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ONE DECADE OF THE "LUSI" MUD VOLCANO: PHYSICAL, CHEMICAL, AND GEOLOGICAL DIMENSIONS

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Abstract. In this article, we have raised more recent phenomenon of mud volcano disaster since May 2006 until now in Sidoarjo, East Java- Indonesia. This rare occurrence has invited the public to enjoy, even for scientist as a mean of doing research or for public as a curiosity. A mud volcano is a geological formation created by the expulsion of pressurized gasses and mud from below the Earth's crust. By using a systematic review process, the authors review the phenomena by using physical, chemical, and geological approaches. The review process comprises five phases: framing questions for a review, identifying relevant work, assessing the quality of studies, summarizing evidences, and interpreting the findings. The results show the physical and chemical dimensions of mud volcano and depict to what extent the physical and geological efforts to stop the disaster. In this study, there are some additional references and sources of new knowledge for scientists, citizens, and government.

Keywords: chemistry; geology; Indonesia; mud volcano; physics

Introduction

Ten years ago (May 29, 2006), in a field near Sidoarjo regency-Indonesia, there were suddenly erupted a flow of hot mud, water, and gasses that spurted high into the air. The phenomenon was similar to the appearance of geysers such as seen in Yellowstone National Park in the USA. The flow of mud has continued until now to eject the mixture among water, mud, and clay, accompanied by methane gas. The spout sometimes is reaching levels of 150,000 cubic meters per day, thus far overwhelming 641-hectares area (Richards, 2011). In fact, the disaster was caused by a technical error during an oil exploration of *Lapindo Brantas Inc* (the company) in the Porong area, a sub-district as part of the Sidoarjo district of the East Java province of Indonesia. The mudflow spread widely,[1)] encompassing 12 villages and forcing around 14,000 households, consisted about 40,000 people to relocate (Richards, 2011).

The eruption of the mud volcano called "LUSI" (an abbreviation of the Indonesian word for mud, "**Lu**mpur" and "**Si**doarjo", the city where the eruption occurred) have been linked by many scientists, both local and international with a powerful 6.3 [Righter scale] earthquake in Jogjakarta- Central Java, which struck 250 kilometers away, two days previously. The earthquake was noted by Indonesian scientist as one of the most powerful ever to vibrate Java island, as these areas were in the category of the *ring of fire*, a country in the basin of the Pacific Ocean where a large number of earthquakes and volcanic eruptions occurred. The ring of fire is sometimes called the circum-Pacific belt. The belt across from the South American plate, the Caribbean plate (Central America), the North American plate (United States, Mexico, Canada), the West Pacific plate (Japan, Taiwan, Philippines, Indonesia), until the Southern-pacific (Mariana islands, Bougainville, Tonga, New Guinea, and New Zealand). However, no feasible method is known by which the Yogyakarta earthquake could have triggered the mud flow and that a blowout from the center of mud well was the most likely mechanism for initiating the Lusi eruption (Tingay et al., 2008).

A volcanic mudflow or "lahar", evoke hazard. The word "lahar" is also from Indonesia [a country with some of the most active volcanoes], but lahars take place worldwide (Sheth, 2003). The Lusi mud volcano was the first time in the world that a mudflow has been observed from the beginning of its explosion. It has been noted that mud flows have occurred in other parts of the world, such as Alaska, Barbados Islands, Black Sea, Caspian Sea, Gulf of Mexico, Koturdag and Lokbatan (Azerbaijan), Nigeria, Nirano (Italy), Piparo (Trinidad-Tobago), Southern Taiwan, etc. (Martinelli & Panahi, 2005). The "Lusi" mudflow is still spreading, and many scientists predicted that it will continue until the next 20 years. A study by Davies et al. (2011), based upon carbonates in the range 2500 – 3500 m depth, estimated that the mud can be expected will develop within the 26 year time periods.

Regarding this phenomena, cannot be avoided in discussing what will happen in the future. A study related to the relevant fields is needed to assess and to evaluate what actually has happened, is happening and will happen. Physics, chemistry, and geology are the study, which closed to this phenomenon makes it possible to review the above phenomena. Therefore, the authors review the mud volcano by using physical ad geological approaches in this study. By doing this, the study is addressed for twofold: (1) what are the physical, chemical, and geological dimensions of mud volcano (with a special case of the Lusi mud volcano)?; (2) to what extent do the efforts in stopping Lusi mud volcano?

Methodology: procedure of systematic review

The procedure of systematic review followed the direction of some previous researchers (such as, Khan et al. (2003), Suprapto (2016) and Suprapto & Pai (2015)). The review process comprises five phases: framing questions for a review, identifying relevant work, assessing the quality of studies, summarizing the evidence, and interpreting the findings. The process has started from defining the purpose of research and has followed by conducting a searching literature. Then the process continued by selecting the references (articles by reading abstracts; books by checking the main point) to capture the main idea of the previous study. For clarification and depth understanding, reading a full paper became important. The procedure continued by data abstraction and conducting analysis to describe the conclusion based on the purpose of the study.

Results and discussion

Physical dimensions

Viscosity

The term of 'viscosity' is well-defined by the dimension of a fluid that resists the force tending to motive the fluid to flow. In simple, viscosity is a measure of a fluid's resistance to flow. Ordinarily, viscosity is associated to the concept of shear force. It can be understood as the effect of different layers of the fluid exerting shearing force on each other, or on other surfaces, as they move against each other. Generally, there are two kinds of viscosity, namely: kinematic and dynamic viscosity.

Kinematic viscosity ($\boldsymbol{\eta}_k$) is a measure of the rate at which momentum is transferred through a fluid. Dynamic viscosity ($\boldsymbol{\eta}_d$) is a measure of the ratio of the stress on a region of fluid to the rate of change of strain it undergoes. It is equal to the kinematic viscosity times the density of the fluid ($\boldsymbol{\eta}_k = \boldsymbol{\eta}_{k.\rho}$).

Real liquids as well mud experience viscosity, a fluid friction that obstructs their flow. Therefore, it is the resistance of a fluid to flow. When liquid flows over a flat surface, a backward viscous force acts tangentially to every layer. This force *F* depends upon the area of the layer, velocity of the layer, and the distance of the layer from the surface.

$$F = \eta \mathrm{A} \frac{\mathrm{d}v}{\mathrm{d}x} \tag{1}$$

where η is the *coefficient of viscosity* of the liquid.

Viscosity saps the fluid's energy, causing pressure to drop as the flow progresses. The volume flow rate (*Q*) through a cylindrical pipe/ tube is proportional to the pressure difference between its ends, which is called the *pressure gradient*.

$$Q = \frac{\Delta \mathrm{V}}{\Delta t} = \frac{\pi \mathrm{R}^4 (P_1 - P_2)}{8\eta \mathrm{L}} = \frac{\pi \mathrm{R}^4}{8\eta} \frac{\Delta P}{\mathrm{L}} \tag{2}$$

The specific relationship in Eq. (2) is called *Poiseuille's law*.

Stoke's law

A Stoke's law was established by an English scientist Sir George G. Stokes (1819-1903). When a spherical body moves down through an infinite column of highly viscous liquid, it drags the layer of the liquid in contact with it. As a result, the body experiences a retarding force.

Then, according to Stokes law, the viscous drag force,

$$F = 6\pi\eta Rv \tag{3}$$

where, R = radius of the spherical body; v = velocity of the spherical body.

It gives the relationship between retarding force and velocity. When viscous force plus buoyant force becomes equal to force due to gravity, the net force becomes zero. If a sphere falling in a viscous fluid reaches *a constant terminal velocity* (v_t) and the total force on it is zero:

$$6\pi\eta rv - \frac{4}{3}\pi R^3(\rho - \sigma)g = 0$$

$$v_t = \frac{2}{9}\frac{R^2 g(\rho - \sigma)}{\eta} \tag{4}$$

where, ρ = density of the liquid; σ = density of the spherical body

When using Poiseuille's law (Eq. (2)), the flow of a fluid of viscosity η through a cylindrical conduit with the radius R is

$$\bar{u} = \frac{\pi g \Delta P R^2}{8\eta} \tag{5}$$

where ΔP is the pressure gradient over the pipe, g is the acceleration due to gravity, and v is the velocity of flux. In order to evaluate the feasibility of mud volcano monitoring to detect strain field variations, a simple physical formula can be considered. The mud volcano complex is assumed that fluid flow in the conduit is driven by the pressure difference ΔP between the top and the bottom of the conduit of length h. The average pressure gradient can be estimated by

$$\frac{\Delta P}{h} = (\rho_{ovb} - \rho_{mud})g \tag{6}$$

where g is the acceleration due to gravity, ρ_{ovb} and ρ_{mud} are overburden and mud densities, respectively (Albarello, 2005; Brown, 1990). If this pressure gradient is chosen to be the buoyancy (bulk density difference between fluidized mud (of 1600 kg/m^3) and consolidated claystone (2100 kg/m^3) alone, ascent velocities in mud volcano conduits can be calculated. For a diameter of 1 m and an average viscosity

(η=10^6 Pa.s), then from equations (5 and 6), the rate would be 0.022 m/s (Kopf & Behrmann, 2000).

As long as the gaseous phases are dissolved in the mud, the fluid can be assumed to be incompressible. Reynolds number *Re*, which characterizes the flow of such a fluid in this condition is given by

$$R_e = \frac{\rho_{mud}\bar{u}D}{\eta} \tag{7}$$

where, is the average fluid velocity, *D* is the diameter of the conduit, η and ρ is fluid viscosity and density, respectively (Albarello, 2005; Turcotte & Schubert, 2002). For Re<2300, the flow can be assumed as laminar. In this case, the average fluid velocity throughout the conduit results to be

$$\bar{u} = -\frac{D^2}{32\eta}\frac{\Delta P}{h} \tag{8}$$

From Eqs. (2) and (8), the corresponding to a flow rate *Q* given by

$$Q = -\frac{\pi D^4}{132\eta}\frac{\Delta P}{h} \tag{9}$$

Eqs. (8) and (9) imply that both the flow rate and average fluid velocity dramatically depend on the conduit diameter (Albarello, 2005; Kopf, 2002). By assuming a density difference between overburden and mud to the order of 10^2 kg/m^3, the pressure gradient results to the order of 10^3 Pa/m (Brown, 1990). Since η is to the order of 10^6 Pa sec (Kopf, 2002), the ascent velocity provided by Eq. (7) results to the order of 10^3 m/y for a 1-meter conduit. Corresponding flow rates are to the order 10^3 m^3/y. By using these illustrations, the relevant Reynolds number results to be very low (<<1) and the laminar flow assumption can be considered reliable.

Velocity of bubble

For low Reynolds numbers, the kinematics of bubbles (in the assumption of a spherical shape) are controlled by the average radius of bubbles and by the mud viscosity (the idea from Eq. (4)). In particular, it holds that the velocity u_{bubble} of a bubble of radius R driven by buoyancy with respect to the moving fluid of density ρ_{mud} is

$$u_{bubble} = \frac{2}{9}\frac{R^2 g(\rho_{mud} - \rho_{gas})}{\eta} \cong \frac{2\rho_{mud} g R^2}{9\eta} \tag{10}$$

where *g* is the gravitational acceleration and η is the fluid viscosity (Albarello, 2005; Brennen, 1995; Turcotte & Schubert, 2002). In order to evaluate the actual possibility that bubbling may significantly produce gas escape from the mud, the ratio between average mud velocity and bubble up-rise velocity can be computed from Eqs. (6), (8) and (10) as

$$\frac{\bar{u}}{u_{bubble}} = -\frac{9}{64}\left(\frac{\rho_{ovb}}{\rho_{mud}} - 1\right)\frac{D^2}{R^2} \tag{11}$$

It results that, for maximum bubbles radius R to the order of 0.1 m and by using the figures adopted above for the relevant parameters, the ratio in Eq. (11) is to the order of one and rapidly increases by decreasing R. This implies that only relatively big bubbles can escape from the mud while smaller ones remain trapped in the mud and participate in the mud flow. This implies that at least as concerns the shallowest part of the muddy path from the reservoir to the surface, the assumption of fluid incompressibility cannot be considered as fully realistic.

Chemical dimensions

Generally, the chemical compositions of mud volcano have distinguished from three phases: gas, solid, or liquid. Mostly, mud volcanoes produced Methane (CH_4) as the main gas components. As reported from the Hsiaokun-Shui (HKS) mud volcano in Southern Taiwan, the major gas constituents are CH_4, which reached more than 90% (Chao et al., 2010). Meanwhile, the remained gases are "air" (i.e., Nitrogen (N_2) + Oxygen (O_2) + Argon (Ar), 1–5%) and Carbon dioxide (CO_2) (1–5%). Accordingly, mud volcanoes are important pathways for CH_4 emission from deep buried sediments; however, the importance of gas fluxes have been neglected in atmospheric source budget considerations. Indeed, the total amount of mud volcano via methane could contribute up to 10% of total natural CH_4 emissions in Taiwan.

In contrast, in the case of the Lusi mud volcano realized only 0.5% of methane, as reported by Vanderkluysen et al. (2014):

> [D]uring May and October 2011 [five years after explosion], the compositions of atmosphere around the center of buble were gases (98% water vapor, 1.5% Carbon dioxide, 0.5% methane). These gases were periodically released by the bursting of bubbles approximately 3 m in diameter, which triggered mud fountains to ~10 m and gas plumes to hundreds of meters above the vent. During periods of quiescence (1–3 min), no appreciable gas seepage occurred..

Vanderkluysen et al. (2014) study also estimated that Lusi releases approximately 2300 t yr^{-1} of methane, 30,000 t yr^{-1} of CO_2, and 800,000 t yr^{-1} of water vapor. Meanwhile, gas bubble nucleation depths are more than 4000 m for methane and approximately 600 m for CO_2. Different with mud volcano in Southern Taiwan, the dominance of the compositions of atmosphere around the center of buble in Lusi mud volcano are gases (~98% water vapor).

For the solid and liquid phase, the chemical composition of mud volcano is Silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), and aluminium oxide, or alumina (Al_2O_3). As reported by Rafiza et al. (2013) who compared the composition of original and the sintered Lusi mud volcano as follows.

Table 1. Chemical composition of original and sintered LUSI mud volcano

Component	Original mud (%)	Sintered mud (%)
SiO_2	40.00	46.70
Fe_2O_3	23.25	21.73
Al_2O_3	14.60	16.09
CaO	5.46	5.68
K_2O	4.28	4.10
Others (TiO_2, SO_3, MnO, V_2O_5, etc.)	12.41	5.70

Re-organized from Rafiza et al. (2013)

Based on Table 1, the major constituent was SiO_2 for both materials, however, after sintered the SiO_2 content was higher than original mud. Finding from their study shows that the Lusi mud volcano has potential as a raw material in geopolymer system due to the characteristic of mud which is comparable to the fly ash except the particle size and shape of the particles. Additionally, heavy metals Hg (mercury), for example, found the 2.5 ppm (Rafiza et al., 2013). Moreover, Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) values and the amount of oil and lubricant in the mud and fluids at the site is quite high, so as to disturb the ecology of the water when directly discharged into waters without being treated, while for the formation of a solid, relatively non-toxic. Still not allowed in irrigation ditches, because its recovery is difficult and time consuming. Therefore, the water quality does not fulfill the criteria set by the World Health Organization (Gashi et al., 2016), and the distribution of pollutants indicated anthropogenic sources of pollutants mainly nearby the central of Lusi mud volcano.

Meanwhile, some studies also consider the probability of mud volcano, according to its soil fertility. Ross[2)] established a simple fertility index of Lusi's mud, by testing for three soil properties that are important for plant growth: (1) carbon to nitrogen ratio (C:N); (2) pH, and (3) cation exchange capacity (CEC). Accordingly, from the case of Lusi mud volcano, Ross' study found:[2)]

> [F]irst, Lusi's C:N ratio (12.1 ± 1.01, n = 13) demolished at the low end of the of corresponding tropical soil data range (10.3-27) (Trumbore, 1993). Second, Lusi's pH was found to be basic (8.22 ± 0.062, n = 13) relative to

the range of tropical soil pH (3.9-6.3) (Motavalli et al., 1995). Third, Lusi's CEC [Cation Exchange Capacity] (19.72 cmol+/kg ± 1.28, n = 12) was high relative to tropical soil CEC (6.55 cmol+/kg ± 1.12, n = 9) (Trumbore, 1993). More specifically, Lusi's %C (1.293% C ± 0.0448, n = 13) and %N (0.1076% N ± 0.0052, n = 13) were both very low (Ewel et al., 1991; Motavalli et al., 1995)).

Those values designate that C and N may need to be fertilized for plant growth because the levels are so minimal, and buffering for the basic pH may be necessary as well. The CEC is defined as the ability of a particle to change positive bases with the environment in which the particle interacts (Aprile & Lorandi, 2012). The CEC is now widely used in the characterization and study of soil fertility. The high CEC levels indicate there are equitable amounts of nutrient cations present in the mud.

Geological dimensions

There are three arguments that presented by some geologists about factors that led to "Lusi" disaster was erupted on May 29th, 2006. The first argument is Yogyakarta earthquake that occurred on May 27th, 2006, the second argument is drilling operations wrong, and the third argument is a combination of earthquake and drilling operations wrong (Davies et al., 2011). Many studies conducted about the causes of existing mud volcanoes, but little is explained about the geological conditions before and during mud volcano eruptions (Istadi et al., 2009).

Geological dimension defined regional geological conditions that related to East Java basin setting, tectonic activities, and the sequence of rocks or stratigraphic, so that it will know the causes of mud volcanoes appearing. "Lusi" disaster causes geohazard risk which is human injure. Istadi et al. (2009) was modeling of growth and geohazard potential to anticipate the worst effects of "Lusi" disaster.

East Java basin evolved as a back-arc basin that result of subduction between Sunda continental plate and Australian oceanic plate (Istadi et al., 2009). East Java basin structural history is divided into two phases. First phase occurred on Middle Eocene to Oligocene and second phase occurred on Neogene (Tanikawa et al., 2010). The early stage of East Java basin formation is characterized by forming half Graben that influenced by the previous structure on Middle Eocene to Oligocene (Istadi et al., 2009), which developed during extensional phase, followed by compressional deformation that occurred on Neogene (Tanikawa et al., 2010).

Sedimentations in East Java basin occurred during the Late Pliocene to Holocene (Tanikawa et al., 2010). They explained the sequence of stratigraphy in "Lusi" area from top to bottom derived are alluvial sediments, alternating sandstone and shale of Pucangan Formation was Pleistocene that located about 500 m depth, clay of Pucangan Formation was Pleistocene that located about 1000 m depth, bluish gray clay of Upper Kalibeng Formation was Pleistocene that located about 1871 m, and volcaniclastic sand was Late Pliocene whose about 962 m thickness. Many mud volcanoes correlated with deposited clay-bearing of Kalibeng Formation sediments (Istadi et al., 2009).

High sedimentation was located in the northern part of East Java forms the backarc basin and "Lusi" was in the backarc area 10 km NE from the Penanggungan volcano (Mazzini et al., 2007). Mud volcano eruption expected because of reactivation of Watukosek fault that located about 700 m in the straightness near of eruption area (Istadi et al., 2009). "Lusi" mud volcanoes spread in some areas add many mud volcanoes and some of them was still active and still erupt. There are three estimations of the fluid origin that contained in mud volcanoes from some experts, first, fluid is sourced from clay diagenetic dehydration within the Upper Kalibeng Formation, second, fluid is sourced from Kujung carbonate formation, and third, fluid is sourced from geothermal activity (Sawolo et al., 2009).

"Lusi" disaster has influenced some losses such as as buried houses, villages, schools, land, government offices, factories, and environmental damages. "Lusi" disaster was part of geohazard that influenced some risks. Geohazard risks which concern of "Lusi" disaster is shear and subsidence that cause some damages such as rupture of gas and water pipes, the emergence of gas bubbles along the weak zone, dike collapse, railroad bending, relief wells casing integrity, and road cracks (Istadi et al., 2009).

The mud volcano area

The area of mud volcano located in Sidoarjo regency. This regency is bordered by Surabaya city and Gresik Regency to the north, by the Madura Strait to the east, by Mojokerto Regency to the west, and by Pasuruan Regency to the south. Sidoarjo is the smallest regency in East Java-Indonesia which has an area of 634.89 km² and consists of 18 districts (*kecamatan*), where Porong district is located in the southeast of the regency, as depicted in Fig. 1.

The specific area of the Lusi mud volcano in Porong district is shown in Fig. 2.

Scientists' and government' response

In general, both scientists and Indonesian government made some efforts to solve this disaster. Table 2 summarizes those efforts equipped with the description, its results, and the interval time duration. Indonesian cabinet meeting on 27 September 2006 finally decided to throw mud directly into the *Porong* river, southern area of the center of spout. The decision was made due to the increased volume of mudflow has reached 126,000 cubic meters per day. Moreover, the resolution was made to provide additional time to seek termination of the mud flow and at the same to prepare alternative handling of the others, such as the establishment of wetland (swamps) has in the region coastal of Sidoarjo regency.

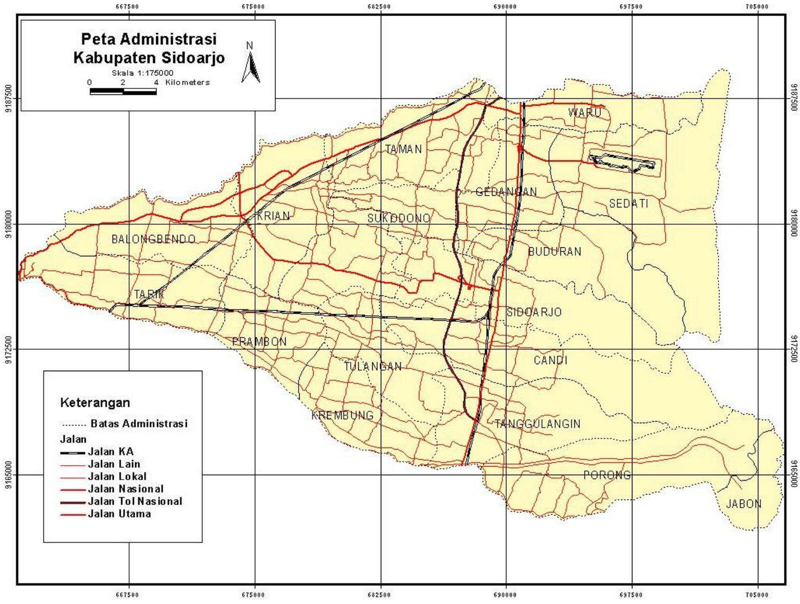

Figure 1. The administration map of Sidoarjo regency

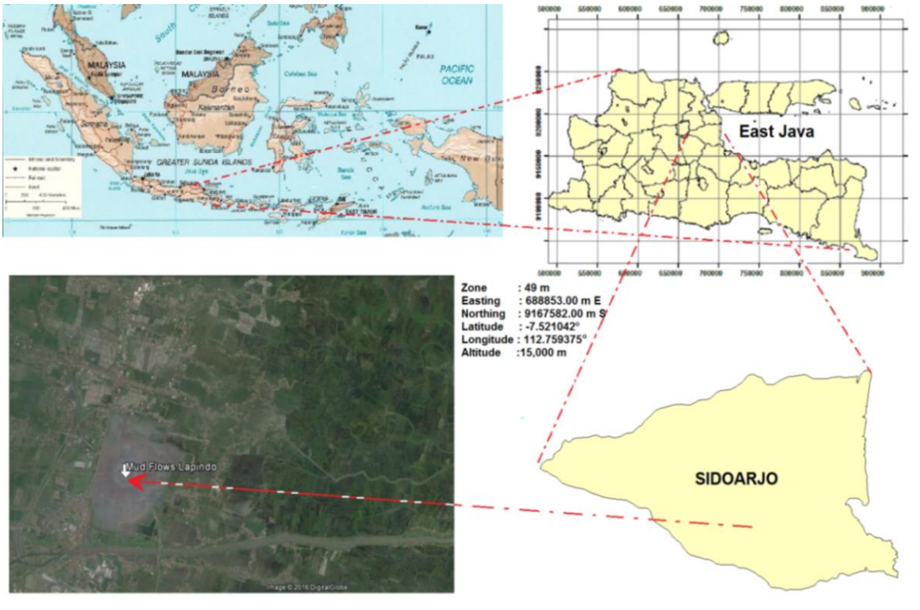

Figure 2. The area of mud volcano in Porong district, Sidoarjo Indonesia

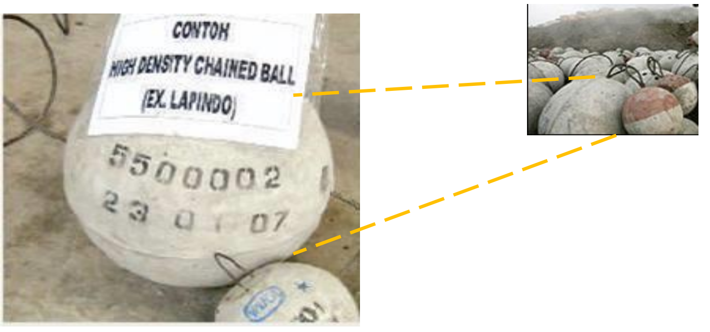

Figure 3. The example of high-density chained ball

Table 2. Physical and geological efforts for stopping "Lusi" mud volcano

	Treatment	Description	Results
1	Top Kill via snubbing unit (June 2006)	Snubbing unit is hydraulic system powered equipment which is generally used for work well-intervention and work over (do a job into an existing well). It was likewise employed to reach a series of drill weighing 25 tons and a length of 400 meters left in the initial drilling. It was expected that when the drill bit is found, then it can be pushed into the bottom of the well (9,297 feet) and then the well was capped by injecting cement and heavy mud.	The method was a total failure. However, the scenario with a snubbing unit was not in vain, because it can locate the position of the drill was caught in depths of 2,991 feet, but snubbing unit failed to push it into the bottom of the well. The flow was strong enough bursts. In addition, the quality of the well has been permanently cemented casing and the pipe casing was dented and damaged.
2	Drilling rig (side tracking) (July 2006)	Drilling sideways (side tracking) avoids lagging behind the drill bit.	The drilling process also fails because it has been found to damage the casing at some depth between 1060-1500 feet, as well as the occurrence of lateral movement in the Banjar Panji-1 (BJP-1) drilling location.
3	Dynamic Killing (Relief Wells) (at the end 2006)	This technology requires some slanted wells, known as „relief well" for the channel injecting heavy mud into the well source bursts. The heavy mud will have a large enough hydrostatic pressure, so it can withstand the pressure coming from below pushing the fluid to the surface.	The method was creating three new wells (relief well). The three locations are: first, about 500 meters southwest of BJP-1 well. Second, approximately 500 meters west- northwest BJP-1. Third, around the north-northeast of BJP-1 well. Unfortunately, new activities run around 20 percent to be halted because of limited costs.

4	The concrete ball chain (at the beginning 2007-middle of February)	The balls (see Figure 3) chained together in groups, into the mouth of the rupture. The operation to lower 2,000 the concrete balls, each weighing up to 400kg, into the rupture will start slowly at first. The hope was to drop the ball and chain set to a depth of 100 meters (330ft) with the aim of slowing the flow by up to 70%.	The method was also a total failure because a series of concrete balls were not falling right into the crater. The process to dampen the energy of the mudflow, also failed to function when the density of the concrete balls, turned out to be lower than the density of the mud. Thus, can't be sunk to the bottom center of explosion, and only hovered amid bursts.
5	Reservoir (from June 2006- until now)	This choice is to continue efforts to handle the mud at the drilling site by building additional reservoirs next to the dikes that exist today. With a bit of effort to dig the soil in place that will be used as an additional reservoir so that their capacity is greater.	This step helps reduce the capacity (volume flow rate) of mud around bursts. However, to liberate the land around the reservoir takes time, as well as to prepare a new dam, while the mud flow continuously, day after day, the volume continued to grow.
6	Pipeline-supplier to a river (from September 2006 until now)	To close it begins with a step „short", i.e. localize bursts with a lower domes are large and heavy and at its peak connected by pipeline as a supplier of water to the surface. This allows the water can be streamed to the tanker and does not spread in all directions and pollute the ocean. A similar analogy is done to stop the mudflow in Sidoarjo, which bursts directed to the Porong River dike for a while.	This effort of little help in reducing the flow of water and mud. However, the streaming process constantly to Porong river would destabilize the ecosystem and the environment around rivers, estuaries, and straits of Madura, the region in the northeast of the center of spurt.

Conclusion

In this paper, the authors have lifted up more recent phenomenon of mud volcano disaster in Sidoarjo. The discussions divide into three parts: (1) physical, chemical, and geological dimensions of mud volcano, (2) the area of mud volcanoes, and (3) scientists' and government' response, including Indonesian government decision after providing the chronology of the disaster in the introduction. Turning to the physical dimensions, the concept of dynamical fluid, including viscosity, Stokes' law, terminal velocity are usefully discussed. For chemical part, the compositions of mud volcano are also depicted as well as some arguments that presented by geologists are raised up in geological part. Regarding some efforts to resolve the disaster, there are six methods used until now: top kill, drilling, relief well, the concrete ball chain, reservoir, and pipeline- supplier. The last method was selected by the government to minimize the risk of this disaster. However, attempts to plug the flow have so far failed. Indeed, Adriano Mazzini, a geologist from the University of Oslo, claimed that "It is difficult to predict when it is going to stop".[3)] A probabilistic estimate of longevity for the LUSI mud volcano is developed based upon the existence of a vertical wellbore that is drilled to immediately. Indeed, Davies et al. (2011) estimated that the mud can be expected to develop within the 26 year time period based upon carbonates at depths in the range 2500–3500 m. As the scientists, we hope through this study, helping the Indonesian government realized to overcome this disaster and find the best solution for residents in the area.

NOTES

1. http://www.hsf.humanitus.org/media/16830/2-A-4.pdf
2. https://nature.berkeley.edu/classes/es196/projects/2008final/Ross_2008.pdf
3. http://www.nature.com/news/2006/060925/full/news060925-13.html

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