STRESS ANALYSIS AND CHARACTERISTICS DUE TO THE SOUTH JAVA EARTHQUAKE, APRIL 10, 2021

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ABSTRACT

The April 10, 2021, earthquake in the south of East Java was classified as destructive. The secondary impact of this earthquake was quite significant. Many houses collapsed, and not a few casualties. This earthquake is unique because usually, destructive earthquakes occur at shallow depths, but earthquakes with a magnitude of 6.1 are classified as medium-depth earthquakes at sea. The earthquake in the south of East Java is classified as an intraplate earthquake because it is located on the continental plate, not in the plate contact area. The question is whether the damage that occurred to the building was purely due to the magnitude of the stress released by the earthquake or whether there were other factors. This study uses seismogram data for the earthquake south of East Java on April 10, 2021, with a radius (Δ) of 30^0-100^0 recorded at MEEK, MORW, and ARMA stations in Australia. It calculates the amount of stress based on the stress drop, while the stress column determines the stress mechanism. Calculation of stress drop from the source spectrum is obtained by the deconvolution method, namely the seismogram component separation technique in the form of Source (f), Path (f), Site (f), and Instrument (f). The analysis of the observed displacement spectrum used the Nelder Mead Simplex nonlinear inversion method. Meanwhile, the Stress Columb calculation was obtained using the Columb 3.3 program from the United States Geological Survey (USGS). The result of this research is that the stress drop value is 1.69 MPa, with the type of focus mechanism being a thrust fault in the sea. The earthquake in the south of East Java was caused by rock activity in the intraplate. The value of the stress drop is more significant when compared to the subduction contact area. This area is of intraplate rock with various variations, and earthquakes are rare. This study aims to analyze the stress, both the magnitude of the stress drop and the mechanism of the column stress results, so that the stress caused by the earthquake can be known and why the earthquake in the south of East Java is destructive. The quake in Southeast Java is classified as dangerous, not because of the magnitude of the stress generated or its mechanism. The damage was due to the amplification of earthquake waves in the building. The injury occurred because most of the buildings were built on soft soil, especially in several areas in East Java, such as Lumajang, Pasuruan, Trenggalek, Probolinggo, Ponorogo, Jember, Tulunggagung, Nganjuk, Pacitan, and several urban areas, namely Blitar, Kediri, Malang, and Stone. So, there is a need for earthquake disaster mitigation, especially in densely populated areas that live on soft soil. This mitigation effort is to minimize the occurrence of casualties by building buildings according to earthquake-resistant standards and avoiding development in the regions that have the potential for amplification of earthquake waves.

Keywords: *Stress Drop, Columb Stress, Earthquake Mitigation.*

1. Introduction

Stress analysis is essential when a destructive earthquake occurs to determine the amount of stress released and the stress characteristics of a deadly earthquake. Analyzing pressure can be done by calculating the Stress Drop and the Stress Coulomb. The stress released by an earthquake can be calculated by Stress Drop, which is the ratio of anxiety before and after an earthquake, where the stress accumulated in the rocks is released right after the earthquake occurs. Meanwhile, the Coulomb stress calculates static displacements, strains, and stresses at specific depths caused by slip faults, magmatic intrusions, or expansion/contraction forces acting on rocks. How an earthquake pushes or compresses a nearby spot or a shear defect or expansion force compresses a nearby magma chamber is closely related to Coulombs [1, 2].

The South Java earthquake occurred on Saturday, April 10, 2021, at 14.00.16 WIB. It was classified as a destructive earthquake because it caused much damage even though it was far from the earthquake source, uniquely this earthquake was classified as a moderate earthquake at sea. Based on BMKG data, this earthquake has M.6.1, located at coordinates 8.83° South Latitude and 112.5° East Longitude and a depth of 80 km. The dominant mechanism of the earthquake source is the dominant upward oblique, including intraplate earthquakes, namely the earthquake's location on the Indo-Australian Plate, which is subducted under the Eurasian Plate. Nine aftershocks were recorded due to the M 6.1

earthquake on April 10, 2018.2021, with magnitudes ranging from M 2.8 - M 5.5 range 20-40 km. This difference in depth is a serious concern because it is very far from the main earthquake, which is 80 km. Is it a different location or due to a lack of sensors being recorded so that an azimuth gap occurs, which impacts calculating the earthquake's depth [3].

The South Java earthquake was classified as a destructive earthquake. BNPB data recorded that eight people died, 36 had minor injuries, and 3 had moderate to severe injuries. BPBD of Lumajang Regency identified five people who died in its area, while Malang Regency had three people. Meanwhile, the impact of damage to the housing sector was recorded in 15 regencies and cities in the East Java region. The total damaged houses according to various categories were 1,189 units, with details of 85 units severely damaged, 250 moderately damaged, and 854 lightly injured. Public facilities were also wounded, totaling 150 units [4].

Judging from the shock map with the MMI scale, Malang Regency and Blitar Regency experienced shock intensity at IV MMI. BPBD Malang Regency reported that 525 houses were lightly damaged, 114 moderately damaged, and 57 severely damaged, while 14 educational facilities, eight health facilities, 26 places of worship, and six bridges were destroyed. BPBD data for Blitar Regency damaged 217 houses, 85 were moderately injured, and ten were heavily damaged, while nine public office facilities and three village halls were destroyed.

Several other damages were reported by several BPBDs in East Java Province, such as Lumajang, Pasuruan, Trenggalek, Probolinggo, Ponorogo, Jember, Tulunggagung, Nganjuk, Pacitan districts, while urban areas, namely Blitar, Kediri, Malang and Batu [4].

This study aims to determine the causes of damage to the South East Java earthquake by looking at its stress characteristics, the amount of stress released during an earthquake, and its relationship with the surrounding geological conditions. From the impact of the damage in several areas in East Java, was it only from the Source of the earthquake or the effect of the soil conditions in East Java? This is what will be discussed in this paper.

2. Tectonics and Geology of Java Island

Java Island is a disaster-prone area where the ring of fire stretches from East to West. Of the 33 volcanoes that cross the island, about 17 are still active and ready to erupt at any time. A series of active volcanoes that cross the Indonesian archipelago follow fault lines parallel to tectonic plate boundaries. This volcanic line begins at the southern tip of Sumatra, extends to Krakatau in the Sunda Strait, explores the central part of Java, Bali, Lombok, Sumba, and Flores, and ends at the Banda Islands [5].

Four active tectonic plates affect the geological structure of Indonesia, namely Eurasia, Indo-Australia, the Pacific, and the Philippines. The interaction of the four plates creates a subduction zone and makes Indonesia a tectonically unstable area, especially on the island of Java. The collision of the Australian and Eurasian plates influenced it. It is from this mechanism that active fractures are formed. Major cities along the north coast of Java, from Surabaya, Semarang to Cirebon, were found to be in active earthquake fault lines. The Source of the earthquake that hit these cities was close to the population center, so it was feared that it could cause massive damage if not anticipated.

The newly identified land fault line is the Kendeng zone, extending from East Java to Central Java. This fault is a continuation of the back arch from the North of Flores Island and continues to the North of Bali Island, and enters the mainland in East Java [6].

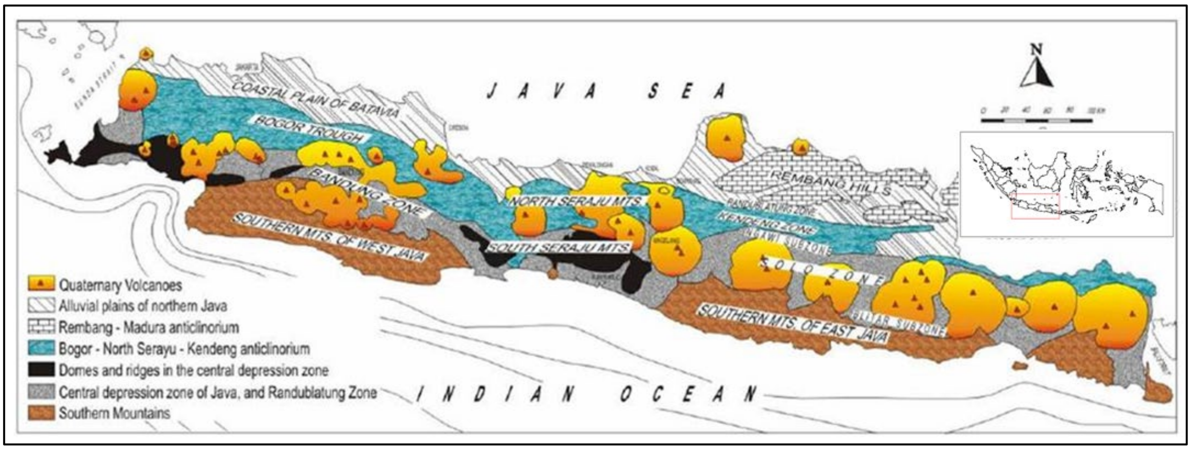

Figure 1. A physiographic map of the islands of Java and Madura [5]

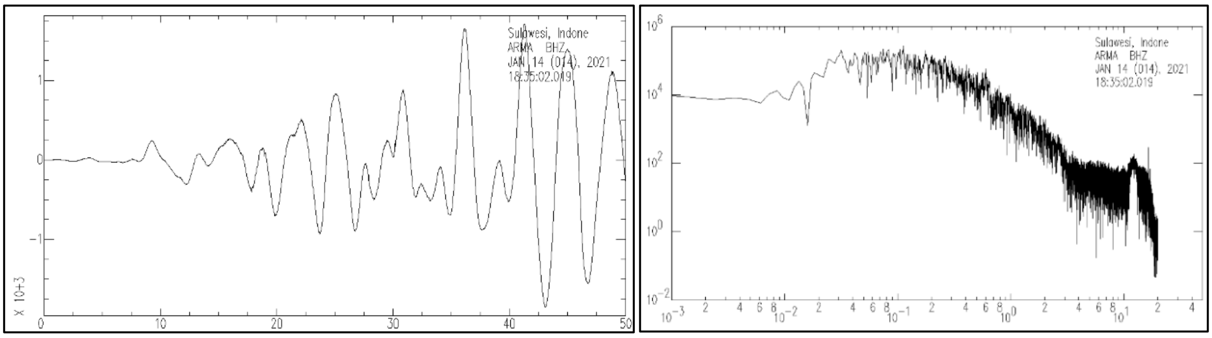

Figure 2. Windowing of 50-second seismogram data (left), FFT (right) [14]

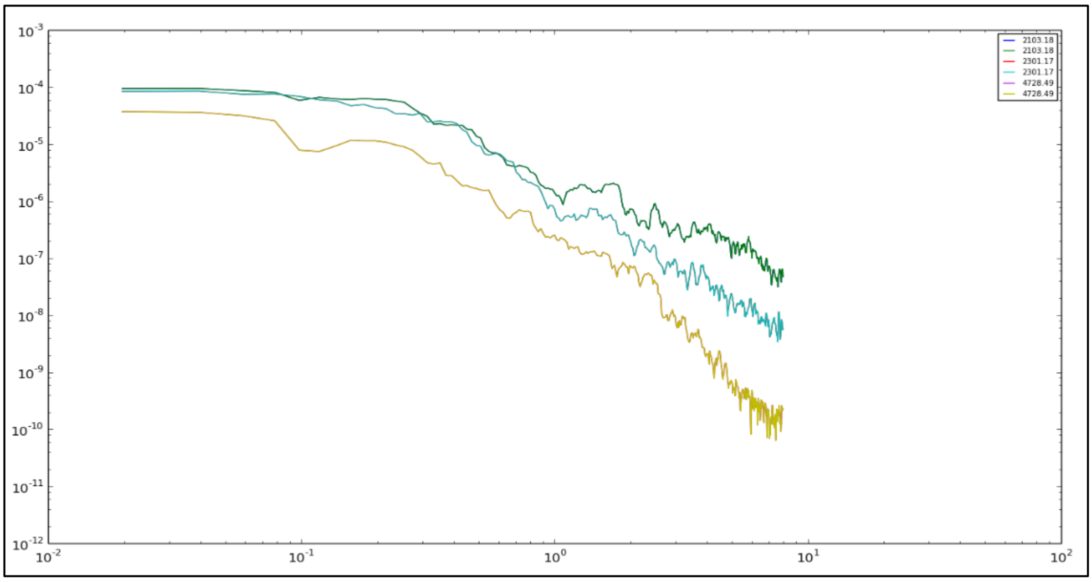

Figure 3. In the observed displacement spectrum, the x-axis represents time (s), the Y-axis represents displacement (cm), green represents the Vertical component, and blue and yellow represent the Horizontal component.

Geologically, Java Island is relatively young, consisting of the Tertiary Quaternary until recently. There is also evidence of the Pre-Tertiary Age. The formation of Java began in the Oligocene and Miocene through a series of intense orogenetic phases. However, the island's current shape was formed during the Pleistocene epoch. The rock structure in Java is formed from a series of hills and lowland basins, as shown in **Figure 1** [7].

The Quaternary volcanic zone contains many volcanoes with an average elevation of 2,000 m or more and is primarily active. The central depression is the main axis of the island from which two significant pits emerged: the Bandung Depression to the west and the Solo Depression to the east. Solo Depression has the Sangiran Dome, which is a famous ancient site.

The middle anticline zone consists of Mio-Pleistocene deposits, with the Kendeng hills extending west to east. The Randublatung Depression, at the foot of Mount Kendengan, was formed from marine and land deposits from the Mio-Pleistocene era. The Rembang-Madura Anticline consists of Miocene limestone formations [8].

3. Research Methods

The data from the April 10, 2021, Southeast Java earthquake recorded at the BMKG, IRIS-DMC, and fault parameter data from the USGS. [9,10,11]. The stations used are from Australia, namely ARMA, MEEK, and MORW, with a distance of 30^0-100^0 from the earthquake source. Stations are used away from the earthquake source to avoid interference from other wave phases, such as refractive, diffraction, or reflection waves [12].

The Stress Drop calculation phase begins using earthquake, seismogram, and fault parameters from BMKG, IRIS, and USGS [2,3,10]. The next step is to convert the seismogram data format from miniSEED to SAC format using the Reads and Interprets Standard for Exchange of Earthquake Data (SEED) Files (RDSEED) program [13]. After the data is converted, the P and S waves are taken using the SAC program. The second stage is data processing, starting with instrument correction and taper with the multitaper method, namely the tapered method with lots of data, after which the waves are integrated into the displacement format using the Fast Fourier Transform (FFT) [14].

Before this spectrum is analyzed, a deconvolution process is carried out, which separates the response from the device, the path response, and the geometric distribution [15]. Next, windowing was performed on the displacement spectrum of the South-Southeast Java earthquake with a window of 50 seconds, 2 seconds before the onset of P [16]. The windowing and FFT results can be seen in **Figure 2,** while the displacement spectrum for the Southeast Java earthquake is shown in **Figure 3**. This deconvolution aims to obtain the scope of the actual earthquake source. The seismogram signal recorded from an earthquake is a combination of some information on the nature of the quake as shown by the following equation [17,18]:

Seismogram (f) = Source (f) * Path (f) * Site (f) * Tool (f)……………..……………………………1.

Where Source (f) is: the effect spectrum from the Source related to parameters such as stress drop, which describes the mechanism at the earthquake source, Path (f): the effect spectrum from the spread of effects from the start to the provider station related to the seismic attenuation parameter (Q), Site (f): spectrum amplification containing local (geological) influence information, and instrument, Tool (f): spectrum caused by the influence of the instrument response [2,15], the entire inversion process is carried out simultaneously using the Python program [19].

After obtaining the source spectrum, the best angular frequency (FC) calculation will be carried out from the most suitable Brune model, namely the earthquake source model as a tangential stress pulse. This model uses three independent parameters (moments, source dimensions, and stress drop), which will be used as input in the stress drop calculation as in the equation:

$$\Delta\sigma = M_0 \left(\frac{f_c}{0.42\beta}\right)^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.$$

Where Δδ is the Stress Drop (Mpa), Mo is the moment magnitude (Nm), FC is the angular frequency, and β is the wave distribution constant at the Source, which is 3.3 km/s [20].

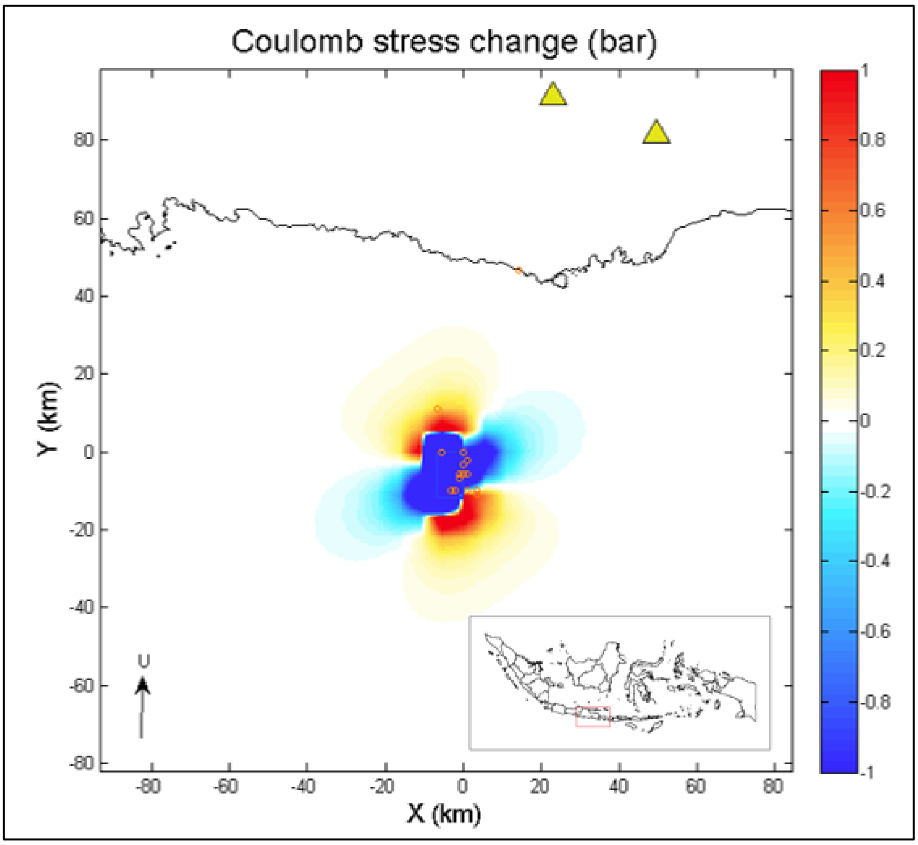

Figure 4. The change in coulomb voltage on the X-axis shows a shift in horizontal stress. The Y-axis shows the vertical stress change. The red color represents the positive Coulomb stress area, while the blue represents the negative Coulomb stress area.

Calculation of Static Coulomb Stress is used to determine whether aftershocks are triggered by the main earthquake or not. Changes in stress due to the main quake disrupt shear anxiety and everyday stress around the fault. This is what causes aftershocks. The difference in static Coulomb stress is the sum of the shear stress and daily stress multiplied by the effective friction coefficient, which can be seen in Equation 3.

$\Delta\sigma_f = \Delta\tau_\beta + \mu'(\Delta\sigma_\beta)$……………………………..3.

Persamaan 3 merupakan persamaan untuk menghitung perubahan stress Coulomb $\Delta\sigma_f$ dengan $\Delta\tau_\beta$ merupakan perubahan *shear stress*, μ' merupakan koefisien gesek efektif, dan $\Delta\sigma_\beta$ merupakan perubahan normal stress. Besar koefisien gesek efektif antara 0 sampai 0,75 dengan nilai rerata μ'= 0,4, potensial slip akan meningkat jika $\Delta\sigma_f > 0$ (pola merah) dan berkurang jika $\Delta\sigma_f < 0$ (pola biru). Perubahan stress Coulomb $\Delta\sigma_f$ bisa bernilai positif atau negative [21].

Equation 3 is the equation for calculating the Coulomb stress change $\Delta\sigma_f$, f where $\Delta\tau_\beta$is the shear stress change, μ' is the effective friction coefficient, and $\Delta\sigma_\beta$ is the average stress change. The effective friction coefficient ranges from 0 to 0.75 with an average value of μ'= 0.4. The potential for slippage will increase if $\Delta\sigma_f > 0$ (red pattern) and decrease if $\Delta\sigma_f < 0$ (blueprint). Coulomb voltage change $\Delta\sigma_f$ can be positive or negative [21].

Areas that experience positive Coulomb Stress changes are defined as areas that experience an increase in stress and can accelerate the occurrence of slip on the fault plane. Areas with a negative Coulomb stress are interpreted as areas that experience decreased anxiety and delay the event of slip on the fault plane, as seen in Figure 4 [22]. This study used the primary earthquake data for the Southeast Java Earthquake on April 10, 2021. The data needed are coordinates, depth, and magnitude information from the BMKG earthquake catalog data, the earthquake focus mechanism, and fault information from the USGS [2,3]. Calculation of static Coulomb stress changes using Coulomb 3.3 software.

4. Results and Discussion

Determination of Stress Drops from digital seismograms at ARMA, MEEK, and MORW stations is carried out with several stages of data processing as described in the following method, namely the best fitting of ARMA, MEEK, and MORW stations. Figure 5 shows that the receiving spectrum is close to the Brune model, so the best source spectrum can be seen in **Figure 5** to the left of the Brune model, which is manifested by a green curve. In contrast, a blue sign exemplifies the receiving signal, and **a green curve displays Figure 5 to the right of the Brune model,** while a red alert shows the signal receiver.

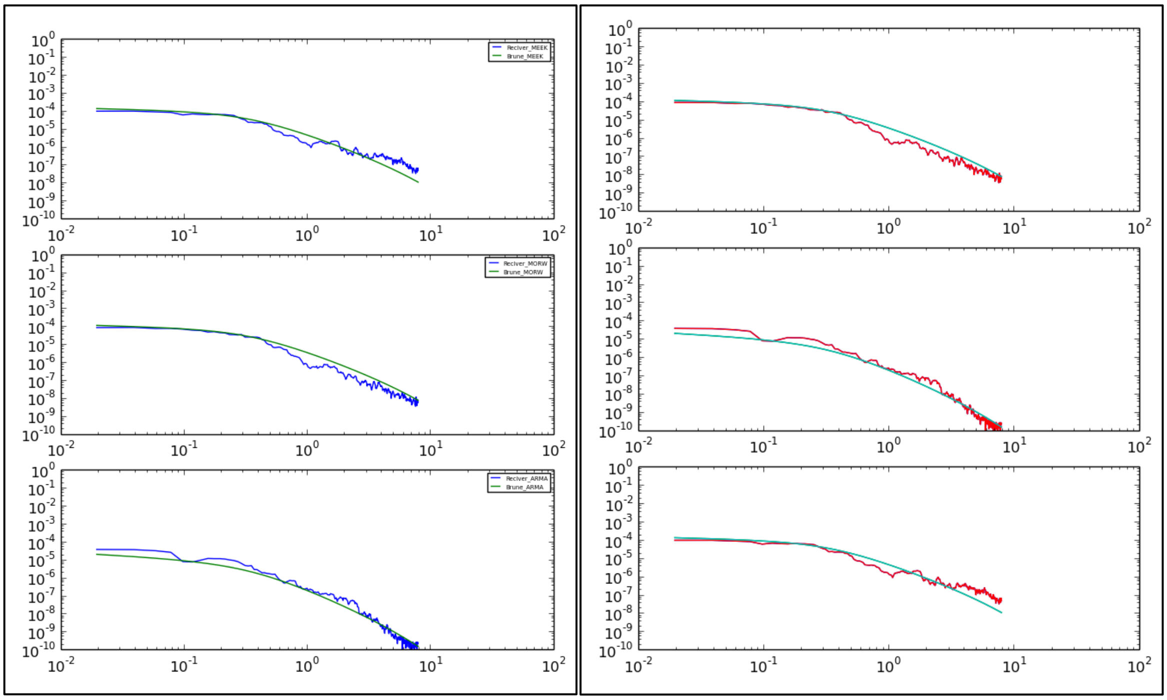

Figure 5. The most suitable receiver spectrum (left) and source spectrum (right) from the South Java earthquake recorded at ARMA, MEEK, and MORE stations, the blue color shows the receiver spectrum, the red color indicates the source spectrum, and the green color shows the Brune model.

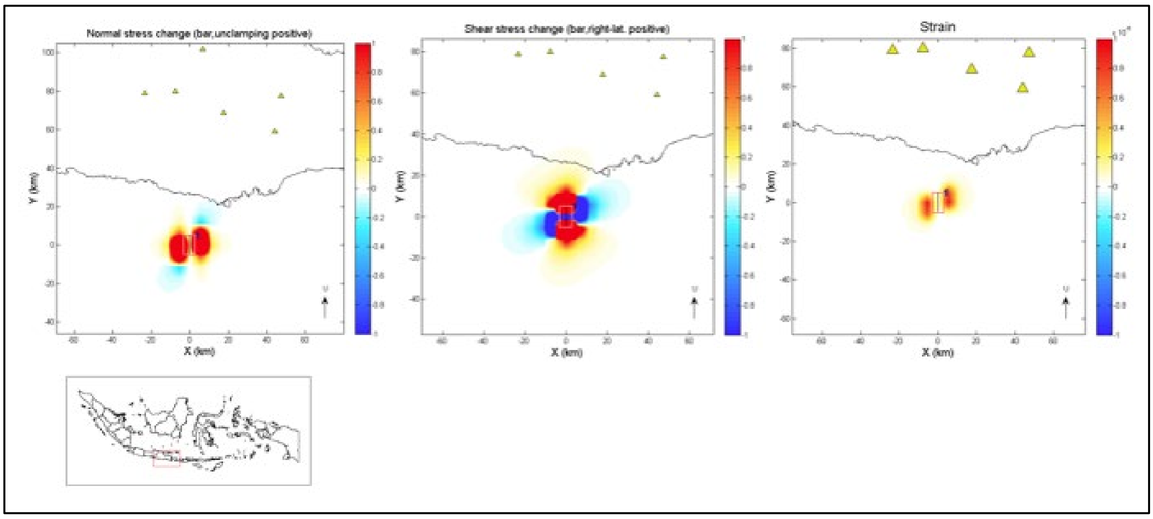

Figure 6. Changes in everyday stress, shear stress, and strain in the South Java earthquake on April 10, 2021. The X mark indicates a shift in Horizontal stress. The Y-axis shows the Vertical stress change. The red color represents the positive Coulomb stress area, while the blue represents the negative Coulomb stress area.

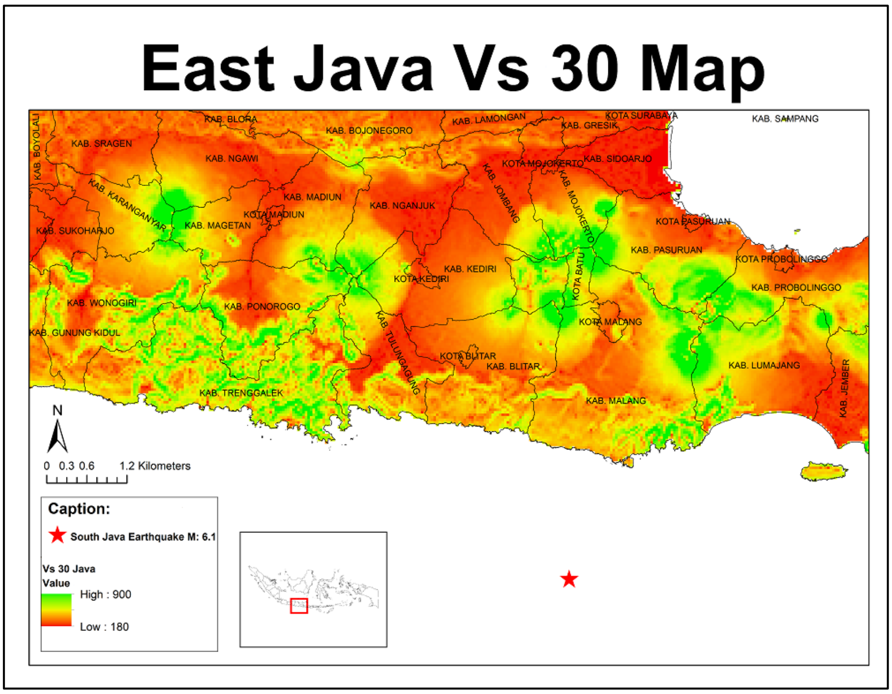

Figure 7. Map of East Java vs. Values of 30 Vs. 30 was obtained from the USGS and interpolated with the East Java base map. The X-axis shows latitude, and the Y-axis shows longitude in degrees. The red star indicates the Epicenter of the April 10, 2022, Earthquake.

The stress drop for the Southeast Java earthquake was relatively small, 1.69 MPa, with an angular frequency of 0.345 Moment Magnitude 1.1E+18. Common to all subduction zones is a very low-pressure drop along the Cocos subduction zone in Central America with an average value below 1 MPa [12].

Type of fault, most of the thrust that occurs in the subduction zone has a relatively minor stress drop value. The value of the stress drop is relatively small because most of it appears in low-stress areas, generally in areas of shallow plate subduction. From calculating the stress drop value of 1.69 Mpa with the focal mechanism type, intraplate thrust faults due to subduction activity give a small Stress Drop value. The stress drop value is small because the area is a subduction area, and the intraplate is also quite deep at the earthquake's depth.

The stress drop value is small because it often occurs in areas with low rigidity, generally in shallow slab subduction, where tectonic plates meet between continental and oceanic plates that are easily deformed. Allmann and Shearer (2009) reveal this variation. Stress drop is affected by variations in stiffness and different plate materials. An earthquake with a magnitude of m 6.1 occurred on April 10, 2021, m 6.1, located at coordinates 8.83º South Latitude and 112.5º East Longitude and a depth of 80 km. USGS data for this earthquake has a dominant oblique thrust fault mechanism with the parameters of the earthquake fault plane having a tilt angle of 180°, a tilt of 29°, and a slip of 135. [1]. The amount of shear stress at the epicenter of the main earthquake was 21,838 bar (1,2838 Mpa), the pressure normal was 0.001 bar, and the coulomb stress was 21.837 bar. The stress drop value with the coulomb stress at the epicenter has almost the same sign, 1.69 MPa, and 2.18 MPa, so the stress mechanism at the earthquake source and the coulomb center is nearly the same, as seen in **Figure 6**.

The change in coulomb stress in the South-Southeast Java earthquake can be seen in **Figure 4**. The coulomb stress in the positive direction is marked in red, indicating that the focus is experiencing a change in pressure. This change has the potential for aftershocks. At the same time, the coulomb stress in the negative direction is marked in blue, indicating that the change in pressure is dilatation. The shift in coulomb stress is negative in the East-West direction. Prediction of aftershocks with changes in coulomb stress can be seen from changes in the red lobe stress. The red lobe area has the potential for positive stress change. In the red lobe in Figure 4, the direction of the coulomb stress change is towards the North with a stress change of 0.4 – 1 bar. If it approaches the MPa of 0.04 – 0.1 MPa, then in that area, there is the possibility of aftershocks, which can be seen from **Figure 4** distribution of aftershocks that occurred in the region.

Whereas in **Figure 6,** the Coulomb stress change ($\Delta\boldsymbol{\sigma_f}$) with ($\Delta\boldsymbol{\tau_\beta}$) is the change in shear stress, (μ^') is the effective friction coefficient, and ($\Delta\boldsymbol{\tau_\beta}$) is the average stress change, the magnitude of the shear stress at the center of the main shock is 21.838 bar in the North and south directions because the shear strain is more dominant, the shear pressure is almost the same as the shear stress so that the shear pressure is nearly the same picture, the everyday stress in the east-west direction is 0.001 bar, and the shear focus is 21.837 bar as well as an effective friction coefficient of 0.4.

The Southeast Java earthquake was classified as damaging not because of the magnitude of the stress or stress but because of the amplification impact of the earthquake waves because most of the buildings were built on soft soil, as seen in **Figure 7**.

These soft soil deposits have not been appropriately consolidated, so that the earthquake waves experience amplification. The energy of the earthquake waves depends on the medium through which it passes. If it passes through the rock layer media, the frequency of the earthquake waves is higher, but the amplitude is small, so the energy is negligible. On the other hand, if it passes through alluvial deposits, the amplitude will increase so that the earthquake's power is also significant. The probability of exceeding the PGA value is 10% for 50 years in the East Java region of 0.25-0.3 gal, with the soil in the East Java region being mostly soft, so there is potential for damage [23].

The value of Vs. 30 is the value of the S wave at a depth of 30 m below the ground surface. The Vs. 30 map was obtained by interpolating with data from the USGS. The value is relatively low on the Vs. 30 map, especially in parts of East Java. The areas affected by the damage caused by the South-Southeast Java earthquake were Lumajang, Pasuruan, Trenggalek, Probolinggo, Ponorogo, Jember, Tulunggagung, Nganjuk, and Pacitan. In contrast, urban areas were Blitar, Kediri, Malang, and Batu [4]. So, it is necessary to have disaster mitigation, especially in areas that live on soft soils, to minimize the occurrence of casualties, namely by paying attention to building construction that is by earthquake-resistant buildings, and it is necessary to pay attention not to building structures on land that is prone to amplification of earthquake waves.

5. Conclusion

The stress drop value for the Southeast Java earthquake on April 10, 2021, was 1.69 MPa, with the type of focal mechanism as a sea fault. This earthquake was caused by rock activity in the Intraplate. The stress drop value is small but more significant when compared to the contact area in subduction because the intraplate rock area has a variety of variations, and earthquakes are infrequent. The orientation of the seismic fault has an angle of 180°, dip of 29°, and slip of 135. The magnitude of the shear stress at the center of the mainshock is 21,838 bar, the everyday stress is 0.001 bar, and the coulomb stress is 21,837 bar. Based on the plotting results, the main earthquake in South East Java on April 10, 2021, had a positive Coulomb Stress change that spread from Southeast to South and Northwest to North. The Southeast Java earthquake was classified as damaging not because of the magnitude of the stress or the stress mechanism but because of the amplification impact of the earthquake waves because most of the buildings were built on soft ground. So it is necessary to have disaster mitigation, especially in areas that live on soft soils, to minimize casualties.

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