

## Dimensional Insights of Subsurface Structures along Eastern Ghats Mobile Belt, India: Mohr Circle Analysis in Magnetotellurics

Abhishek Yadav<sup>1</sup> Sudha Agrahari<sup>1</sup> and Nitya Prakash<sup>1</sup>

<sup>1</sup>Indian Institute of Technology Kharagpur, abhishek47268@gmail.com

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### SUMMARY

The use of the Mohr Circle, traditionally employed in mechanical stress analysis, has been adapted in Magnetotellurics (MT) to interpret impedance tensors. Unlike stress tensors, which are real, impedance tensors are complex, necessitating two Mohr circles—one for the real component and one for the imaginary component. These circles reveal distinctions such as 2D, 3D, anisotropy, skewness, and distortion within the impedance tensor. To investigate subsurface dimensionality using Mohr circle principles, a ~74 km profile running predominantly north-south was traced in the southern EGMB region, covering the Mahanadi and Angul-Dhenkanal shear zones. This study presents Mohr circle responses and property values from two MT stations near these shear zones. At higher frequencies, both sites show circles near the abscissa, indicating two-dimensional characteristics at shallow depths. In contrast, lower frequencies reveal circles deviating from the abscissa or intersecting the vertical axis, indicating three-dimensional features, anisotropy, or 2D distortion. Property values at both sites further clarify the 2D and 3D characteristics of the subsurface structure.

**Keywords:** Mohr Circle, Eastern Ghat Mobile Belt, Mahanadi Shear Zone, Magnetotellurics, Angul-Dhenkanal Shear zone

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### INTRODUCTION

Dimensionality analysis in Magnetotellurics (MT) is crucial for interpreting the geometry and complexity of the subsurface features, whether they are one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D). The dimensionality of the subsurface depends upon the mechanical activity of the rock body. The pre-existing rocks become very complex due to the gradual changing of temperature and pressure. Eastern Ghat Mobile Belt (EGMB) is one of the severely distorted and transformed Precambrian crustal parts of the Indian Shield.

The EGMB region encompasses various geological features, including folds, faults, lineaments, and shear zones, resulting from processes such as metamorphism, magmatism, and deformation (Chetty 2014). Shear zones are areas where significant shearing stress has deformed existing rocks in the Earth's subsurface, typically due to natural mechanical forces. This deformation can lead to the formation of fault lines, critical for understanding seismic activity and earthquake risks. These geological features play crucial roles in Earth's dynamics, underscoring the importance of understanding their dimensional characteristics to interpret the geological properties of subsurface rocks. The Mohr circle, a graphical tool linking

normal stress with shear stress, provides valuable insights into dimensionality (Lilley 1993a).

Mohr Circle was introduced by German engineer Otto Mohr in 1882, to demonstrate the transformation equation for plane stress graphically. In 1976, Lilley was the first one who introduced the Mohr circle concept in the MT studies to represent the information of impedance tensor in terms of 1D and 2D structures. To enhance the interest in understanding complex MT data, Lilley (1993a) expanded the Mohr circle theory where he considered the real and imaginary components of impedance tensor separately for plotting the Mohr circle and revealing the information about the presence of three-dimensionality, skew angle, anisotropy angle, and Groom-Bailey decomposition method (Raju and Patro 2020). It can also be applied to investigate the distortion and three-dimensional character of MT data (Lilley 1993c). All the MT tensor's invariants can be represented through the Mohr circle that had been explained in the earlier paper (Lilley 1993a). The effect of local static shift around a one-dimensional structure can also be identified by analyzing a specific pattern of the Mohr circle (Lilley 1993b). The visual representation of the Mohr circle in the connection of the Bahr skew angle is used for the identification of certain classes of locally present distortion (Lilley 1993c).

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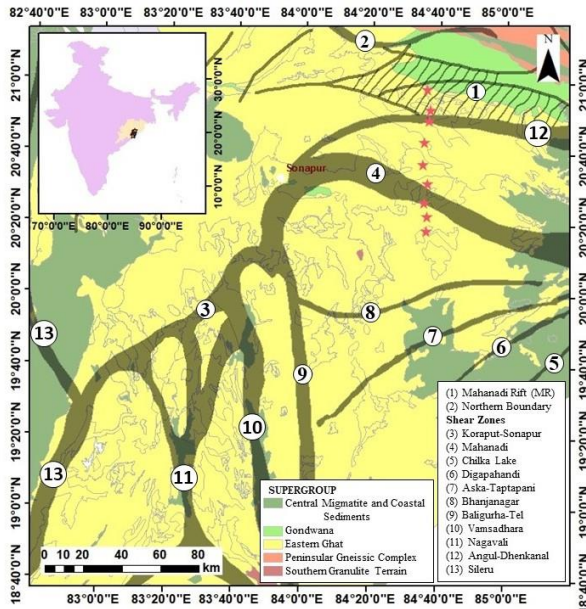
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In the present study, MT data were measured across the two shear zones (Mahanadi Shear Zone (MSZ) and Angul Dhenkanal Shear Zone (ADSZ)).

### STUDY AREA AND FIELD MEASUREMENT

This study examines the structural characteristics of two shear zones within the EGMB region: the Mahanadi Shear Zone (MSZ) and the Angul-Dhenkanal Shear Zone (ADSZ) (Figure 1). The MSZ spans approximately 150 km in length and ranges from 2 to 8 km in width, oriented WNW–ESE. It exhibits a northern dip of approximately 50°, transitioning gradually to the east and sharply to the west. The ADSZ, extending about 200 km in length and 2-3 km in width, represents the eastern extension of the Sileru-Shear zone (Figure 1), dipping steeply toward the south.

Nine MT soundings were conducted along a profile spanning approximately 74 km using the ADU-06 instrument (M/S Metronix GmbH, Germany). The profile is oriented nearly perpendicular to the geological strike, intersecting both shear zones. Data were recorded across the frequency range of 10<sup>-2</sup> Hz to 10<sup>4</sup> Hz in five channels (Ex, Ey, Hx, Hy, and Hz).



**Figure 1:** The map showing the geology of Odisha (<https://bhukosh.gsi.gov.in/Bhukosh/Public>), the nearby shear zones (Chetty 2014), and the location of the MT sites (red star).

### THEORY: MOHR CIRCLE

The real and imaginary components of impedance tensor are represented as:

$$\begin{bmatrix} Z_{xx_r} & Z_{xy_r} \\ Z_{yx_r} & Z_{yy_r} \end{bmatrix} \text{ and } \begin{bmatrix} Z_{xx_i} & Z_{xy_i} \\ Z_{yx_i} & Z_{yy_i} \end{bmatrix} \quad (1)$$

Now the rotated real (denoted with *r* subscript) and imaginary (denoted with *i* subscript) components of impedance tensor are given as

$$\begin{bmatrix} Z_{rotxx_r} & Z_{rotxy_r} \\ Z_{rotyx_r} & Z_{rotyy_r} \end{bmatrix} \text{ and } \begin{bmatrix} Z_{rotxx_i} & Z_{rotxy_i} \\ Z_{rotyx_i} & Z_{rotyy_i} \end{bmatrix} \quad (2)$$

The generation of the Mohr circle requires rotated impedance tensor values ( $Z_{rotxx_r}, Z_{rotxy_r}$ ), which are obtained after the rotation of measured impedance tensors ( $Z_{xx_r}, Z_{xy_r}$ ). These rotated values of impedance tensor are used as the abscissa ( $Z_{rotxy_r}$ ) and ordinate ( $Z_{rotxx_r}$ ) of coordinate axes (Lilley 1993b). After the rotation, the Mohr circle is plotted using the center points (*A* and *B*) and the length of the radius (*L*) of the circle on the coordinate axes. The values are shown below only for the real part, similarly, values can be computed for the imaginary part also (Lilley 1993b).

$$A = \frac{(Z_{xy_r} - Z_{yx_r})}{2} \text{ and } B = \frac{(Z_{xx_r} + Z_{yy_r})}{2} \quad (3)$$

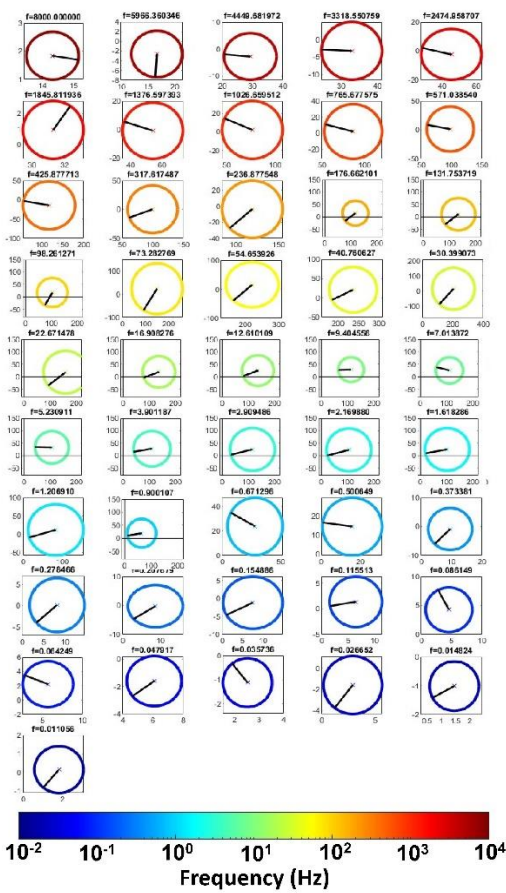
$$L = \frac{1}{2} [(Z_{xx_r} - Z_{yy_r})^2 + (Z_{xy_r} + Z_{yx_r})^2]^{1/2} \quad (4)$$

### RESULTS AND DISCUSSION

MT data were used to plot Mohr circles at various frequencies for all MT stations to assess dimensionality variations along the profile line. Here, the plotted Mohr circles are shown for two specific MT sites – 3 and 7 (Figures 2 and 3). In the high-frequency range, the Mohr circle centers are near the horizontal axis, indicating a 2D nature of the shallow subsurface. In contrast, at lower frequencies, the circles deviate from the horizontal axis, suggesting that the deeper subsurface has a 3D character (Figure 2).

Similarly, Mohr circles are plotted for MT site-7 across all frequencies on individual axes (Figure 3). At high frequencies, most circles are positioned very close to the horizontal axis, indicating 2D structures at shallow depths. Conversely, at lower frequencies, the circles intersect the vertical axis, suggesting high anisotropy or 2D distortion at deeper levels (Figure 3).

Mohr circles are plotted for all frequencies using common abscissa and ordinate axes (Figure 4). The disorganized plots of Mohr circles from lower to higher frequency ranges for both sites suggest the presence of noise-affected impedance tensors (Raju and Patro 2020). The radial arms are not parallel for both the real and imaginary parts, indicating a 3-dimensional nature of the subsurface (Bayrak et al. 2000). Additionally, the centers of the Mohr circles deviate from the horizontal axis, further demonstrating 3D behavior at lower frequencies.

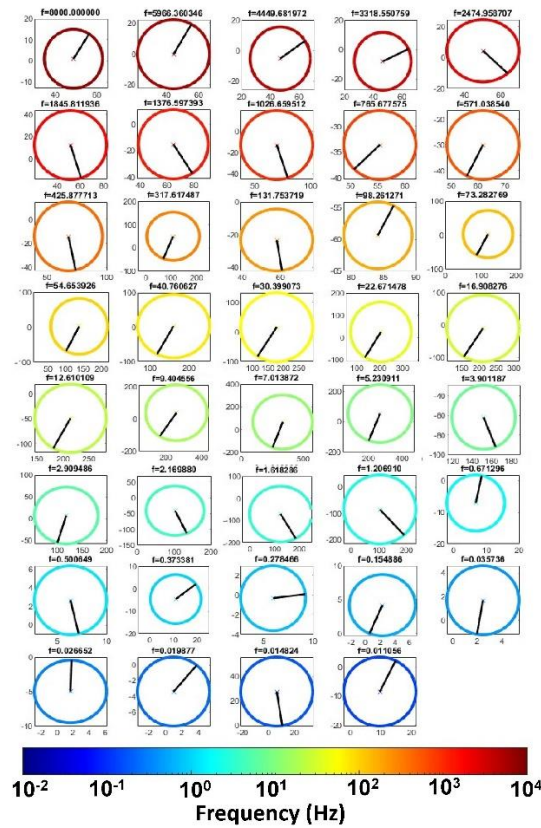


**Figure 2:** Mohr circles are plotted for real components only on individual axes for each frequency of MT site-3.

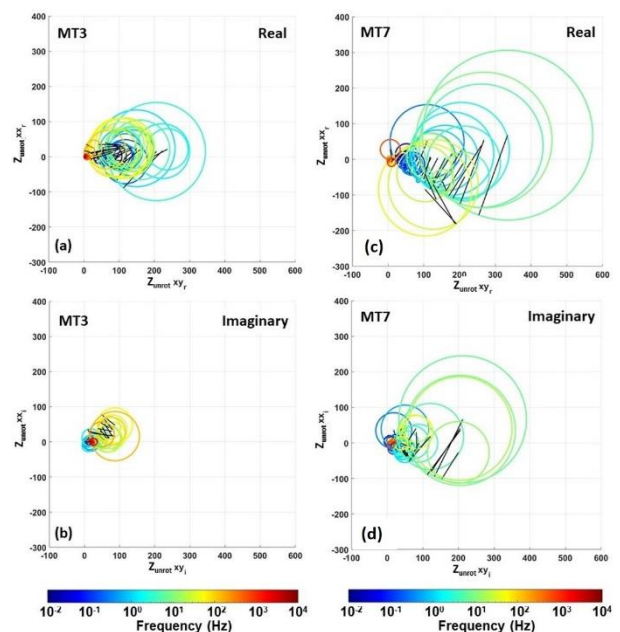
Different property values (Radius, effective impedance, central impedance, arithmetic mean of diagonal elements, center points of circle) of Mohr circles are plotted together to check the characteristics of the Mohr circle. The Arithmetic mean (D) governs the circle's vertical movement along the horizontal axis, which indicates the subsurface structure's dimensionality. The 1D and 2D nature is shown when the value of D approaches zero, while the 3-dimensionality of the structure is characterized by a non-zero value of D. Similarly, for the 1D structures, the Mohr circle radius (R) becomes zero while for 2D and 3D, it has a non-zero value (Raju and Patro 2020). Hence, the dimensionality of the subsurface is clearly shown in the Mohr circle properties plot when D and R are analyzed simultaneously.

In the properties value plot, the D value is very close to zero at the higher frequency for MT site-3 (Figure 5) while at the lower frequency, it has a non-zero value. This indicates the 1D structures at the shallower level while 3D at the deeper level. Also, the radius (R) shows a non-zero value that points out the 2D or 3D subsurface structure. Similarly, the D and R values for the MT site-7 show departure

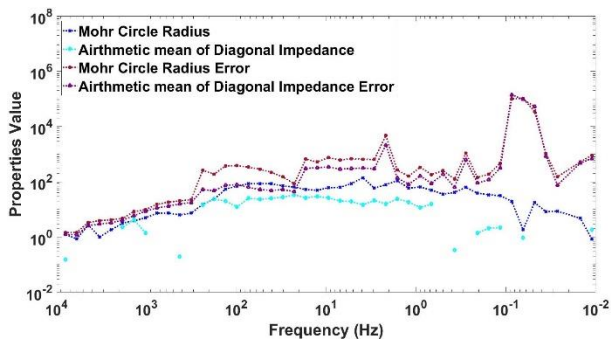
from the zero and notify the existence of 2D or 3D structures (Figure 6).



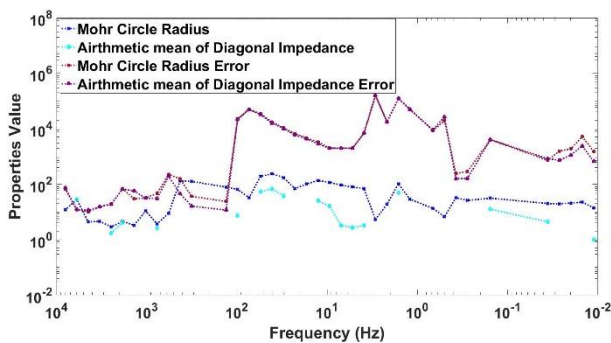
**Figure 3:** Mohr circles are plotted for real components only on individual axes for each frequency of MT site-7.



**Figure 4:** Mohr circles are plotted for all the frequency ranges. The plots in the first row belong to real components while the second-row plots belong to the imaginary component of MT data from site-3 and site-7.



**Figure 5:** Mohr circle radius and arithmetic mean of the diagonal impedance values are plotted for all the frequency ranges for MT site-3.



**Figure 6:** Mohr circle radius and arithmetic mean of the diagonal impedance values are plotted for all the frequency ranges for MT site-7.

### CONCLUSIONS

Mohr circle is a graphical tool that is used to represent the information related to the impedance tensor of MT data. This Mohr circle approach is utilized for the determination of dimensionality using MT data collected from the northern EGMB region across the Mahanadi Shear Zone (MSZ). In the process of this, Mohr circles are plotted in two types. The first type of plot represents the Mohr circles at individual axes for each frequency value (Type-1) which aids in determining the dimensionality of the subsurface. However, the Mohr circles are plotted at common axes in the second type of plot (Type-2) in the search for noise present in the data set. The type-1 plot for both the MT sites displays the 2D signature for a higher frequency range for real components. Type-2 plots exhibit the random distribution of Mohr circles for both real and imaginary parts which is the indication of noise

affected data set. Also, the non-parallel orientation of radial arms for both real and imaginary plots in all plots shows the 3D nature of Earth's structures. The non-zero value of the property values indicates the three-dimensionality of the subsurface structure at lower frequencies.

### ACKNOWLEDGMENTS

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