Sanding Wells on The Island of Lombok due to Earthquake Vibrations

Bagus Endar B. Nurhandoko¹, M. Rizka Asmara Hadi², Kaswandhi Triyoso³, Rio K. Martha¹, Sri Widowati³, Bakti Sukrisna⁴, Syamsuddin⁴, Nur Isnaini Romli⁵

¹ Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung
² LPIK, Institut Teknologi Bandung
³ Telkom University
⁴ Mataram University
⁵ Formerly FMIPA ITB, Presently Rumah Amal Salman ITB

Correspondence: bagusnur@bdg.centrin.net.id

Abstract. The Lombok earthquake in 2018 was unique, the shocks occurred sequentially. Several major earthquakes were followed by thousands of aftershocks. The earthquake caused a devastating disaster which destroyed many homes, buildings including wells as the main fresh water supply in the Lombok Island. The focal mechanism of main earthquake shows a thrust fault mechanism. Lombok Island is originally a volcano Island which is still growing actively. Therefore surface of Island is dominated by volcanic materials, such as: volcanic rock, volcanic ash, pumice. This paper describes the phenomenon of sanding wells in Lombok, including the physical mechanisms among rock’s grains when vibrating earthquake waves. These earthquake waves can eliminate static friction between grains and reduce cohesion between grains of rock. Some subsurface images shows a strong correlation between damage grade and the existence of loose sand and hard rock.

1. Introduction
In 2018, the Lombok earthquake occurred over a long period time. The Lombok earthquake occurred serially for more than one month. The seismic waves caused the disaster that destroyed many homes and buildings. North Lombok was almost completely collapsed. All of the Groundwater wells in northern Lombok are almost silting due to the sanding phenomenon. The sanding phenomenon is the phenomenon where wells produce sand due to loss of rock strength. The sanding phenomenon associated with earthquakes maybe related to the phenomenon of liquefaction. The sanding problems have been published by some authors i.e.: Rissness et al. [1], Bratli and Risnes [2], Fattahpour et al. [3], Morita et al. [4], Bradford and Cook [5], Nurhandoko et al. [6], Melcafe et al. [7]. This paper present the massive sanding phenomenon occurred on Lombok Island related earthquake parameters. There is a strong correlation with the damage condition in the area, including the severity of the sanding phenomena on the wells during the earthquake.

2. Lombok Earthquake 2018 and Geology of Lombok
The focal mechanism of the Lombok earthquake showed thrust fault mechanism [8] as shown in Figure 1. Analysis of land deformation show the northern part of Lombok Island had been uplifted for
range 25 cm [9] to 29 cm after the earthquake series [10]. Geological map published by the Ministry of Energy and Mineral Resources of the Republic of Indonesia, the lithology around North Lombok consists of mostly gravel, sand, clay tuff, peat, and a fragment of coral. The surface area in Northern of Lombok Island consists of volcanic products i.e.: volcanic ash, pumice, and loose sand.

3. Grains of rocks parameters of North Lombok
Parameter grains of the samples show low specific mass (about 1.0 to 1.3 g / cc) and contains pumice which has a very low mass density (0.5 g / cc). The grain size measurement showed that the dominant size is 0.4 mm, see in Figure 2.

When the 2018 Lombok earthquake occurred, almost all of the groundwater wells in Northern Lombok suffered shallowing and structural damage due to earthquake vibrations. The earthquake vibration can result the shear stress exceeds the static friction’s stress which impact the vibration causes the grains of the matrix to separate from each other. The release of bonds among grains causes a loss of shear modulus. The siltation phenomenon due to the sanding mechanism observed in almost whole groundwater wells in Northern Lombok.

4. Acceleration and focal mechanism of the 2018 Lombok Earthquake
The hypocenter of the 2018 Lombok earthquake was spread over almost all of northern Lombok and formed a half-ring pattern. Based on data from USGS peak ground acceleration (PGA), the main earthquake occurred in Lombok in the range of 20%–50% g. PGA played a dominant role in the occurrence of the liquefaction phenomenon in several areas in North Lombok when the earthquake struck mainland Lombok. Figure 1 shows that focal mechanism of earthquakes in Lombok was the thrust fault mechanism. The existence of the thrust fault mechanism shows that vertical motion during the earthquake was very dominant. Therefore, the waves generated during the earthquake were most likely P waves and Rayleigh waves (P and S waves).

5. Grain dynamics mechanism during earthquake
The well shallowing caused by the sanding phenomenon in the northern part of Lombok Island was significantly influenced by decreased effective stress contact among grains. When effective stress on the contact area among grains decreases, the grains tend to separate from each other, creating fluid-like movement. Furthermore, the sand flows to reach the water table. These phenomena are predominantly influenced by the dynamic mechanism of pressure induced by earthquake vibrations.
The mechanism of vertical vibration caused by the thrust fault mechanism causes dynamic pressure in grains and pore rocks through vertical movement. Under ambient conditions or conditions of no earthquake vibrations, the static vertical force of each grain can be determined as follows:

\[ F_{\text{effective}} = (\rho_{\text{grain}} - \rho_{\text{water}})V_{\text{grain}}g + F_{\text{overburden}} - F_{\text{pore}} \]  

(1)

\( F_{\text{effective}} \) indicates the vertical force of each grain, \( F_{\text{overburden}} \) indicates overburden force, \( V_{\text{grain}} \) indicates the volume of grain, \( \rho_{\text{grain}} \) indicates the density of grain, \( \rho_{\text{water}} \) indicates the density of water, and \( g \) indicates gravity acceleration. The earthquake waves are considered to be made up of vertical dominated waves on a set of rock pores with a pore pressure \( P_0 \), where \( P_{\text{earthquake}} \) denotes the maximum pressure generated by waves. The static vertical effective pressure on grains contact is as follows:

\[ P_{\text{effective}} = - (P_0 + P_{\text{earthquake}}e^{i(kr-\omega t)}) + P_{\text{overburden}} + (\rho_{\text{grain}} - \rho_{\text{water}})V_{\text{grain}}g \]  

\[ \rho_{\text{grain}} \]  

(2)

Therefore, the vertical vector of stress (\( P_{\text{vertical}} \)) at the interface among grains is estimated as follows:

\[ P_{\text{effective}} = - P_{\text{pore}} - P_{\text{earthquake}} + \int_{h=0}^{h=\text{depth}} \rho(h)_{\text{overburden}}gdh + (\rho_{\text{grain}} - \rho_{\text{water}}) 2.67 \ g \cdot r_{\text{grain}} \]  

(3)

Equation (3) indicates that the liquefaction parameters are the pore pressure \( (P_{\text{pore}}) \), maximum pressure generated by waves \( P_{\text{earthquake}} \), grain density, overburden stress \( P_{\text{overburden}} \), grain size \( r \), and acceleration of earthquake waves. The sanding mechanism will occur if the \( P_{\text{vertical}} \) of equation (3) is negative.

\[ P_{\text{effective}} = - \int_{h=\text{water table}}^{h=\text{total depth}} \rho_{\text{water}}gdh - \frac{P_e}{\omega}a_{\text{max}} + \int_{h=0}^{h=\text{total depth}} \rho(h)_{\text{overburden}}gdh \]  

\[ + (\rho_{\text{grain}} - \rho_{\text{water}}) 5.33 \ g \cdot r_{\text{grain}} \]  

(4)

When the effective + tensile stress of rock was less than zero, the grains were separated from each other or the well under sanding conditions. The well became shallower due to these grains flowed to fill the wells until reaching the water table. The center zone at the bottom of the well suffered the most severe sanding phenomenon due to the absence of rock overburden pressure resulting in the smallest value of effective pressure among the grains. Therefore, when the earthquake with thrust fault mechanism hit northern of Lombok, the greatest upward vertical pressure occurred at the bottom of the well. The distribution of rock grains size is Figure 2. The rock were thrown upwards and caused a sanding mechanism, as illustrated in Figure 3.

When the earthquake waves shock the grains in the range of peak ground acceleration (PGA) 20% g to 50% g, the sanding phenomenon happened. Sand became like fluid flowing from the bottom of well and reached the water table.
Figure 2. Distribution of the sample size (in mm diameter) as determined by sieve analysis.

Figure 3. Illustration of the sanding mechanism phenomenon causing siltation on wells in the North of Lombok island

6. Conclusions
The island of Lombok was rocked by a series of earthquakes in 2018 which destroyed large numbers of homes. The earthquake also vibration caused silting of wells due to the sanding phenomenon. The focal mechanism of the Lombok earthquake shows the vertical movement of the thrust fault mechanism. The surface of North Lombok Island dominated by volcanic products and has a very shallow water surface.

Earthquakes can reduce the effective stress between the grains and grains are separated from each other.

We have presented a physical mechanism which correlates wave parameters and saturated water pore pressure, radius, and grain buoyancy pressure, leading to a drop in the effective pressure between grains. The north of Lombok has suffered a sanding phenomenon because the effective pressure between the grains is negative at their original depth conditions. Wells in North Lombok lost their water column, and there was catastrophic water scarcity.

References
[1] Risnes R, Bratli R K and Horsrud P 1982 Sand stresses around a wellbore Society of Petroleum Engineers Journal 22(06) pp 883–898
[2] Bratli R K and Risnes R 1981 Stability and failure of sand arches Society of Petroleum Engineers Journal 21(02) pp 236–248
[3] Fattahpour V, Moosavi M and Mehranpour M 2012 An experimental investigation on the effect of rock strength and perforation size on sand production Journal of Petroleum Science and Engineering 86–87 pp 172–189 doi: 10.1016/j.petrol.2012.03.023
[4] Morita N, Whitfill D L, Massie I and Knudsen T W 1989 Realistic sand-production prediction: numerical approach SPE Production Engineering 4(01) pp 15–24
[5] Bradford I D R and Cook J M 1994 A semi-analytic elastoplastic model for wellbore stability with applications to sanding Paper presented at the Rock Mechanics in Petroleum Engineering Delft Netherlands

[6] Nurhandoko B E B, Susilowati and Listiyobudi M 2018 Thick Walled Core Testing for Sanding Analysis of Chalky Carbonate Reservoir in Production Borehole The 43rd Annual Scientific Meeting Himpunan Ahli Geofisika Indonesia

[7] Metcalfe G, Tennakoon S G K, Kondic L, Schaeffer D G and Behringer R P 2002 Granular friction, Coulomb failure, and the fluid-solid transition for horizontally shaken granular materials Physical Review E 65(3) pp 031302

[8] USGS Catalog 2020 https://earthquake.usgs.gov accessed 2020 https://earthquake.usgs.gov

[9] NASA Earth Science Satellite-Derived Map of Ground Deformation from Earthquake beneath Lombok, Indonesia [Online] Available: https://disasters.nasa.gov/lombok-indonesia-earthquake-2018/satellite-derived-map-ground-deformation-earthquake-beneath-lombok

[10] Ramdani F, Setiani P and Setiawati D A 2019 Analysis of sequence earthquake of Lombok Island, Indonesia Progress in Disaster Science 4 pp 100046 doi: 10.1016/j.pdisas.2019.100046