Forensic investigation of Gumbasa irrigation main canal damage due to large-scale flow liquefaction in Sibalaya caused by the 2018 Sulawesi Earthquake

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Abstract. This study conducted an extensive soil investigation in the Sibalaya liquefaction area to identify the Gumbasa main canal's damage triggered by flow liquefaction. Several field tests and trenches with approximately 4 m were excavated to observe liquefied soil layers directly near the canal. A borehole, standard penetration test, and multichannel analysis surface waves (MASW) were performed beside the trench to obtain each layer’s penetration resistance. This research aims to understand the landslide's whole aspect. The ground movements were analyzed by using satellite photos before and after the earthquake. The displacement of the main canal, the typical damage inventory, and the proposed reconstruction of the main canal are the focus of this study. As a result of the forensic investigation, the liquefied layers and debris flow contributing to the massive landslide were identified to impact the primary canal. The typical damage of the canal was due to surface rupture that occurred both horizontally and vertically. A solution for reconstructing the main canal is to use a flexible pipe canal structure. That will be resilient to future earthquake and ground movements, stabilize the ground downslope of the existing canal to limit the risk of future lateral movement in future earth tremors.

Keywords: earthquake, liquefaction, forensic investigation, Gumbasa irrigation, main canal.

1. Introduction
An earthquake of MW 7.5 hit the Central Sulawesi province in Indonesia on September 28, 2018. This earthquake was followed by liquefaction-induced, large-scale ground flows in several areas in Palu city and its neighborhood. Four sites with extensive ground flow incidents were identified: Balaroa, Petobo, Jono Oge, and Sibalaya, located 80–110 km south of the epicenter [1]. This earthquake was preceded by a sequence of foreshocks, the greatest of which was MW 6.0 that occurred three h before the mainshock. The peak ground accelerations recorded in an acceleration observatory located in Balaroa, western Palu City, were 203 gals (NS), 281 gals (EW), and 335 gals [2].
The National Disaster Mitigation Agency in Indonesia (BNPB) estimates $911 million in Central Sulawesi's economic losses. There were 4,340 fatalities as a result of the earthquake and tsunami (Jakarta Post, 2019). This count includes 667 people who had been declared missing. Search and rescue operations were halted on October 12, and the landslide areas were considered mass graves for those buried by the slides. The earthquake has also resulted in 4,438 major injuries, damage to 68,451 homes, and displacement of 206,494 people. The provincial capital of Palu City, which has a relatively large population of approximately 350,000 inhabitants, suffered the most significant human and economic losses. The enormous loss of life made the Palu-Donggala earthquake the deadliest natural disaster worldwide in 2018 and the deadliest earthquake to affect Indonesia since the 2006 Yogyakarta earthquake. Many fatalities were directly related to landslides, making this one of the most significant landslide disasters of the past several decades [3].

This research aims to understand the landslide's whole aspect. The ground movements were analyzed using satellite photos before and after the earthquake. The displacement of the main canal, the typical damage, and the proposed reconstruction of the main canal are the focus of this study. Trenches near the main canal with a depth of approximately 4 m were excavated to enable direct observation and identification of soil layers liquefied and highly sheared. The surface geology and topography of the main canal have been measured. Finally, a series of field tests were conducted.

1.1. Area of Study

The main five liquefaction areas (Balara, Petobo, Jono Oge, Lolu, and Sibalaya) where the large-scale landslides occurred were located at the end of alluvial fans formed in a relatively new era [4]. Balara was a residential area near the coast, where the number of landslide-related casualties was most significant. This was the only landslide on the left bank side of the Palu River among the four landslides. Petobo, located south of Palu Airport, was also a residential area that suffered many fatalities due to the landslide. The damaged area in Jono Oge and Lolu was located approximately 5 km south of Petobo. It was the largest of the five major areas. However, casualties were fewer than the others because most of the area was used for rice fields. Sibalaya, where the site investigation was conducted, is located approximately 18 km south of Jono Oge, upstream of Palu River. In Sibalaya, the site was well preserved and suitable for investigation because there were no casualties due to the landslide [5](figure 1).

![Image](image_url)  
**Figure 1.** Locations of major flowslide and houses of interviewed eyewitnesses in Sibalaya. (a) Locations of major flowslide and earthquake fault and irrigation channel [2], (b) Satellite image before the earthquake with locations of houses of interviewees, surveyed wells, main road, irrigation channel and flowslide affected area [6]
Figure 1 shows the satellite photo taken in the Sibalaya area in July 2019. The solid line shows the boundary of the affected area of the landslide. A significant amount of ground was moved from the right side of the photo (east-southeast) to the left side (west-northwest). At the upstream of the landslide, an unlined irrigation channel extends north to south, which connects to downstream areas of Jono Oge and Petobo. In both areas, the landslide mass flowed westward from this channel, suggesting a contribution of channel and irrigation water to the occurrence of landslide [7]. The affected area and the overall length calculated based on the photos are approximately 0.52 km² and 1.1 km. The original slope of the area obtained from Google earth is approximately 5%, similar to the other three areas. Before the landslide occurred, the main road passed from north to south, and about 60 houses were built around the road. An athletic field and rice fields initially spread to the east side of the main road, and the rice fields also spread to the west. After the landslide occurred, a new unpaved road was constructed at the exact location as before. In this paper, the moving and new roads are referred to as the original and main roads.

![Figure 2. Geology Map and Geohydrology Area of Study: (a) Regional geology map of Sibalaya area and (b) Groundwater Level Around Gumbasa Irrigation system. Modified from [8][9]](image)

1.2 Geology, Active Faults, and Hydrogeology Of Gumbasa Irrigation Project Area

Geological information of an area is a crucial factor that will support the planning, construction, or repair of post irrigation construction. Geological information of an area requires regional geological references to understand local geological conditions that regional factors will strongly influence. Geomorphological conditions, lithology, and geological structures are the crucial factors in identifying the causes of irrigation structures’ damage. The damage might result from the geological structures that cause earthquakes, ground cracks, ground motion, liquefaction, and other factors that can also be supported by the morphological and lithological conditions of the area.

The available 1:250,000 geological mapping of the Palu Quadrangle (1973), Pasangkayu Quadrangle (1993), and Poso Quadrangle (1997), Sulawesi, indicates that the stratigraphy of the Palu area (from the oldest to youngest) is composed of the Metamorphic Complex, Gumbasa Complex, Latimojong Formation/Tinombo Formation, and Pakuli Formation/Celebes Molasse. The alluvium and coastal
deposits overlay most of the coastal plain area. Several generations of intrusive rocks are present in the project area. Alluvial and coastal deposits can be found overlying the Pakuli Formation/Celebes Molasse and Metamorphic Complex Towards the Palu Bay area. Approximately 15km south of the Palu Bay area, alluvial deposits can be found overlying the Pakuli Formation/Celebes Molasse (with coastal deposits absent), which in turn overly the Latiomong Formation/Tinombo Formation, with the Gumbasa Complex and the intrusive rocks located at depth. The geological map presented in Figure 2 presents a similar geological map obtained from the GEER (2019) study [6]. The course of the canal and the flow slide locations are highlighted.

The Palu-Koro Fault is an active north-northwest shear fault that is still active and has triggered various geological natural disasters recorded in the history of the Palu area [10], [11]. The last record of this geological structural activity occurred on September 28, 2018, which caused a magnitude M7.4 earthquake followed by a tsunami and liquefaction [10].

The shear fault rate of the Palu-Koro Fault based on geological studies is 58 mm/year [12], 40 mm/year by the results of GPS measurements [13]. Meanwhile, based on the 2016 GPS measurement data outlined in the 2007 Indonesia Earthquake Hazard and Source Map, the shear rate of the Palu-Koro Fault is 20-40 mm/year. The last activity recording of this geological structure occurred on September 28, 2018, which caused an earthquake of magnitude M7.4, followed by a tsunami and liquefaction [1].

The Palu-Koro Fault borders the eastern and western ridges of the Palu Valley, characterized by a line of springs, including hot springs along the surface of the fault line. Other faults and straightness half parallel to the main direction of the fault are found in the eastern ridge [2].

The Palu River flows through the Palu Valley in an approximate north-south direction towards the Palu Bay area. Several drainage networks east of Jono Oge are associated with the mountains located to the east of the site. A seasonal river (named the Paneki River) is present, which runs north of the Jono Oge site from the mountains to the east to the Palu River. There is evidence for the drainage of tributaries to the east of the Sibalaya site location.

In regards to the Groundwater Flow Regime, the JICA study indicates that in the northern section of the Palu Valley within the vicinity of Jono Oge, Lolu, and Petobo, surface water from the mountains on both sides of Palu Valley, is noted as flowing underground upon encountering the alluvial fans within the valley before springing out on the ground surface near the toe of the alluvial fans except for one location. JICA study carried out a groundwater analysis that identified the spring zone associated with the alluvial fan and calculated the groundwater level using a three-dimensional lattice model. The groundwater level is interpreted to be very shallow at the Jono Oge failure zone (figure 2) [9].

The groundwater level was monitored in several people's wells around the Sibalaya liquefaction area in June 2019. The groundwater table was at 5.6 m and 17.5 m before and after the earthquake [5].

![Figure 3](image_url)

**Figure 3. Situation Map Of Main Canal Of Sibalaya Liquefaction area:** (a) Countour map of a long section of the main canal, (b) Typical cross-section of the main canal

Source: Modified from Lidar Data (DTM) of Badan Infomasi Geospatial (BIG) (2020)
2. Materials and Methods
This research is in the South Sibalaya Liquefaction area, Sigi Regency, Central Sulawesi, Indonesia, with 520 m². The situation map of the main canal with long and cross-section is in figure 3. And for The several field test location point is presented in the following Figure 4:

![Field test point](image)

Figure 4. Field test point and result: (a), (b) N-SPT of two bore at 50 and 300 m of the main canal, (c) Trenching picture near to the main canal, and (d) 3 point of MASW Field test line.

Source: (Field test conducted with PUSAIR Bandung)

2.1 Field Test Position and Results
The two deep drill holes and SPT and 3 MASW tests have been carried out in the main channel area in the affected Sibalaya liquefaction area. The test results show that the eastern region (hilly side BH.01) of the main canal leads the results of the NSPT test on drill hole BH.01. The soil type is silty sand on the top layer containing gravel fractions with solid densities ranging from 1.5 meters to 5 meters with N_SPT value > 30. While the layer below 5 meters is in the form of silty coarse sand containing gravel fraction with very dense density. The results of the NSPT test on Drill Hole 2 show that the soil layer is in the form of fine silty sand on the top layer up to 3 meters with loose density. Below is a layer of loamy sand to a depth of 9 meters with medium density. The layer above 9 meters is silty sand containing gravel with a solid density to very dense value of N_SPT > 30.

Test MASW or Multichannel Analysis Surface Wave is a non-destructive method to determine the level of soil hardness based on the shear wave velocity (Vs) measured from the surface. MASW is one of the geophysical techniques. This method is a seismic survey method used to identify the
character of the soil near the surface by utilizing Rayleigh surface waves. The shear wave velocity can be used for subsurface images, especially knowing the distribution of the soft layer. In line 1, the MASW test shows that the soil type in the surface layer up to 12 meters is very loose. Interspersed with a layer with a thin medium density of about 2 meters and then a loose layer again up to 22 meters. It is almost similar to line 3, only at a depth of 3.5 meters to 5.5 meters, there is a medium-density layer. While on line 2, there is a layer with a medium-density above up to 5 meters, then a loose layer between 5 meters to 14 meters. Followed by a medium density layer up to 22 meters and followed by a loose layer up to 31 meters 9 (Figure 4).

The trenching results clearly show that about a 2-meter deep layer is very loose uniform sand followed with original silty sand layer. The loose sand layer is sedimentation that comes from the channel that collapsed through the area after the earthquake. The original layer had been bottomed into debris flow due to the overflow of the main channel that collapsed after the earthquake.

![Image](image_url)

**Figure 5.** The surface rupture moves downward about 2-3 meters and opening up to 3 meters on the Main Canal of Sibalaya Liquefaction Area (BGKn 8), which is heavily damaged.

### 2.2 Main Canal Damage Inventory in Sibalaya Liquefaction Area

Based on the survey results, it is known that heavy damage from irrigation structures was caused by surface rupture (Figure 5). Its traversed north-south and north-east-south-southwest indicate the existence of geological structures triggered by high seismicity activity in the Central Sulawesi Region, especially Palu and Sigi, on September 28 2018. The damage was also exacerbated by irrigation structures that have been built on sedimentary rocks that were unconsolidated due to not being well cemented. It is causing the rock to tend to have a lower density. This condition causes the need for particular engineering to avoid damage to new structures due to the rehabilitation of damaged irrigation structures at this time.

Based on the results of geological investigations in the field (Figure 5) that the area around the Sibalaya primary canal is composed of several types of rock, where the old to young rocks are
metamorphic rock units consisting of phyllite and muscovite schists originating from the Metamorphic Rock Complex Formation (Km). Unconsolidated sedimentary rock units are composed of conglomerates and sandstones from the Pakuli Formation (Qp), as well as river deposits consisting of boulders, gravels (from older rocks formation), sands to clay from the Alluvium Formation (Qa).

The results of the inventory of structural damage that occurred in the main canal at the Sibalaya liquefaction area showed the type of damage due to surface rupture that occurred both horizontally and vertically, where the rupture length is up to 15 meters, with openings rupture up to 2.5 meters and vertical movement up to 2.0 meters (table 1).

**Table 1. The Damage Inventory of Main Canal in Sibalaya Liquefaction Area**

| STATION | COORDINATE | Elevation (m) | DESCRIPTION | Direction of Rupture |
|---------|------------|---------------|-------------|----------------------|
| BGKn.8  | 119 55 29.3 -1 8 57 | 93 | Surface rupture; length about 12m, opening rupture 100-250cm, vertical movement downwards: 20cm-200cm | 35 |
|         | 119 55 32 -1 7 51 | 89.73 | Surface rupture around the irrigation central line, extending north-south to BGKn.10 with an increasingly narrow opening. Opening rupture: 20cm-220cm, depth rupture: 30-150cm. | 350 |
|         | 119 55 32 -1 7 52 | 87.3 | Surface rupture; vertical movement downwards: 30-150cm. Length of rupture 15m. Vertical movement caused damage in irrigation lining. | 10 |

3. **Result and Discussion**

There was some strategy to develop a solution of reconstructing the main canal with build back better solution. Some of the strategies include: (1). The prime objective is presumably to get the canal back operational in a short time frame and at a reasonable cost (2). The canal should have an affordable resilience to future earthquake and ground movements, and (3). Any solution developed should focus on Resistance and Resilience and stabilize the ground downslope of the existing canal to limit the risk of future lateral movement in future earth tremors.

Before we propose a solution to reconstruct the main canal in the liquefaction area, there is a need for well-defined Performance Objectives of the main canal services. Several objectives need to be considered, including:

- The canal shall be considered as critical infrastructure bordering on lifeline structure
- The canal does not support any firefighting efforts
- Important to limit future leakage from the canal to the lowest practical level.
- The canal shall be designed for the serviceability limit state (SLS) and the ultimate limit state (ULS) criteria.
- For SLS case – Serviceable & Operational, recoverable in days, Approximate magnitude is Mag 6, with PGA 0.25g-0.35g, and Return period 5-10 years
- For ULS case – controllable damage, Repairable, recovery in months, Approximate magnitude is Mag 7.5, with PGA =0.5g – 0.75g

The National Earthquake Study Center (PUSGEN) provides recommendations for a deterministic approach to structural analysis in earthquake areas. For irrigation structures of Gumbasa is recommended to use 50-percentile (Figure 6).
Figure 6. Deterministic Seismic Hazard Analysis (DSHA) map of Palu-Koro Fault in Central Sulawesi.
Source: PuSGeN (2020).

Therefore, the option for the rehabilitation of the main canals considers various canal lining options. The objectives of canal lining are; (1). Prevent water loss/leakage. The soil properties highly determine this through or of which the canal is built. Ideally, test pits and soil investigation are necessary to decide the design and extend of linings; (2). Prevent scouring and erosion: for high velocities condition, at sharp bends, and as part of the exit transitions from canal structures; (3). To aid embankment stability: providing stability specifically for steep slope-high embankment and high water table; (4). Provide additional resistant earthquake loads; (5). Reducing maintenance costs; Various main canal reconstruction options are proposed.

3.1. Several Options to reconstruct the main canal structures
There are several options to improve the main canal in the Sibalaya liquefaction area by considering resistance, resilience, and stabilizing the existing canal’s ground downslope. These options limit the risk of future lateral movement in future earth tremors.

1. The Flexible Pipe Canal Structure
The Flexible Pipe Canal will be the best option for earthquake resilience because it will be resistant to vertical and lateral forces due to earthquakes (Figure 7). With pipes and flexible connections will be able to absorb the earthquake forces that occur. Even if there is damage, it will be easily repaired and does not require a long time.

With the plan of lining with precast concrete and an impermeable layer in the form of geomembrane along the main canal and changes in land function from paddy fields to secondary crops or parks in former liquefaction areas, the potential for liquefaction in the future will decrease, especially after the earthquake that the groundwater level is now below 15 meters refers to [6].
Figure 7. Option of the Flexible Pipe Canal Structure

The disadvantage of the option is not resilient for future liquefaction underneath the main canal if it returns.

2. HDPE Pipe Canal with Stone Column Reinforced
The HDPE Pipe Canal with stone column reinforced will be a good option for the earthquake resilient and future liquefaction potential (Figure 8). HDPE Pipe is very resistant to vertical and lateral forces due to earthquakes. It will be able to absorb the earthquake forces that occur in the future. The stone column under the main canal pipe will be very efficient in releasing the pore water pressure during the earthquake, reducing the liquefaction potential. Furthermore, this is easy to be repaired and does not require a long time.

The disadvantage of the option is not easy to maintain due to sediment any other material that goes through to the main canal hole. When the lateral spreading (horizontal movement) occurs at the stone column body, it will interfere with the function of the stone column.

Figure 8. Option of the HDPE Pipe canal with stone column reinforced

3. Precast sheet pile canal structure/Embedded retaining wall structure
Using the main canal structure with sheet piling of precast concrete will provide advantages, especially in resistance to lateral forces caused by earthquakes. Lateral spreading, which is a follow-up of a large earthquake, will be damped by the sheet pile structure. Furthermore, the penetration of depth must pass through a layer with a high liquefaction potential of up to 5 meters, which refers to borehole one. This sheet pile canal structure will be an ideal alternative (Figure 9). The weakness of this structure is that it is rather challenging to install, especially on gravel soil conditions, and the relatively high cost and time-consuming. The method of implementation must be considered when choosing this sheep pile canal structure.
Figure 9. Option of the precast Sheet pile canal Structure / Embedded retaining wall structure

It needs to realize that the geotechnical data supporting the design optionaire to be more reliable is required, and some of the most suited design options could change in the future if the data of soil investigation reveals materially different ground and or groundwater conditions.

4. Conclusions

The Gumbasa Irrigation System has not been operational since the 2018 earthquake caused significant damage to the infrastructure network. Farmers have resorted to growing rainfed crops. Implementing civil works to rebuild the irrigation infrastructure would restore the required supplies to farmers across the command area. This condition increases the income, livelihoods, and food security of communities in the area. Additional non-civil components would enhance the operation of the network, maximize the potential benefits and enhance long-term resilience to future disasters. The significant findings are as follows:
1. Reconstruction of Gumbasa Irrigation System to its required design capacity
2. Improved resilience of the network by Building Back Better Preferred options have been selected, balancing the need to build back quickly whilst considering increased stability to future disasters.
3. It should be noted that some repair and reconstruction will still be required following future disasters.
4. Design analysis of preferred infrastructure options (including canal lining and structures) and review their resilience, including potential design life. The standard of earthquake protection and repairability shall be prior consent.

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