roofing system (84%), followed by hipped (16%, see Figure 23). Heavy material (i.e. concrete block or clay brick) was the most common material (79%) used for gable (see Figure 25) and only 21% used light material such as wood plank, plywood, or CGI sheet (see Figure 25). Roof covering was usually of CGI sheet (see Figure 26) or thatch (Figure 27).

Figure 22. Confined masonry house with gable roof

Figure 23. Confined masonry house with hipped roof

Figure 24. Heavy gable with confining beam

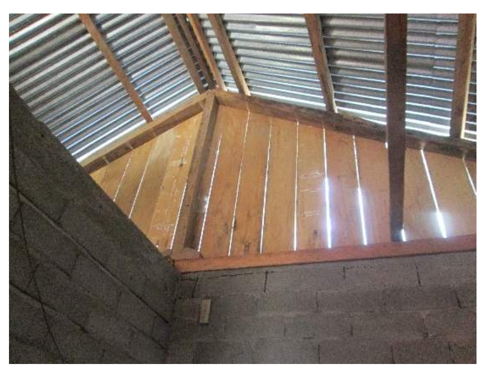


Figure 25. Light weight gable

Figure 26. CGI roof covering

Figure 27. Thatch roof covering

This building was usually supported by shallow continuous stone masonry foundation (Figure 28a). The dimension of stone foundation was not observable. At some buildings, a plinth beam was present, but for others, it was absent (Figure 28b). Confining concrete columns and beams were usually 13cmx13cm to 13cmx20cm (see Figure 29) and provided every 2m to 5m (Figure 30). The longitudinal rebar was of smooth rebar Ø6mm - Ø10mm (mostly 6mm) as shown in Figure 31, while the stirrup was of smooth rebar Ø4mm - Ø6mm (mostly 4mm) provided every 20cm - 50cm as can be seen in Figure 32.

(a) A house with stone foundation with plinth beam

(b) A house with stone foundation without plinth beam

Figure 28. Typical stone foundation

Figure 29. Confining element of 13cmx13cm to 20cmx20cm

Figure 30. Confining column was provided every 2.5m to 5m

Figure 31. Smooth longitudinal rebar Ø6mm

Figure 32. Stirrup of smooth rebar Ø4mm

The concrete block was typically 12cmx8cmx35cm (Figure 33) and clay brick was mostly 19cmx10cmx4.5cm (Figure 34). Typical mortar thickness was 2cm – 5cm (Figure 35) with plaster thickness ranged from 2cm to 3cm, provided at each side of wall (see Figure 36), making the total thickness of walls to be around 12cm – 15cm (see Figure 37).

Figure 33. The concrete block of 12cmx8cmx35cm

Figure 34. Typical brick of 19cmx10cmx4.5cm

Figure 35. Mortar of 2cm - 4cm

Figure 36. Thickness of plaster was 2cm – 3cm

Figure 37. Thickness of wall of 12cm

Roof framing was usually of timber (Figure 38) or light-gage metal trusses (e.g. TASO C.75.55, see Figure 39). The confining elements were connected to roof trusses using protruding rebar from column (see Figure 40) for timber or bolts (Figure 41) for light-gage metal. When roof trusses were absent, rafters rest on top of confining element (see Figure 42). Timber roof truss was usually of Grade II (E ≥ 10,000 MPa) or higher, even though timber with Grade III (E ≥ 8,000 MPa) or lower was also encountered. The connection of inter-elements of roof truss was usually of bolts and nails (see Figure 43).

Figure 38. Typical timber roof truss

Figure 39. Typical lightweight steel roof truss

Figure 40. Typical connection between confining element and timber roof truss using rebar Ø8mm

Figure 41. Connection between confining element and lightweight steel roof truss

Figure 42. When roof truss was absent, rafters sit on top of confining elements

Figure 43. Connection between roof truss elements using bolts

The confining concrete elements were usually of poor quality, with compressive strength of less than 10 MPa using a rebound hammer test (see Figure 44). Insufficient concrete cover and exposed rebar was common to encounter (see Figure 45), causing the rebar to be rusted and fragile (Figure 46). Typically stirrups were only provided every 20cm – 40cm (Figure 45). The connection between each confining element was usually insufficient (see Figure 47). Minimum or no overlapping was provided between confining elements.

(a) poor quality of concrete column

(b) poor quality of concrete plinth beam

Figure 44. Poor confining element

Figure 45. Insufficient concrete cover (exposed rebar), stirrup was provided every 20 - 40cm

Figure 46. Exposed rebar that were rusted and fragile

Figure 47. Insufficient seismic detailing between confining elements

At several houses, the confining elements, such as the columns and beams, were absent (see Figure 48). Usually, masonry around openings were not confined (see Figure 49). At some houses, masonry was laid poorly, especially around openings (Figure 50).

Figure 48. Absence of ring beam or columns at wall intersection

Figure 49. Absence of confining elements around openings

Figure 50. Masonry was poorly laid around openings

Several houses that were built in Donggala area were built on top of muddy, sandy and loose soil (Figure 51) with high liquefaction potential, leading to partial settlement of houses to be common (Figure 52). Some parts of the house, such as the kitchen, toilets or storage were sometimes of a different type of structure, such as timber frame with masonry infill or timber frame with wood plank (see Figure 53), causing a significant difference in building response and performance during the earthquakes.

Figure 51. Poor location, sandy and muddy soail, near river, high liquefaction potential

Figure 52. Settlement due to poor soil

Figure 53. House with partial confined masonry and timber frame with masonry skirt was common

Cracks in the foundation was very common to encounter due to ground settlement at these sites and poor mortar quality, which lacked cement (see Figure 54). The cracks that were caused by partial settlement also led to damage to other structural elements such as columns, plinth beams and walls. Separation between the plinth beam and foundation was encountered, showing the absence of a connection between the plinth beam and stone foundation (see Figure 55).

Figure 54. Cracks on stone foundation

Figure 55. Separation between plinth beam and foundation

The separation of confining elements (i.e. column – beam, foundation – columns, column – plinth beam) was common (see Figure 56) due to poor seismic detailing, poor concrete strength and insufficient concrete capacity. Cracks on columns due to captive column mechanism were also prevalent (see Figure 57). A case was found where a wall panel without a top confining element led to splitting the adjoining column that had to support all the lateral load at the adjoining wall (see Figure 58). Separation between confining elements and masonry was also common to encounter (see Figure 59).

(a) (b) (c) (d)

Figure 56. Separation of confining elements

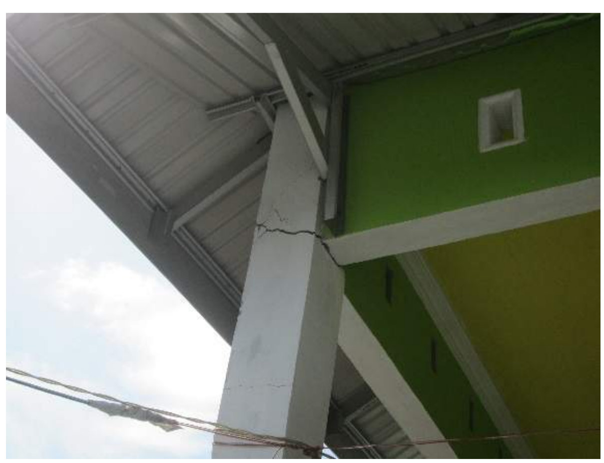


Figure 57. Captive column crack

Figure 58. Splitting column due to poor concrete quality

Figure 59. Separation between confining elements and masonry

Partial or complete out-of-plane collapse (see Figure 60) of slim-slender walls, diagonal cracks around openings (see Figure 61) caused mainly due to the absence of confining elements, and flexural vertical cracks at mid-length of walls (see Figure 62) were common. Stair-step diagonal cracks that showed the poor quality of mortar were also prevalent (see Figure 63). Damage to non-structural components such as floors were found in most houses (see Figure 64), while damage to ceiling (Figure 65) only happened to heavily damaged or collapsed buildings (Figure 66).

Figure 60. OOP collapse of wall

Figure 61. Diagonal cracks on wall around openings

Figure 62. Vertical flexural cracks of walls


Figure 63. Diagonal stair-step cracks on wall


Figure 64. Cracks on concrete floor


Figure 65. Damage to ceiling


Figure 66. Collapsed confined masonry building

2. Reinforced Concrete Frame with Masonry Infills

This type of building took 6% of the total houses assessed and was the least common building in Cental Sulawesi. Buildings usually one-story with floor area ranged from $46m^2$ to $153m^2$ with the average of $85m^2$ (see the distribution in Figure 67) Compared to other building types, RCF buildings usually had larger floor areas. It was recorded that the oldest building was built in 1980.

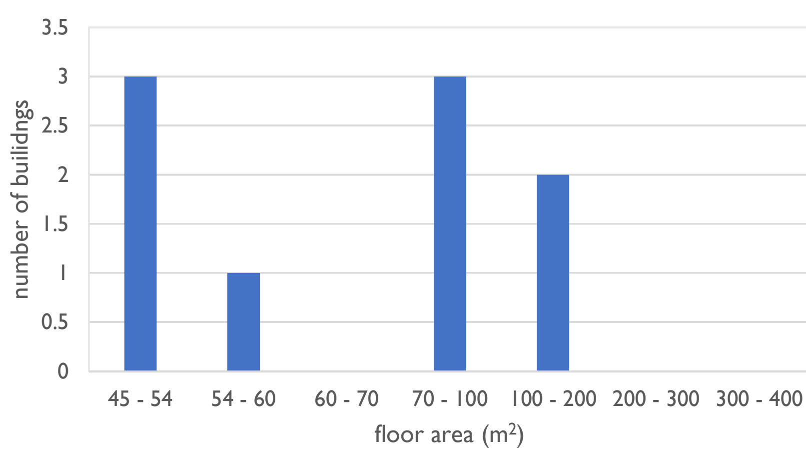


Figure 67. Distribution of plan area of RCF buildings

Sixty percent of total buildings experienced severe or moderate damage, while the rest suffered minor or no damage (see Figure 68).

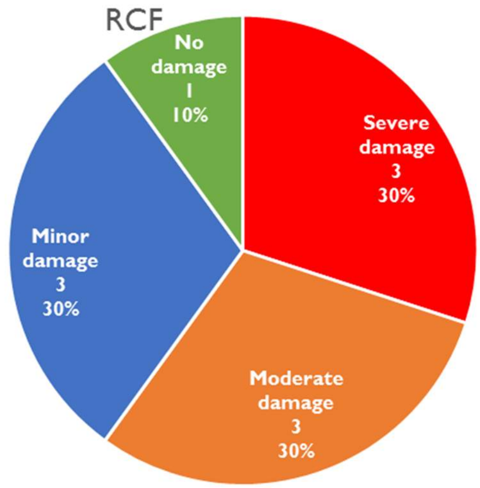


Figure 68. Damage breakdown of RCF residential buildings

The roofing system was dominated by gable (82%), where 63% of this number were built with heavy gable walls (see Figure 69), and only 37% were built with gable walls of light materials (see Figure 70). The Roof truss was mostly of timber of Grade II (E ≥ 10,000 MPa) as or higher (see Figure 71) even though timber with lower grade was also encountered. The roof truss member size varied but were mostly of 5/7cm (Figure 72). The roof truss was usually connected to the RCF using protruding rebar from columns (see Figure 73).

Figure 69. Typical RCF with masonry infill house with heavy gable

Figure 70. Typical RCF with masonry infill house with light gable

Figure 71. Roof truss of timber Grade II or higher

Figure 72. Roof truss of 5/7cm timber

Figure 73. Typical protruding column rebar as connector between column and roof truss

The size of visible and measurable reinforced concrete frame ranged from 10cmx10cm to 20cmx20cm for columns and 10cmx10cm to 10cmx15cm for beams (see Figure 74), usually provided every 2.5m to 4m (see Figure 75)

(a) Column and beam of 10cmx10cm

(b) Column of 25cmx25cm and beam of 10cmx15cm

(c) Beam of 13cmx15cm

Figure 74. Typical size of reinforced concrete frame

(a) RCF provided every 2.5m

(b) RCF provided every 2.5m to 4m

Figure 75. Typical distance between RC frame

Some deficiencies encountered for this house type were the insufficient concrete cover at concrete slab canopy (see Figure 76). Some concrete frames appeared to be reinforced using one smooth rebar Ø8mm only (see Figure 77).

Figure 76. Concrete slab canopy with insufficient concrete cover

Figure 77. Ring beam with one longitudinal rebar

The most common damages are separation between RCF elements (see Figure 78), separation between RCF and masonry infill (see Figure 79), splitting columns (see Figure 80), diagonal cracks around openings (see Figure 81), out-of-plane (OOP) collapse of masonry infill (see Figure 82), leaned walls (see Figure 83), cracks on floor (see Figure 84) and damage and fall of ceilings (see Figure 85).

Figure 78. Separation between column and ring beam

Figure 79. Separation between RCF and masonry infill

Figure 80. Splitting of column

Figure 81. Diagonal cracks around openings

Figure 82. OOP collapse of masonry infill

Figure 83. Leaned masonry infill

Figure 84. Cracks on wall due to ground settlement

Figure 85. Damage in ceilings

3. Timber Frame with Heavy infill

Timber frame with heavy infill is the second most common residential building type in Central Sulawesi, where 32% of buildings assessed fall into this category. The building plan usually had rectangular shape with the area ranged from 24m^2 to 400m^2, with the average of 81m^2 (see Figure 86). The oldest building observed was built in 1950. The number of this building type kept increasing until the early 2000 (see Figure 87).

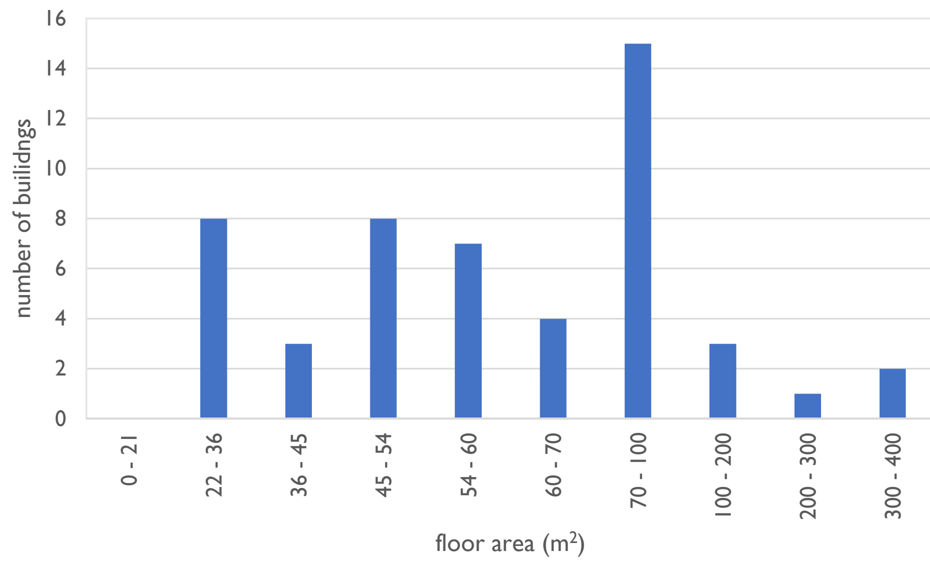


Figure 86. Distribution of TFH buildings plan area in Central Sulawesi

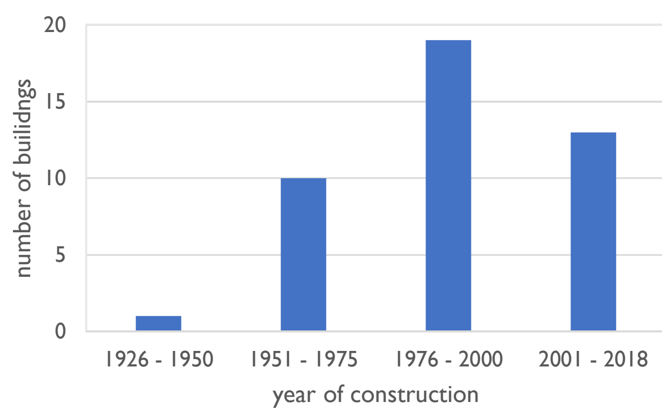


Figure 87. Distribution of construction period for TFH in Central Sulawesi

This type of building was popular in Sulawesi because sand is widely available in all areas of Sulawesi and most Homeowners (HO) made their own concrete blocks, that reduced the construction cost significantly. The most common ratio of cement to sand was 1:7 to 1:4 (yet the measure of cement and sand was different). With one sack of cement, HO usually could produce 80 – 200 concrete blocks. This made concrete blocks of poor quality common. Wood is relatively cheaper compared to other areas in Indonesia such as Padang, Aceh, Lombok and Yogyakarta. The timber used mostly of Grade I (E = 12,000 MPa) or Grade II (E = 9,800 MPa), even though in some cases, timber of Grade III (E = 7,800 MPa) or lower was also encountered.

In terms of building performance, most buildings encountered experienced moderate (45%) and severe damage (29%). Only 26% of buildings with minor or no damage (see Figure 88).

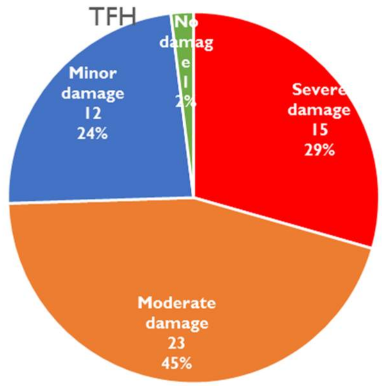


Figure 88. Damage breakdown of timber frame with heavy infill (TFH) residential buildings

There are three types of heavy infill encountered in this area, namely unreinforced and partly reinforced cast-in-situ concrete (see Figure 89), concrete block (see Figure 90), and clay bricks (see Figure 91). The concrete blocks were common for new houses while the clay bricks and cast-in-situ concrete wall were common for older houses. The majority of this type of building were one-story and only few buildings were two-story (see Figure 92). In some houses, some parts of the house had the combination of heavy infill and lightweight wall panel (see Figure 93). The infill was mostly plastered (see Figure 94). Gable roofs were the most common type encountered in this area (see Figure 90), followed by hipped roofs (see Figure 89).

Figure 89. Typical house of timber frame with cast-in-situ concrete wall

Figure 90. Typical house of timber frame with concrete block infill

Figure 91. Typical house of timber frame with clay brick infill

Figure 92. Two-story timber frame with clay brick infill houses

Figure 93. Partial cast-in-situ concrete wall and lightweight panel

Figure 94. Typical plastered cast-in-situ concrete wall

The building was usually supported by a shallow continuous stone foundation with a sill plate provided between the foundation and heavy infill (see Figure 95). Most of the sill plates in the houses were covered with plaster so that the condition of the sill plate was unknown. For those that were exposed, the wood was in fair to good condition as most were relatively newly constructed buildings. The size of timber posts varied from 4/5cm to 10/10cm, usually embedded into foundation, even though in some cases, they simply sit on top of foundation. Posts were usually provided every 2m – 4m (see Figure 96). The most common timber frame members connection was mortise and tenon cuts using wood pegs (see Figure 97).

Figure 95. Stone foundation with sill plate, post rest on top of foundation

Figure 96. Timber post was provided every 2m – 4m

Figure 97. Mortise-tenon cuts and wood pegs for timber member connections

Most houses (78%) had gable roofing system (see Figure 90 and Figure 93), and the rest (22%) was hipped (see Figure 98) and one-slope (see Figure 100). The typical roof frame can be seen in Figure 99 to Figure 101. The roof support usually connected to heavy masonry by using rebar Ø8mm (see Figure 102).

Figure 98. Typical houses with hipped roof

Figure 99. Typical roof truss

Figure 100. Typical support for one-slope roof

Figure 101. Roof support for hipped roof

Figure 102. Connection between heavy wall and sill plate

The quality of timber structure was varied from Grade I (see Figure 103) to Grade III (see Figure 104). In some cases, a deteriorated timber frame and roof truss were encountered because most of timber structural (and non-structural) elements were not protected (see Figure 105).

Figure 103. Timber structure of Grade II or higher

Figure 104. Timber structure of Grade III or lower

Figure 105. Deteriorated timber frames that were not protected

At most cases, all of the masonry was confined by sill plates, but in several cases, the sill plate was absent (see Figure 106). Knee bracing at the corner of timber frame was sometimes provided (see Figure 107), but mostly, knee bracing was absent (see Figure 108). At most houses visited, nails with various length and sizes were used as connector between heavy infill and timber frame (see Figure 109). At one house with cast-in-situ concrete infill, barbed wire, aside from nails, was used to connect the timber frame and the infill (see Figure 110a). For another house, a 4mm rebar was provided every 40cm as the connector (see Figure 110b).

Posts were usually embedded into foundations, but for several cases, posts that rested on top of foundation without any additional connection were also encountered (see Figure 111).

Figure 106. Absence of sill plates at the top of masonry

Figure 107. Posts with knee bracing (top left)

Figure 108. Post without knee bracing

Figure 109. Connection between timber frame and heavy infill using nails

(a) barbed wire (b) 4mm rebar provided every 40cm

Figure 110. (a) Barbed wire and (b) 4mm rebar as connector between timber frame and cast-in-situ concrete infill

Figure 111. Post was not embedded into foundations

The quality of masonry infill varied. Most of the concrete blocks were of poor quality and easily scratched using bare hand (see Figure 112). The clay brick was relatively better compared to concrete block overall, but weak unburnt bricks were also quite common to encounter (see Figure 113). The cast-in-situ concrete infill quality varied greatly, where at some houses the concrete lacked in cement and was easily scratched, while at others, the cement was sufficient, yet lacked in sand (see Figure 114).


Figure 112. Typical concrete block of poor quality


Figure 113. Under burnt clay brick used for a collapsed house


Figure 114. Cast-in-situ concrete infill

The most common damages encountered were total collapse of some part of the house (see Figure 115), OOP collapse of heavy infill while the timber frame remained undamaged (see Figure 116), diagonal cracks on heavy infill around openings (see Figure 117), separation between heavy infill and timber frames (see Figure 118), cracks of heavy infill at the corner of wall panel (see Figure 119), sliding cracks on heavy infill (see Figure 120), toe crushing and horizontal cracks of infill (see Figure 121), stepped cracks (see Figure 122), flexural vertical cracks on heavy infill (see Figure 123), vertical splitting of heavy infill (see Figure 124), cracks on foundation due to the poor quality of mortar (see Figure 125), dislocation of posts due to poor connection to other adjoining structures (see Figure 126), leaned walls because the timber frame could not support the heavy infill (see Figure 127), and cracks on concrete floor (see Figure 128).

Figure 115. Total collapse of some part of a house

Figure 116. OOP collapse of heavy infill

Figure 117. Diagonal cracks around openings

Figure 118. Separation between timber frame and concrete block infill

Figure 119. Cracks of heavy infill at wall corner

Figure 120. Sliding cracks of masonry infill

Figure 121. Toe crushing, and horizontal cracks on heavy infill

Figure 122. Stepped cracks at heavy infill

Figure 123. Flexural vertical cracks on masonry infill walls at the mid span of wall

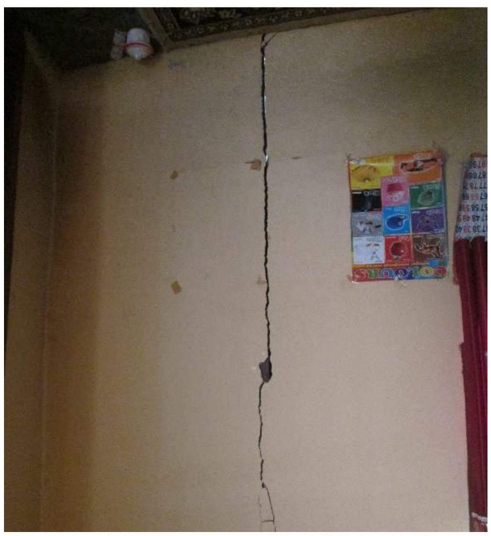


Figure 124. Vertical splitting of heavy infill

Figure 125. Foundation crushed due to poor mortar quality

(a) (b)

Figure 126. Dislocation of (a) sill plate and (b) timber post that were not well-connected to foundation

Figure 127. Leaned infill walls

Figure 128. Cracks on concrete floor

4. Timber Frame with Lightweight Wall Panel

This building was the oldest building system and was rarely encountered during the observation. There were only 12 timber houses (7.6% of total buildings assessed) with lightweight panel that were encountered during the visit (see Figure 129 and Figure 130). The house was usually one-story and sitting on the ground. One two-story (see Figure 131) and one raised house (see Figure 132) were found.

Figure 129. Typical timber frame with lightweight panel with roof thatch

Figure 130. Typical timber frame with lightweight panel with CGI roof covering


Figure 131. Two-story timber frame with lightweight wall panel


Figure 132. One-story raised timber frame with lightweight wall panel

The building plan was usually rectangular with area that ranged from 12m² to 84m² (see Figure 133). These observed buildings were built in 1920 to 2016 (see Figure 134).

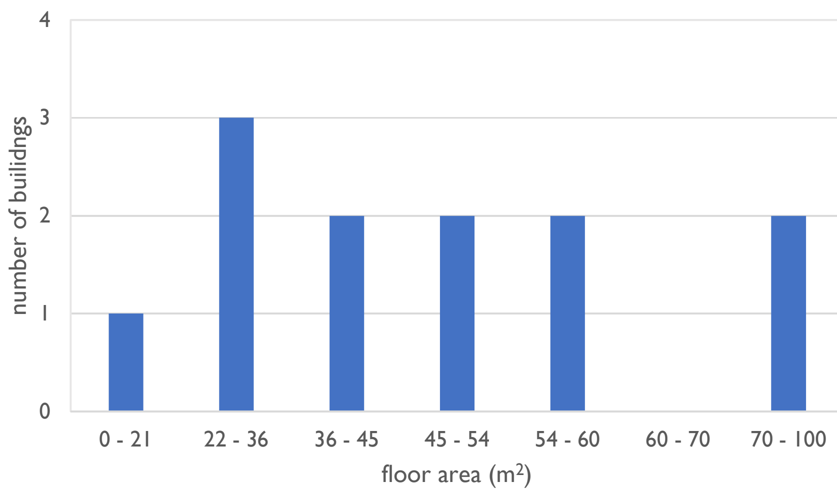


Figure 133. Distribution of plan area of TFL residential buildings

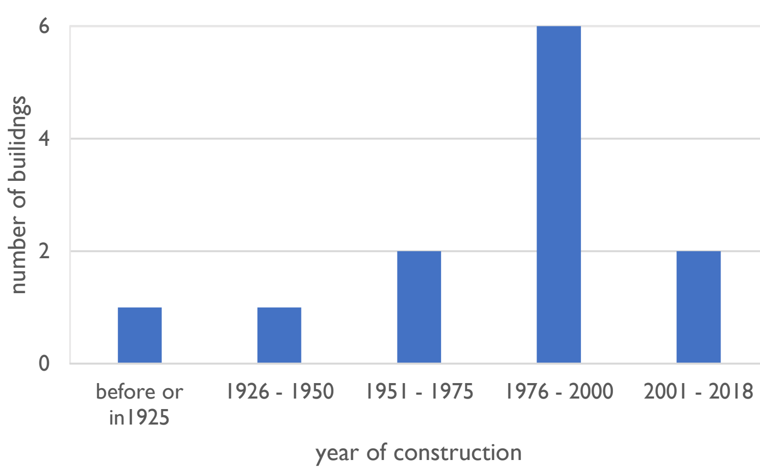


Figure 134. Distribution of construction periods of TFL residential buildings

The posts ranged from 4cmx10cm (see Figure 135) to 9cmx9cm (see Figure 136). Posts were usually provided every 1m – 2m (see Figure 137). At several houses, knee bracing was evident (Figure 138) at two intersection members, but for most, it was absent. For two story and raised house, floor joists were usually provided every 50 cm (see Figure 139).

Figure 135. Post of 4cmx10cm

Figure 136. Post of 9cmx9cm

Figure 137. Post was provided every 1m - 2m

Figure 138. Knee bracing when present

Figure 139. Joists of 5cmx7cm provided every 50cm

This house type was usually covered by CGI sheet or thatch at the roof. Most of the roof trusses only consisted of top chords, bottom chords, and a king post. Web/struts were usually absent (see Figure 140).

Figure 140. Typical roof truss

All of exterior wall panel of this house type was made of wood plank that was arranged horizontally (see Figure 141) or vertically (see Figure 142). Ceilings, when present, were made of plywood (see Figure 143). The interior walls were usually made of plywood of various thickness (see Figure 144).

Figure 141. Wall of horizontal wood plank

Figure 142. Wall of vertical wood plank

Figure 143. Ceiling with plywood

Figure 144. Interior wall made of plywood

Most of the houses (64%) only suffered minor damage or no damage despite the poor quality of timber and poor connection between timber structures (see Figure 145). Moderate and severe damage observed was mostly due to the deterioration of timber main structural elements (see Figure 146) and tilted structure due to soft story mechanism for raised house (see Figure 147). Cracks on the concrete floor was prevalent (see Figure 148).

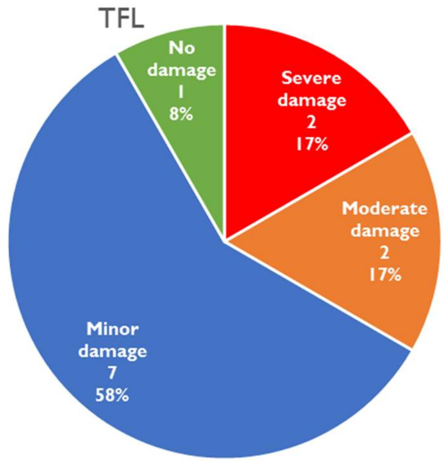


Figure 145. Damage breakdown of timber frame with light wall pnel (TFL) residential buildings

Figure 146. Damage due to deteriorated timber

Figure 147. Soft-story failure for raised timber house

Figure 148. Crack on concrete floor

B. School Buildings

Twelve schools were visited and evaluated, where two schools were in Donggala sub-district, nine in Palu city and one in Sigi sub-district as follows:

1. PAUD Terpadu Negeri Pembina (Donggala), see Figure 149

2. SMPN 01 Sirenja (Donggala), see Figure 150
3. MAN 01 Palu (Palu), see Figure 151
4. MAN 02 Model Palu (Palu), see Figure 152
5. SDN Inpres 01 Sirenja (Palu), see Figure 153
6. SDN Inpres 02 Lasoani (Palu), see Figure 154
7. SDN 04 Palu (Palu), see Figure 155
8. SDN 20 Palu (Palu), see Figure 156
9. SDN Inpres 02 Kamoji (Palu), see Figure 157
10. SDN 21 Palu (Palu), see Figure 158
11. SDN 02 Panau (Palu), see Figure 159
12. SDN 01 Tinggede (Sigi), see Figure 160

Figure 149. PAUD Terpadu Pembina

Figure 150. SMPN 1 Sirenja

c

Figure 151. MAN 1 Palu

Figure 152. MAN 2 Palu

Figure 153. SDN Inpres 01 Sirenja

Figure 154. SDN Inpres 02 Lasoani

Figure 155. SDN 04 Palu


Figure 156. SDN 20 Palu

Figure 157. SDN 02 Kamonji


Figure 158. SDN 21 Palu


Figure 159. SDN 02 Panau


Figure 160. SDN 01 Tinggede

Most school buildings were one or two story. All of buildings were either confined masonry or RCF with masonry infill. A single school usually consists of several buildings that are made up of one to seven adjoining classrooms each (see Figure 161 and Figure 162). The size of a single classroom ranged from around 7mx8m to 8mx9m (see Figure 163 and Figure 164).

Figure 161. Building layout of MAN 1 Palu

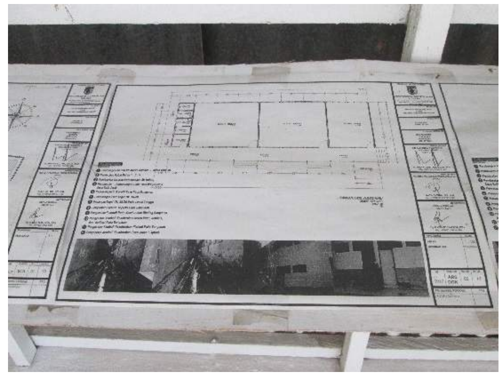


Figure 162. Building layout of SDN 21 Palu

Figure 163. Classroom length of 8m

Figure 164. Classroom length of 9m

The size of RCF columns or confining concrete varied from 13cmx13cm for one story buildings to 40cmx40cm for two story buildings (see Figure 165 to Figure 168), and were provided every 2.6m to 3m (see Figure 170), with the height of columns and walls around 3m (see Figure 171). The ring beam was usually of 13cmx13cm to 16cmx25cm (see Figure 169). All concrete observed was reinforced using smooth rebar for both longitudinal reinforcement and stirrups (see Figure 172 and Figure 173). The diameter of longitudinal rebar varied from 6mm to 12mm, while for stirrups, 4mm to 8mm was usually provided every 18cm to 25cm (see Figure 173 and Figure 179).


Figure 165. Column of 15cmx15cm


Figure 166. Column of 15cmx25cm


Figure 167. Column15cm x 20cm


Figure 168. Column of 15cmx15cm to 40cmx40cm


Figure 169. Ring beam of 16cmx 25cm

Figure 170. Column provided every 2.6m

Figure 171. Floor to ceiling distance was 2.9m

Figure 172. Column with smooth longitudinal rebar Ø10cm

Figure 173. Column with stirrup of smooth rebar Ø4mm every 23cm

The material quality of columns, beams and confining elements varied from poor to good. One-story and old school buildings usually had a very low compressive strength (see Figure 174) and this concrete was easily broken using bare hands. However, two-story and newer school buildings had higher compressive strength. Rebound hammer test showed that these school buildings had compressive strength of around 17 MPa to 32 MPa (see Figure 175). Concrete of old school buildings usually lacked in cement (see Figure 176) and was not well-compacted (see Figure 177). The exposed reinforcing rebar was usually badly rusted and fragile (see Figure 178). This was due to thin concrete cover (see Figure 180) or in some cases, when the concrete cover was excessive (Figure 181), the rusted rebar might be caused by the lack of cement allowing moisture and oxygen to easily penetrate into the RCF and allow the oxidation process to take place and cause rust. From all RCF that was exposed so that the reinforcing could be evaluated, none of them that had sufficient seismic detailing (see Figure 182).

Figure 174. Old building had a very low compressive strength (less than 10 MPa)

Figure 175. New and two-story school buildings had relatively high compressive strength

Figure 176. Concrete lacking in cement

Figure 177. Concrete that was not well-compacted

Figure 178. Rusted reinforcing rebar

Figure 179. Smooth rebar Ø6mm every 18cm

Figure 180. Thin concrete cover

Figure 181. Excessive concrete cover (10cm)

Figure 182. Poor seismic detailing

The clay brick was of 4cmx8cmx22cm (see Figure 183), with the thickness of plaster ranging around 2cm – 3cm (see Figure 184) at each side of the wall. Even though the compressive strength for bricks were not tested, it was predicted that most of them were around 5 MPa.

Figure 183. Clay brick of 4cmx10cmx22cm

Figure 184. The thickness of plaster was of 2cm – 3cm

Building collapse was common for one-story older buildings (see Figure 185). For new two-story buildings, collapse was due to soft-story mechanism (see Figure 186). For buildings that remained standing, the most common damage encountered to structural RC columns was crushing at joints (see Figure 187), splitting cracks (see Figure 188), cracks due to corrosion of rebar (see Figure 189), diagonal cracks (see Figure 190), horizontal cracks (see Figure 191), bending (see Figure 194), and cracks due to captive column mechanism (see Figure 195). For beams, the most common damage encountered was shear cracks (see Figure 192), diagonal cracks that probably caused by corrosion rebar (see Figure 193),

Figure 185. Total collapsed of old, one-story school building

Figure 186. Total collapsed of new school building due to soft-story mechanism


Figure 187. Concrete crushed at joints


Figure 188. Splitting crack


Figure 189. Cracks on columns due to rebar corrosion and poor concrete quality


Figure 190. Diagonal cracks on columns


Figure 191. Horizontal cracks on columns


Figure 192. Shear cracks on beams


Figure 193. Diagonal cracks on beams


Figure 194. Bending column


Figure 195. Cracks due to captive column mechanism

In one case, verandah columns were not embedded into the foundation and simply sat on the foundation without additional connection to plinth beams, causing the structure to overturn and causing damage to the adjoining columns, roof truss, ceiling and roof covering (see Figure 196). In another case, one school building was damaged by the nearby collapsed building (see Figure 197).


Figure 196. Unembedded columns caused structure overturning and collapse

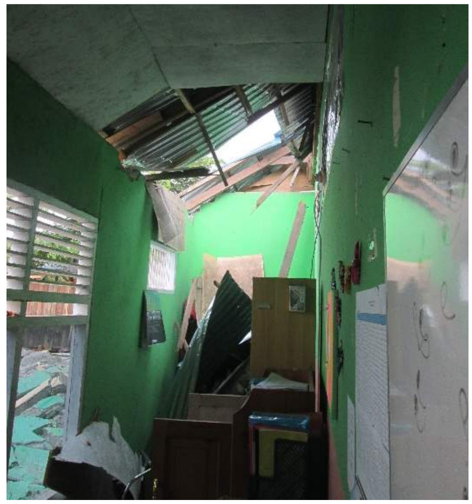


Figure 197. One school building that was damaged due to the collapsed building nearby

For walls, the most common damage encountered was cracks on the heavy gable (see Figure 198), OOP collapse of masonry gables (see Figure 199), OOP collapse of walls (see Figure 200 to Figure 201), diagonal cracks at wall around openings (see Figure 202), separation between confining elements and masonry walls (see Figure 203), and vertical cracks on wall (Figure 204). For walls without openings, diagonal cracks were also observed due to long and slender walls (see Figure 205).

Figure 198. Cracks on heavy gable

Figure 199. OOP Collapse of masonry gable

Figure 200. OOP Collapse of wall panel

Figure 201. OOP Collapse of masonry wall

Figure 202. Diagonal cracks on walls around opening

Figure 203. Separation between RCF or confining elements and wall

Figure 204. Vertical cracks on wall

Figure 205. Diagonal cracks on long and slender wall

Cracks on foundation either due to poor mortar quality, ground settlement or ground cracking were also common (see Figure 206). Damage to concrete floors (see Figure 207), falling ceilings and damage to roof covering (see Figure 208), and damage doors and windows (see Figure 209) were also prevalent. Significant ground settlements that caused the floor to be uneven were also observed (see Figure 210). Some school's fences were collapsed (see Figure 212).

Figure 206. Cracks on foundation and plinth beam

Figure 207. Cracks on floor

Figure 208. Damage and falling ceiling and roof covering

Figure 209. Damage to doors and windows

Figure 210. Ground settlement

Figure 211. Damage to foundation and plinth beam

Figure 212. OOP Collapse of masonry fences

C. Infrastructure and Other Structures

1. Roads

Many roads were damaged and/or destroyed by the earthquake and its subsequent tsunami and liquefaction. Eyewitness stories described the roads cracking and splitting, lifting up and down due to earthquake shaking. CCTV and amateur videos later confirmed these, as roads were seen cracking and spreading as a result of the movement of the ground underneath. Figure 213 shows a snapshot of the video, showing significant ground failure

Figure 213. Destroyed road near Jono Oge immediately after the earthquake *(Lotus Sunda Art, 2018)*

Near the coastline, the foundation of the road was eroded by the earthquake and subsequent tsunami, causing lateral spreading and partial collapse of the road into the bay. This was seen extensively both in Palu coastline (Figure 214) and Kampung Muara in the city of Dongala (Figure 215). In the mountainous region, several landslides and rockfall that occur due to the intense ground shaking caused temporary blocking of access to several villages.

Figure 214. Part of the road eroded into the bay due to earthquake and tsunami

Figure 215. Road collapse into the bay due to foundation failure in Dongala city

In the four villages where severe liquefaction occurred (Balaroa, Petobo, Jono Oge, and Sibalaya), roadways were destroyed long with the villages by the mudflow. Figure 216 shows the aftermath of the liquefaction in the village of Petobo, with damage to the main road that runs through it. Figure 217 shows the before and after of the view from the bridge, at one end of the liquefaction zone in Jono Oge. The before view was taken from Google Maps street view, while the after view was taken during the visit. The roadway that connects the two-end point has been taken by the flow a few kilometers downstream.

(a) (b)

Figure 216. (a) Bridge overpass leading towards Petobo village. (b) Remains of the main road that runs through Petobo village

(a) (b)

Figure 217. (a) Before and (b) After picture of the village of Jono oge due to the liquefaction*

*Note the same tree at the right side of the picture. The houses and road has been swept away downstream along with the liquefaction.

In the Sigi district, uplift and cracking of the ground was still observable, one month after the earthquake event. In the only main artery road that connects Palu with Kulawi, the road was uplifted approximately 50 cm (20 inches) on one side (see Figure 218). Pipelines buried underneath the ground are visibly bent (see Figure 219). There was a major separation crack on the ground, with its width measured at 50 cm (20 inches), and depth of crack about 1 meter (40 inches). This measurement is taken one month after the event, which means the crack was probably deeper during the earthquake. This ground lifting causes significant damage to the structures that rest along the crack line. (see Figure 220)

Figure 218. Uplift of the ground of approximately 50cm

Figure 219. Bent pipelines exposed due to uplift

Figure 220. Ground uplift causes significant damage to the houses along its path

2. Bridges and Overpasses

One of the short overpasses near the coastline was pushed approximately 8 meters away by the tsunami (Figure 221). The earthquake also caused the collapse of renowned Palu Bridge IV, which cuts down one of the main between from West Palu to East Palu (Figure 222). A bridge in Parigi Moutong was fractured due to the settlement of piers at its mid-span (see Figure 225).

Figure 221. A short bridge overpass near the Palu coastline was swept and shifted 8 meters inland due to the tsunami

Figure 222. Collapsed Palu IV bridge *(Kapoor, et al., 2018)*

Figure 223. Bended bridges in Oti villages

Figure 224. Damaged bridge in Petobo village

Figure 225. Damaged bridge in Parigi Muotong

3. Airport

Parts of the airport were damaged due to the earthquake. Some significant cracking was observed in the brick masonry wall. Partial collapse of the brick wall was observed near the restroom. Evidence of broken glass in the airbridge was observed (see Figure 226). The entire second floor of the airport was closed to the public during the visit. Some cracking was observed on the stairs. These damages did not significantly impact the operation of the airport, and repair efforts had begun at the time of the visit

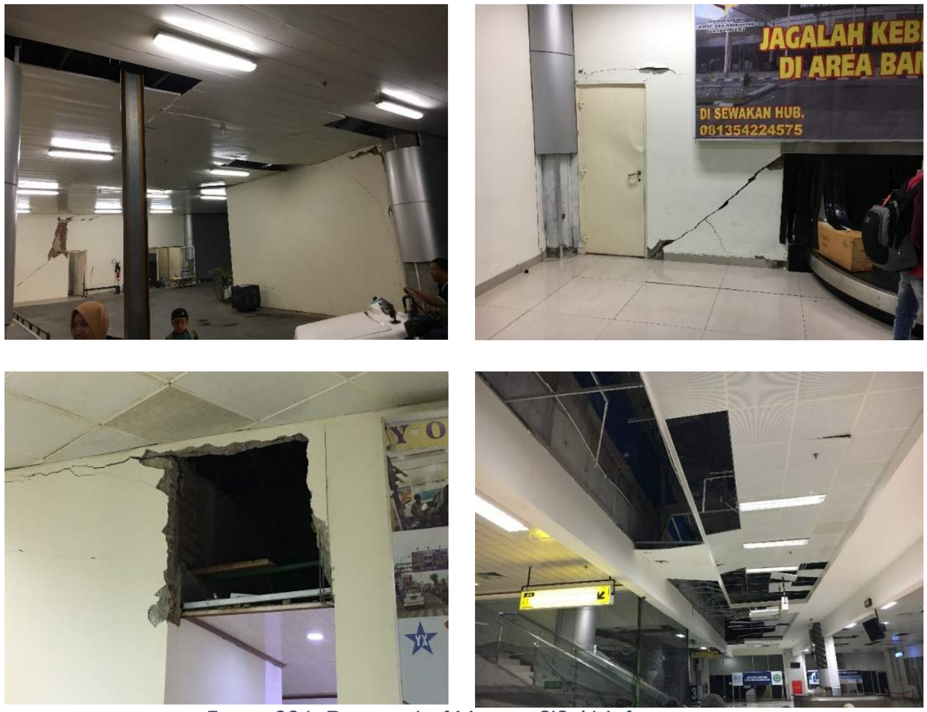


Figure 226. Damaged of Mutiara SIS Al-Jufrie airport

4. Religious Places

Study of the performance of religious places was not the primary purpose of the reconnaissance trip, but several observations were made during the trip. Religious places are important, however, as it often was perceived by the public as a safe place for evacuation or refuge.

One mosque was located at the Palu coastline, and had fallen off its foundation due to the earthquake and tsunami (see Figure 227). Masjid Agung, the largest mosque in the city of Palu (see Figure 228), also observed substantial nonstructural wall damage and some column damage, potentially due to captive column condition. Non-structural walls and tiles had fallen off the structure due to shaking. The mosque and its surrounding courts were still used as evacuation site during the time of the visit. Partial collapse and significant cracking are also observed in some of the churches visited in Palu (see Figure 229).

Figure 227. A mosque near Palu coastline

Figure 228. Agung Mosque

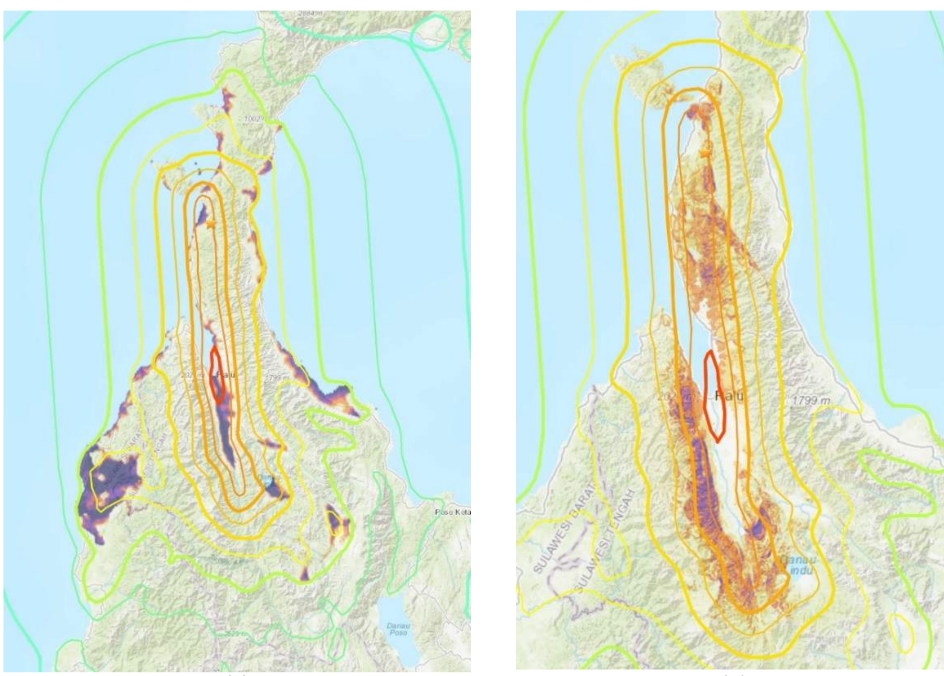
Figure 229. Damaged churches in Palu

III. TSUNAMI AND LIQUEFACTION AFFECTED AREAS

In addition to the intense ground shaking that was caused by the earthquake, significant landslide and liquefaction and ground movement occurred in the city of Palu, Donggala regency, and Sigi regency. It is estimated that 94km^2 area of central Sulawesi was exposed to landslisde and 300km^2 to liquefaction and the population exposed to landslide and liquefaction were 5,600 and 110,000, resepectivley (see Figure 230). In Kampung Muara in the city of Dongala, parts of the neighborhood located along the coastline sank into the bottom of the bay.

Four villages (Balaroa and Petobo in Palu city, Biromaru and Sibalaya in Sigi district) experienced severe liquefaction where houses, streets, and other structures were completely destroyed by the liquefied soil flows. Most buildings were buried under the liquefied soil while the remaining ones were either collapsed/severely damaged (due to settlement of up to 5 meters, large cracks and lateral spreading of soil) or half-buried by the moving soil (see Figure 231 - Figure 234).

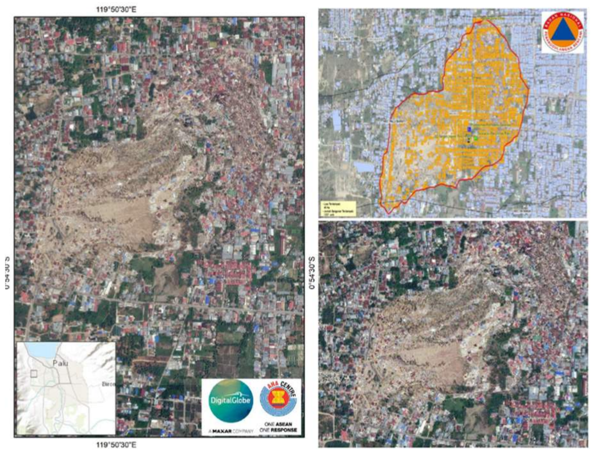
Based on the observation, it was found that the soil in the four villages were either peat or sand, with shallow ground water level. Water was easily observed in all areas in these villages even though it was not in rainy season.



(a) (b)

Figure 230. Estimated area exposed to (a) landslide and (b) liquefaction from the Mw 7.5 near Palu earthquake (USGS, 2018)

(a)



(b)
(The ASEAN Coordinating Center for Humanitarian Assitance on Disaster Management, 2018)

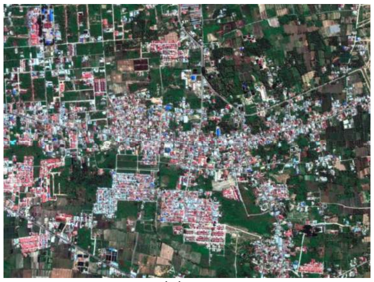
Satellite image of Balaroa village (a) before and (b) after liquefaction

(c) Remaining damaged buildings in Balaroa

(d) Water emerged in Balaroa, showing shallow ground water level

(e) Typical sandy and loose soil in Balaroa

Figure 231. Balaroa village, significantly affected by liquefaction



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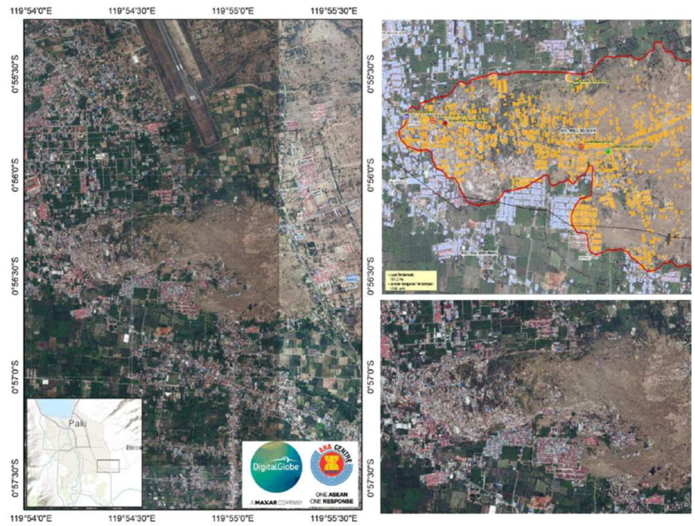


(b)

(The ASEAN Coordinating Center for Humanitarian Assitance on Disaster Management, 2018)

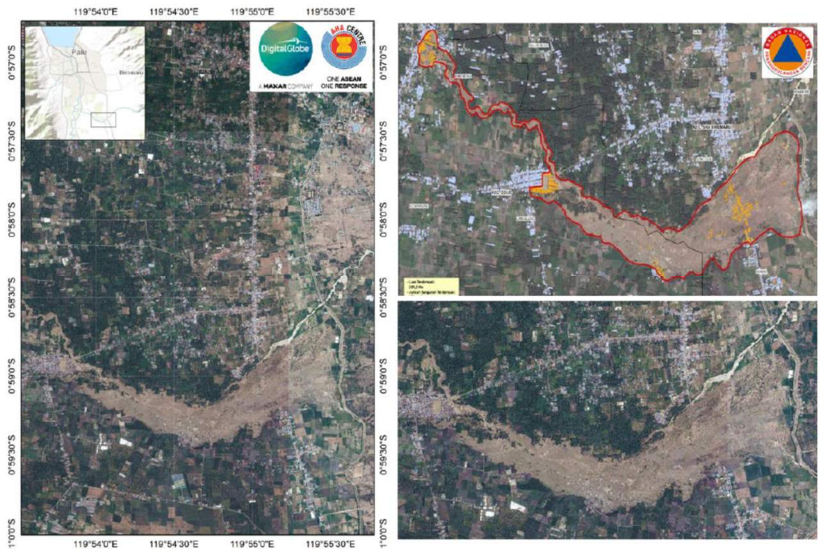
Satellite image of Petobo village (a) before and (b) after liquefaction

(c) Remaining damaged buildings in Petobo

(d) Water emerged in Petobo, showing shallow ground water level

(e) Sandy and loose soil in Petobo

Figure 232. Petobo village, significantly affected by liquefaction



(a) Satellite image of liquefaction site in Biromaru *(The ASEAN Coordinating Center for Humanitarian Assitance on Disaster Management, 2018)*

(b) Remaining damaged buildings in Biromaru after liquefaction

(c) Water emerged in Biromaru, showing shallow ground water level

(d) Soft peat soil dominated Biromaru village

Figure 233. Biromaru area affected by liquefaction

(a) The remaining buildings in Sibalaya village after liquefaction

(b) Sandy soil in Sibalaya village

Figure 234. Sibalaya village that was affected by liquefaction

The earthquake also caused a tsunami, which struck the majority of the coastline along Palu Bay. The narrow shape of the bay most likely intensified the tsunami waves, as waves much higher than predicted for a strike-slip earthquake (6 meters or 20 feet) hit the coastlines of Palu, with maximum height of 11.3 m and run-up of 468m.

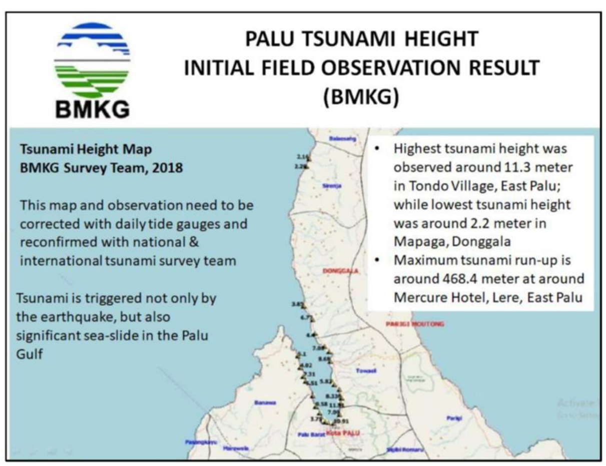


Figure 235. Tsunami height due to the 28 September earthquake *(The ASEAN Coordinating Center for Humanitarian Assitance on Disaster Management, 2018)*

IV. BUILDING CODES/GUIDELINES AND COMPARISON WITH EXISTING BUILDINGS

Based on the observations, it is evident that none of the buildings observed fully meet the applicable standards. Deficiencies were always encountered, either of material quality, structural detailing, workmanship or the combination of all, showing the minimum (if not absent) involvement of technical support, such as engineers, technicians and authorized government body during design and construction process. The most notable discrepancies between the existing buildings observed and the related standards are provided below.

The SNI 15-2094-2000 (regarding clay brick for masonry wall) stipulated the compressive strength of clay bricks to be no lower than 5 MPa. Most bricks seemed to meet this minimum standard, but some clearly not. For concrete blocks, it was regulated in SNI 03-0349-1989 (regarding the concrete block for masonry wall) that concrete blocks for masonry wall should have compressive strength no less than 10 MPa. However, most of the concrete blocks encountered were of poor quality and it was estimated to be less than 5 MPa. The SNI 2847:2013 (regarding the requirement of structural concrete for buildings) limits the structural concrete compressive strength to be no less than 17 MPa. Although the compressive strength of structural concrete was not tested in the field, most structural concrete in buildings observed was estimated to be of poor quality. In some cases, the concrete could easily be broken by hand.

In SNI 2847:2013, article 3.5.1, it is mentioned that the longitudinal rebar of reinforced concrete must be deformed, while from all buildings observed, it was found that all of the longitudinal rebars were smooth. Due to the smaller surface area of smooth bars, around 40% more are required to achieve the same strength as deformed bars and the development and splicing of the bars is affected. The concrete cover of structural concrete is also limited in SNI 2847:2013 to be no less than 4cm. However, from the observation, exposed rebar due to thin concrete cover was prevalent.

In SNI 1726:2012 (regarding design procedures for earthquake resistant-buildings) article 7.14.2, it is stated that the minimum transverse rebar of no less than Ø8mm must be provided every 150mm. However, the field investigation showed that the transverse rebar with diameter 4mm-6mm was provided every 20cm or more. Only in a few cases where the transverse rebar was provided every 150mm.

Based on the decree of Ministry of Housing and Infrastructure No 403/KTPS/M/2002 (regarding the technical guidelines for simple houses), connection between stone foundation and plinth beam must be provided by using Ø12mm rebar every 1.5m. Despite the inability to confirm the use of this anchorage, a total shift of plinth beam from foundation was encountered at one house, which shows the absence of anchorage.

The longitudinal reinforcement of reinforced concrete frame building must be of deformed rebar with the diameter of 12m, while all of the houses assessed used smooth rebar with smaller size. Roof truss must be placed on top of columns, while many roof trusses encountered were of placed on ring beams.

For timber frame and raised houses, in the decree of Ministry of Housing and Infrastructure No 403/KTPS/M/2002, it was stated that the column of timber frame column house should be no less than 10cmx10cm and the beam should be at least 6xmx12cm with timber or no lower than Grade II (E = 10,000 MPa). However, in most houses, timber with smaller size was common to encounter. Wood of Grade II was common to use for structure frame, but for some houses, timber of Grade III was still used. For timber frame with masonry skirt house, a sill plate with dimension of no less than 5cmx10cm must be provided on top of masonry wall, while during investigation, most buildings were not supported by sill plates.

Based on the Ministry of Public of Work and Housing No 05/PRT/M/2016 (regarding the permit of house construction) and stated that the maximum area of walls is limited to be no more than $9m^2$, which means that for buildings with wall height of 3m, the length of a single wall panel should be no more than 3m, and as a consequence, the distance between columns must be no more than 3m. However, most houses appeared to have walls with area of more than the maximum area prescribed, where at some cases, the columns were only provided every 6m. The size of reinforced concrete columns must be no less than 15cmx15cm, while houses with columns dimension of 13cmx13cm were prevalent.

Exclusive for school buildings, despite being regulated in the Ministry of Education and Culture regulation No. 8 year 2018 that the columns of school building must be of 20cmx20cm, the size of some columns and ring beams of one-story school buildings were only around 13cmx13cm.

V. RECOMMENDATIONS

The three major natural disasters that happened at the same time in Central Sulawesi province emphasize the importance to plan and design buildings carefully. The location of buildings, the type of soil, and the structure of buildings must be designed in such a manner that they are safe from tsunami, liquefaction and earthquakes. The fact that many people built their houses in areas with high potential of liquefaction shows the minimum knowledge local people have on natural disaster hazards in their area. Activities such as training and dissemination of flyers/posters are deemed to be critical in helping the society to better choose and determine the location of their houses. The hazard maps should also be evaluated, developed, updated, and disseminated as soon as possible.

The surveys with 28 homeowners showed that only one hired engineers to design their house. However, even this one engineered house still did not fully meet the related standards specified for residential buildings, which might have been cause by an error in the design or due to the initiation of the homeowner or builders to use materials that were not in the design. In either case, it showed the need to do trainings regarding earthquake-resistant building standards to homeowners and workers. The training should include materials that will increase the awareness of homeowners and workers on the importance of implementing the earthquake-resistant house standards to their buildings or the buildings they are working on.

The fact that none of the houses inspected meet related standards is partially caused by the regulations that were not updated. A review of the regulation issued by the Ministry of Public and Works regarding the Residential Housing showed discrepancies between related SNIs. Thus, a review and update on regulations related to housing construction would also be helpful.

Considering that Timber buildings were the least affected buildings due to the earthquake, even when the buildings were non-engineered and the quality of the materials were poor, it is recommended to consider promoting this type of building. However, if homeowners prefer other types of buildings, it is encouraged to get some support from engineers or qualified technicians. If under various circumstances, professional support is not available or not affordable, it is strongly advised to study and follow a design and construction manual provided by various organizations.

The affected communities should be supported in recovery from this disaster through both financial and technical assistance for reconstruction. Our general recommendations for this support are:

1. **Reviewing the existing location**. Reconstruction initiatives or any new constructions should be initiated with a careful site selection, discouraging reconstruction among

stakeholders in hazard-prone sites. The information of the hazard in the existing location also should be made available to the communities, including for those that may tend to rebuild in the hazardous locations, such as adjacent to the fault lines, liquefaction and tsunami zone.

2. **Providing access to the communities to clear and simple, low-cost, culturally appropriate technical resources to rebuild, or repair and retrofit, disaster-resistant homes.** The consideration includes local materials availability, sources, quality, and cost; common structural system (which may vary depending on the materials availability and builder skill); architectural and cultural preferences; and climate and other hazards, such as tsunami zone, high winds, landslides, and flooding.
    a. Prescriptive design guidelines (for engineers and architects).
    b. Simple step-by-step construction guidelines (for builders and homeowners).

    The Ministry of Public Works and Housing has several documents which include requirements for pre-engineered simple housing which can be referenced during reconstruction, such as Technical Requirements for the Construction of Simple, Healthy Housing (Pedoman Teknis Pembangunan Rumah Sederhana Sehat, 2002) and Technical Guidelines for Earthquake Resistant Houses and Buildings, Including Recommendations for Damage Repair (Pedoman Teknis Rumah dan Bangunan Gedung Tahan Gempa, 2006).

    Build Change has also developed an image-based booklet that contains the recommended practices for improving the performance of timber and masonry houses in Indonesia, as seen in Figure 236. which can be used as guideline by builders and homeowners.

Figure 236. Handbook titled "You Can Keep Your Family Safe from Earthquakes: How to Build Strong and Sturdy Houses" (Build Change, Indonesia)

c. Promotional materials, such as posters and flyers, which contain core messages of disaster-resistant design and construction (see Figure 237 and Figure 238).

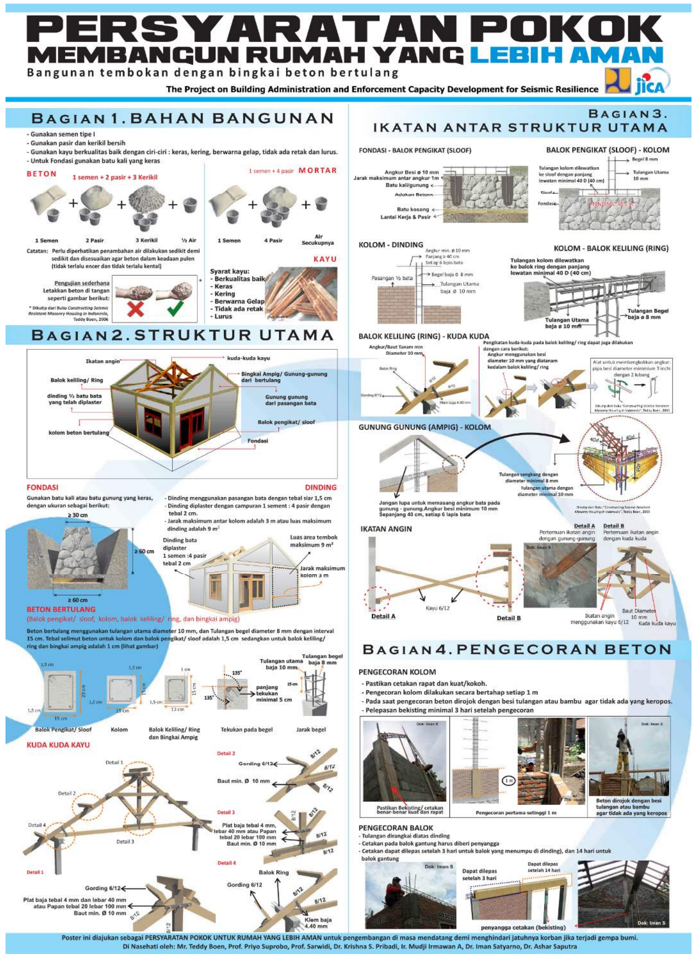


Figure 237. Poster of Principal Requirements for a Safer House (JICA and Ministry of Public Works and Housing, Indonesia)

(a)

(b)

(c)

(d)

Figure 238. Posters/Flyers (a), (b), (c), and (d) Contain Key Messages for Good Connections, Confined Masonry House Construction, Timber Frame House Construction, and How to Choose Good Quality Materials (Build Change, Indonesia)

d. Detailed design drawings, bills of quantity, technical specifications for a range of housing options. Build Change has developed several design packages for a disaster-resistant confined masonry house type and a timber frame house type that available for public use (see Figure 239).

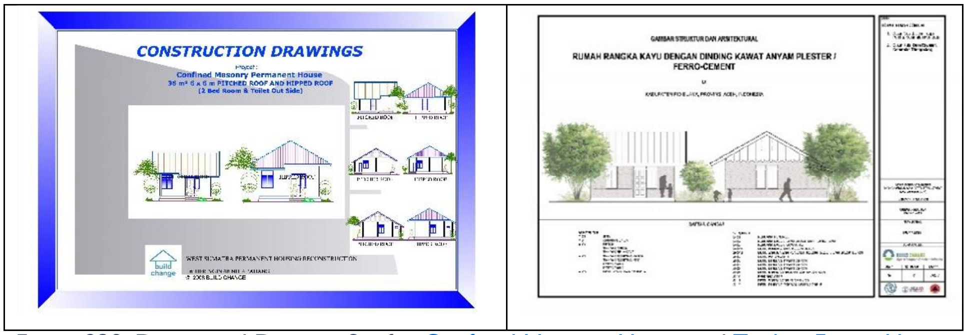


Figure 239. Design and Drawing Set for Confined Masonry House and Timber Frame House (Build Change, Indonesia)

e. Simple guidelines to improve the quality of building materials (for traditional material producers, such as clockmakers and brickmakers). Many of masonry wall materials, such as blocks and bricks, were visually observed in bad quality. Our recent study shows that majority of bricks in several areas in Indonesia are below the requirement of building codes. Providing better quality control, coaching, and a simple manual that contains recommended practices for the traditional producers to improve the quality of their materials, as shown in Figure 240 would be beneficial to improve the construction quality.

Figure 240. Manual on How to Produce Good Quality Bricks (Build Change, Indonesia)

3. **Providing training of good construction practices.** Depending on the level of construction familiarity, skills, and training objectives for each homeowner, school communities, builders, village leaders, local authorities, and engineers, specific training needs to be provided for each segment in order to improve understanding of and building awareness

on disaster-resistant design and construction. Build Change has developed a training module to accommodate specific targeted communities in Indonesia.

4. **Providing technical assistance during construction.** Technical assistance should be provided in accordance with the applicable standards and latest building code, SNI, to aim for proper implementation of disaster-resistant structures. The trained technical facilitator should also be accompanied with technical documents, such as construction quality checklist. A simple construction quality checklist can be developed for each building type, as shown in Figure 241, to be used by facilitators and homeowners.

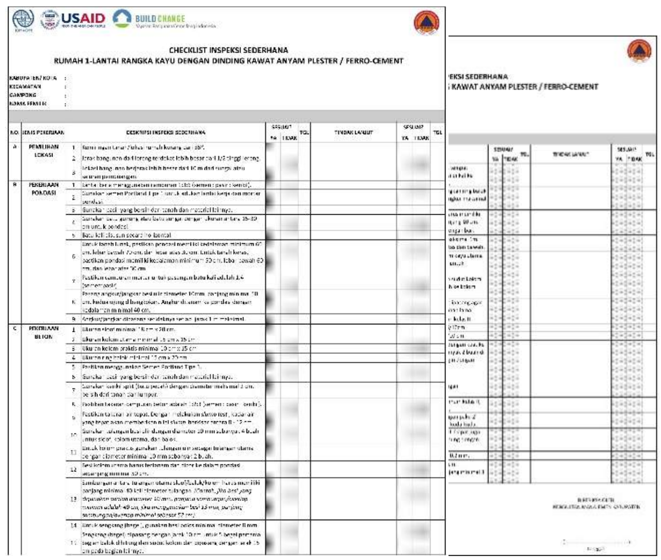


Figure 241. Example Simple Checklist and Visual-based Construction Quality for Timber Frame House with Masonry Skirt and Ferro-cement Wall (Build Change, Indonesia)

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