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SLIP, DISPLACEMENT AND STRESS SCENARIOS ON THE LHOKSUMAWE FAULT TO DETERMINE THE MOVEMENT AND DIRECTION OF THE RUPTURE AREA

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ABSTRACT

Aceh Province has 23 active faults in land which very devastating and destruvtive. It makes Aceh very vulnerable to earthquake, same like in one of major cities in Aceh Province, Lhoksumawe, which has an active fault that passes through inside its territory. Lhoksumawe fault is located in the Northen part of Aceh, very close to Lhoksumawe city as the mother city in there. According to BMKG earthquake information, there was a moderate earthquake with M4.7 at June 19th 2016. The hypocenter is located in the sea and suspected by Lhoksumawe fault. So far, some reference about Lhoksumawe fault can't describe exactly this fault, whether it's down to the sea or not. We must concern and know the activity of this fault, because the fault is still active even has small slip rate just 1 mm/year, but can generate the earthquake until M 6.5. We make the seismicity map and some scenarios to calculate and analyze the slip direction, displacement and stress model. We assume the earthquake has strike-slip mechanism with right-lateral movement at 10 km depth and located in the center of this fault. With M6.5, slip until 5 m and fault dimension 40 x 15 km, we can get good model and scenarios. The results show us, if the vertical displacement has positive value until 0.5 m and horizontal until 1 m, which following the double couple pattern. For stress, we use the effective stress which very simple to knowing the stress rate, the highest value until 1 MPa. This results is very important to know how the earthquake activity with strike-slip mechanism occurred Lhoksumawe Fault, because, Lhoksumawe city has large population and highly developed economic growth, natural disasters such as earthquakes must really be a concern in this region.

KEY WORDS : Earthquake, Slip, Displacement, Stress

INTRODUCTION

Lhoksumawe is located on The North Aceh district and one of the largest city in Aceh Province, that lies between Banda Aceh and Medan. This city has an important role for economic in Aceh and also, has a population that is growing very rapidly, and slowly becoming a modern city in Aceh. Behind it all, this area has an earthquake path, which is generated by tectonic faults. This should be a concern for the government, the last in December 2016, the Pidie Jaya Fault which was completely unknown and its location very close to the city of Lhoksumawe, generated a large and very destructive earthquake. This earthquake was also felt very strongly in cities in the northern part of Aceh. The lhoksumawe fault, which is located very close to Pidie Jaya Fault, need a special concern because the considerable stress produced by Pidie Jaya Fault can trigger the activeness of the Lhoksumawe Fault.

The Lhokseumawe fault extends from southeast to northwest and passes through northern Aceh district, which extends to the Malacca Sea. This fault may have a length of almost 50-100 km because it extends to the sea, and has a movement every 1 mm/year. Although, this fault movement is quite small, but in the long term it will accumulate and can generate huge earthquake energy such as the Pidie Jaya Fault.

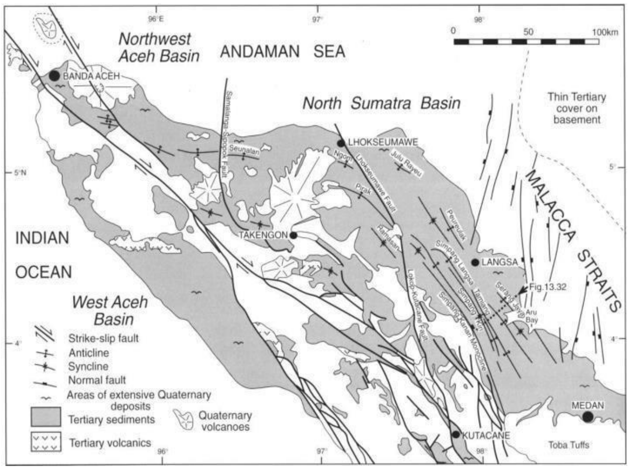

Fig 1. The Northen Sumatera Basin Map (Barber et al. 2005)

In addition, there is another fault to the east of the city of Lhoksumawe called Samalanga-Sipopok which has the same movement which is horizontal (strike slip). Both the Samalanga-Sipopok faults and the Lhokseumawe fault were equally at the bottom of the Andaman Sea and joined by a number of active faults there. In addition to these relatively long faults, the earth of Rencong land also still has a number of other relatively short faults.

Lhoksumawe Fault which is one of many fault on Sumatran fault is purely strike slip fault and extend to the entire length of island and coincides geographically with the volcanic arc through most of its length. Studies of the surface lineaments, representing fault structures in the northern part of the North Sumatra Basin using SAR (synthetic aperture radar) imagery showed that NW – SE (Sumatran) and NE – SW trends are dominant throughout the basin (Barber et al., 2005).

In the NorthWest part of Aceh Basin between Banda Aceh and Lhokseumawe, the fold trends mostly in east – west direction and parallel to the north coast. This is surprising as the underlying basement structures trend north – south. It has been suggested that the E – W orientation of folds is due to the incipient development of southward- dipping subduction system in the southern Andaman Sea, offshore northern Sumatra (Barber et al., 2005).

On Tuesday, June 19th 2016, According to the BMKG earthquake information, there was a moderate earthquake with magnitude 4.7 occurring in the Northwest of Loksumawe, Aceh, Indonesia. The hypocenter of the earthquake was located at a depth of around 10 km and in sea and 51 km from Lhoksumawe. Even the hypocenter was located in sea, but no tsunami was happened and generated, it caused by the fault mechanism which slip move to strike direction and make a displacement changes only in horizontal. Due to its shallow source and close to Lhoksumawe cities, this earthquake was felt so strong with MMI scale range between 2 - 4 MMI.

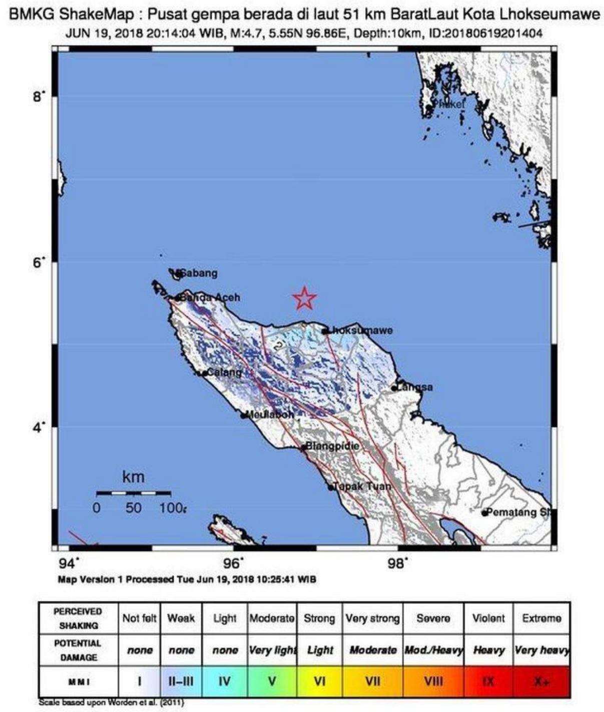

Fig 2. Shakemap from Lhoksumawe Earthquake on June 19th 2018 by BMKG.

This is very important to know the characteristic of Lhoksumawe fault. Because from last event, we know even this fault has very small slip rate but can generate moderate earthquake. To make sure, In this paper we make a model and scenario for slip and stress by different mechanism which based on strike, dip and rake. The earthquake phenomenon which based on static stress can give us some information to knowing stress trigger and transfer techniques. Stress system of earthquakes very important to know and estimate the seismic hazard.

Based on the earthquake event at northen part of Lhoksumawe, we assume the epicenter is located in one part of Lhoksumawe fault which go down to the sea. But, it is difficult to say it very clear, we need very good bathymetry to know and imaging, to know how long the Lhoksumawe fault, is this fault up to sea or not.

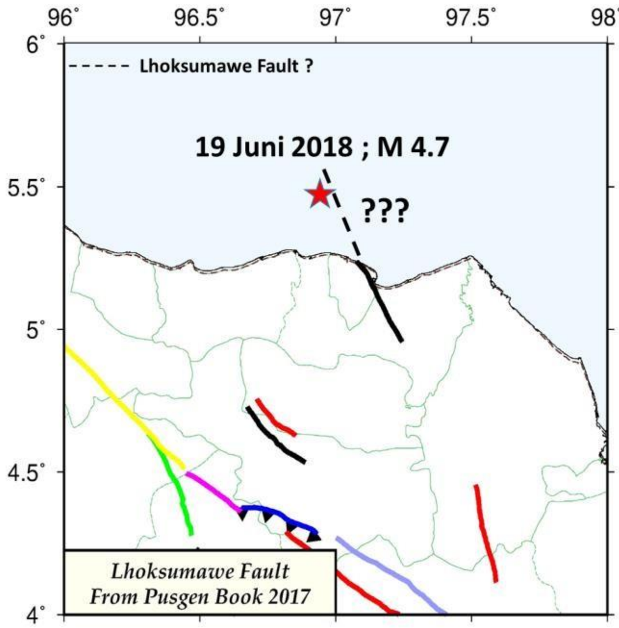

Fig 3. Some Fault Information in Aceh Region, with 19 June 2018 earthquake in unknown fault in the northern part of Lhoksumawe Fault.

METHOD

From the earthquake, we have a future plan to do more research about the Lhoksumawe fault. In this paper, we make a model and some scenarios to calculate and analysis the slip direction, displacements, and stress. We make an earthquake that occurs on the land not at sea, because we still don't have much reference about the bathymethry and how the characteristics of the lhoksumawe fault that reaches the sea.

We must give the interpolation to get a good contour, with 0.07 x 0.07 grid which can cover all the interest area. Slip happened at 10 km depth, and can generate the ground displacement in surface. We assume the area is an half-elastic medium. Assuming the medium is an elastic half-space, very useful and simple to know the ground displacement in half volume which based on Okada (1985) and Okada (1992).

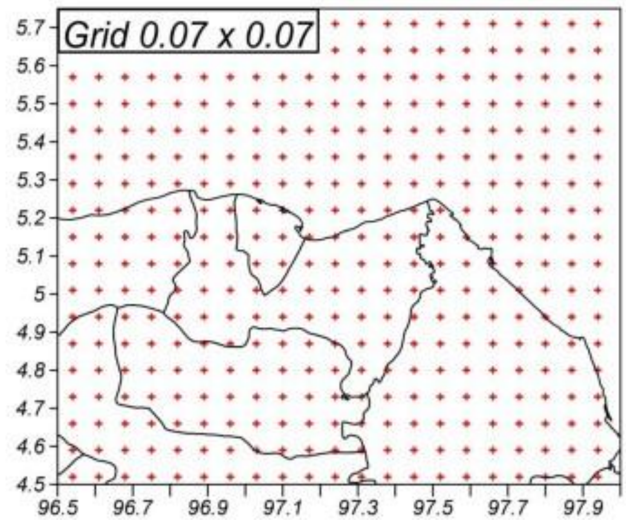

Fig 4. Grid Spacing to Interpolate the displacement result from slip.

An elastic halfspace is a 'semi-infinite' elastic body, for our purposes, this means that it is infinite in the $\pm x$, $\pm y$, and $+z$ directions (where $+z$ is down). It's like an infinitely wide, infinitely deep ocean. With a flat (not spherical) surface, but elastic and not fluid. Dislocation model is about rectangular fault within an elastic half-space. To do the calculation, we need nine parameters like coordinates of the centre of the upper edge of the fault, two angles (azimuth, dip), length and width (fault dimension), and also the type of slip and rake (dip-slip or strike-slip).

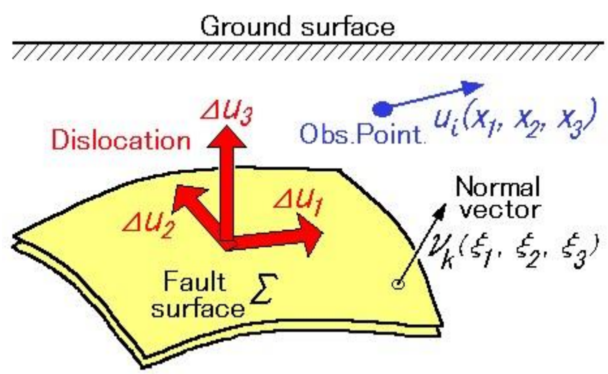

Fig 5. The schematic picture to show the slip which occurred on fault plane in an half-elastic space make ground displacement in surface.

Here, *(U1, U2, U3)* is *(X1, X2, X3)* which is the displacement vector at the observation point. ΔUj *(ξ1, ξ2, ξ3)* is $\sum$ for the dislocation discrepancy vector on the *V*k*(ξ1, ξ2, ξ3)* of $\sum$ plane. The normal vector of *Ui*^{j} *(X1, X2 , X3 ; ξ1, ξ2, ξ3)* in the plane, is the component of displacement at the point in the medium due to the force in the direction placed ∑ on the point on the plane , is the elastic constant of the medium. *(ξ1, ξ2, ξ3) j F (X1, X2 , X3) i λ, μ*. In fact, in order to apply the above basic formula to real problems, there are the following two approaches.

1. Numerically perform (integrate) the above integral calculation using a computer.
2. Mathematically perform the above integration to derive a direct expression (analytical solution).

In principle, there is no room for (2) to enter the calculation error, and it is possible to obtain a much faster and accurate answer than (1). For this reason, many researchers have submitted a theoretical formula to calculate the deformation of the earth's surface and the interior with respect to a specific fault model (bottom figure). In order to avoid mathematical difficulty, initially, assuming the Poisson solid (when the above elastic constant values are equal) as a medium and expressing expressions for a simple case such as when the fault plane is vertical or horizontal.

Subsequently, a theoretical expression that can be gradually applied in the general case has been known, but most of it is targeted to the "shear fault" as a model of the earthquake, and for the "open fault" as a model of the volcano Less research has been done. For this reason, a complete general solution applicable to all cases has not been submitted, and some past theoretical expressions give the same result in the end, but they are very embarrassing In many cases, redundant expressions were given to them.

Okada (1985) and Okada (1992) unified the models of earthquakes and volcanic eruptions that had been tackling up to then, and in a completely general form, a very simple and beautiful expressive expression that can be applied to any fault model. This result was posted as "Okada model" in the glossary recorded in IASPEI's 100 th anniversary commemorative issue (2003), and it is internationally wide as a standard model in this field It came to be recognized.

This method used as a standard tool for modeling earthquake / volcanic phenomena and as a powerful tool to evaluate the influence of specific earthquakes and volcanic phenomena on surroundings. This is the suface displacement equation due to a finite fault, the equation based on strike, dip, rake and fault dimension.

$$\begin{cases} u_x = -\frac{U_1}{2\pi}\left\{\frac{\xi q}{R(R+\eta)} + \tan^{-1}\frac{\xi\eta}{qR} + I_1 \sin\delta\right\}\Big\| \\ u_y = -\frac{U_1}{2\pi}\left\{\frac{\tilde{y} q}{R(R+\eta)} + \frac{q\cos\delta}{R+\eta} + I_2 \sin\delta\right\}\Big\| \\ u_z = -\frac{U_1}{2\pi}\left\{\frac{\tilde{d} q}{R(R+\eta)} + \frac{q\sin\delta}{R+\eta} + I_4 \sin\delta\right\}\Big\| \end{cases}$$

where

$$\begin{cases} I_1 = \frac{\mu}{\lambda+\mu}\left[\frac{-1}{\cos\delta}\frac{\xi}{R+\tilde{d}}\right] - \frac{\sin\delta}{\cos\delta} I_5 \\ I_2 = \frac{\mu}{\lambda+\mu}\left[-\ln(R+\eta)\right] - I_3 \\ I_3 = \frac{\mu}{\lambda+\mu}\left[\frac{1}{\cos\delta}\frac{\tilde{y}}{R+\tilde{d}} - \ln(R+\eta)\right] + \frac{\sin\delta}{\cos\delta} I_4 \\ I_4 = \frac{\mu}{\lambda+\mu}\frac{1}{\cos\delta}\left[\ln(R+\tilde{d}) - \sin\delta \ln(R+\eta)\right] \\ I_5 = \frac{\mu}{\lambda+\mu}\tan^{-1}\frac{\eta(X+q\cos\delta)+X(R+X)\sin\delta}{\xi(R+X)\cos\delta} \end{cases}$$

and

$$\begin{cases} X^2 = \xi^2 + q^2 \\ R^2 = X^2 + \eta^2 \\ q = y\sin\delta - d\cos\delta \\ \tilde{y} = \eta\cos\delta + q\sin\delta \\ \tilde{d} = \eta\sin\delta - q\cos\delta \end{cases}$$

There are various types of fault model depending on the direction of the fault plane (vertical, horizontal, diagonal) and the type of fault movement (lateral displacement, longitudinal deviation, opening), and as the medium, when the elastic constants are equal (Poisson solid) And an optional case. Furthermore, as for the physical quantity to be calculated, in the case of ground deformation, three components of displacement, four components of the strain, two components of the gradient, in the case of internal deformation, three components of displacement and nine components of distortion are necessary.

In the past, Okada (1985) and Okada (1992) did not have a perfect general expression that covers all of these, but by choosing the direction/fault motion type/medium of the fault plane and selecting all A set of general theoretical equations that can calculate physical quantities has been submitted.

RESULTS AND DISCUSSION

We do the modelling, first we assume the focal pattern and fault dimension. The Magnitude is 6.5 based on maximum magnitude on Pusgen Book 2017, the slip maximum is 5 m , the width and height is 15 x 40 km which include all part of Lhoksumawe Fault. For the focal, we assume the strike, dip and rake is 150°, 45°, and 50°. And, the epicenter is located in the center of Lhoksumawe Fault with its coordinate 97.2° E and 5.1° N.

Slip Direction

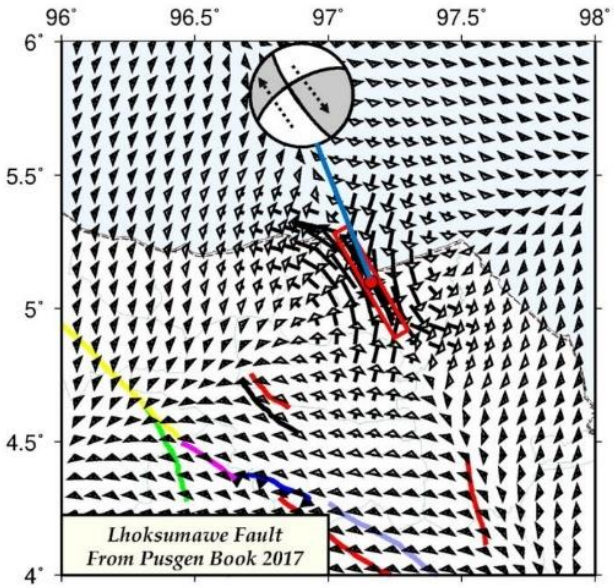

Fig 6. Slip direction model from strike slip right lateral follow the stress and tension pattern of focal mechanism

The slip direction mostly follow the right lateral from SouthEast to NorthWest. The slip results actually by making a grid nod 0.07 x 0.07 in map. Each arrow has azimuth, and vertical and horizontal displacement value. This scenario just to understand how the earthquake with strike slip mechanism and right lateral occured in Lhoksumawe fault.

After got the slip, we also make grid again to plot the horizontal and vertical displacement to know how ground displacement happened. The slip is different with displacement, because slip is occurred in fault plane at depth, and displacement in the surface with depth = 0 km. So, in Okada (1985), to know very simple this mechanism , the earthquake must be assumed in an-halp space.

Displacement

This is the horizontal displacement, which the high value follow the fault. The horizontal displacement has positive values, because the mechanism has slip on strike direction. The high values is concentrated in the center of fault, but actually the displacement really following the mechanism. The high values until 1.4 m because the strike slip can make very big displacement in horizontal than vertical.

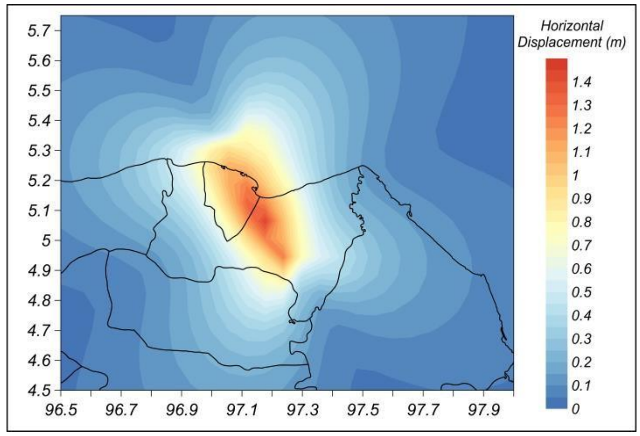

Fig 7. This is the horizontal displacement from slip direction value

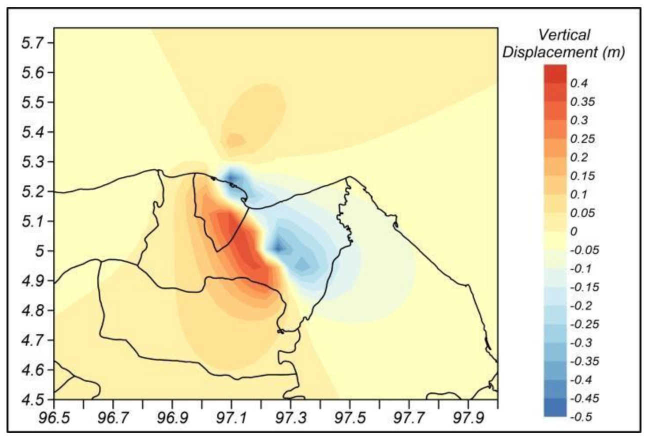

Fig 8. This is the vertical displacement from slip direction value

This the vertical displacement, which have different values, betwen positive and negative. Because, the vertical displacement is occurred in z+ and z- , so we can see from the picture where area will go up and go down. From that picture, because we have the earthquake with strike- slip mechanism and right-lateral, it make The Southeastern part and Westnorthen part has negative values and the area go down until 0.5 meter. And, another area mostly in left side go up until 0.4 m.

This scenario will tell us how the earthquake can make massive displacement in the surface. But, to make sure we must make a validation with InSar data , if the earthquake really happened. The displacement can be true but never really same in the field.

Stress

We also calculate the stress scenario which can be genereated by the earthquake. The stress we call the effective stress, because the effective stress is very useful to know the stress without concern about surrounding fault. The stress contour scale show us the double-couple shape, which is relevant to source physics of earthquake. Actually, the earthquake mechanism just can be explained in double couple force. We can see if the high value concentrate in the center, and another area has different value. The different value following the P and T axis , and very clear imaging the strike –slip with right-lateral mechanism.

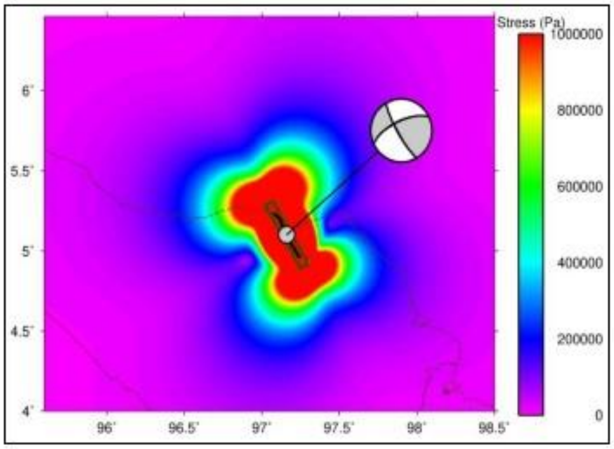

Fig 9. The Effective Stress in Lhoksumwe Fault with M 6.5

The high values of effective stress is 1 MPa , this usually we can get from the moderate earthquake. We can add some various stress , like dipping stress, and striking stress after know very clear the surrounding fault. After modelling stress, slip and displacement, we can know which area has maximum value , and also it very important to know the activity of lhoksumawe fault. In future, we must make all mechanism of earthquake like thrust, normal and oblique. And also, site classification on lhoksumawe is needed to know which area has high amplification.

CONCLUSIONS

From assume the earthquake occurred in Lhoksumawe Fault, we finally get the good results to imaging the slip, displacement, and stress in Lhoksumawe Fault. From this results we can know the maximum displacement and effective stress. But this is just one scenarios, we need other strike-slip mechanism with left lateral movement, to compare and know the difference. Lhoksumawe fault has very small slip-rate just 1mm/yr, but we must concern after the earthquake on June 19th 2018 in the northern part of Lhoksumawe.

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