Imaging a Dike at Dive Ghat (Pune, India) using Piecewise 2D Inversion incorporated Multichannel Analysis of Surface Waves (MASW) technique

*Rashi**
Indian Institute of Science Education and Research, Pune

sharma.rashi@students.iiserpune.ac.in

Keywords

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Abstract

Lava-flow structure and morphology help to understand the eruption style, emplacement mechanisms, and post-emplacement alterations such as weathering. It is challenging to quantify the subsurface structure like dike and the extent of multiple generations of lava flows that are buried under soil and vegetation cover. In this study, limitations of seismic methods for imaging a Dike in the Dive Ghat region of the Pune district located in the Deccan Volcanic Province are examined. We conducted a seismic survey using a 48-channel engineering seismograph. To analyze the acquired data, we employed the Multichannel Analysis of Surface Waves (MASW) technique. However, the conventional inversion delivers a horizontally smoothened image, which is counterproductive in the case of thin vertical structures. Therefore, I developed an improvised workflow referred to as the piecewise 2D approach, for performing inversion of phase-velocity-frequency curves. It is demonstrated using the case study that the novel piecewise 2D approach enables a more insightful image of the subsurface structure compared to the conventional inversion scheme in the case of a thin vertical anomalous body.

Introduction

The Deccan Volcanic Province (DVP) is a significant geological region in the Indian subcontinent, encompassing states such as Maharashtra, Gujarat, Madhya Pradesh, Andhra Pradesh, and Karnataka. Eruptions in this region, called the Deccan Traps by E. Vrendenburg, 1908 (Valdiya, 2015), occurred rapidly between 66 and 68 million years ago (Duncan & Pyle, 1988).

To study the unexposed lava flows in this area, one can employ different methods. One approach is the direct method, involving drilling and examining the core samples. However, this method is expensive and provides limited information especially when trying to understand the geology of a larger area. As a result, geophysical techniques, such as DC resistivity, electromagnetic, and seismic methods, are commonly utilized to image the subsurface. Seismic methods can be used to obtain valuable geophysical information, including P-wave velocity and S-wave velocity. Geological features such as dikes, sills, and faults can be mapped by analyzing the seismic characteristics. Dikes are particularly significant in the geological history of the DVP, and they also play a role in facilitating the movement of water. The cooling down process of magma after dike formation often leads to the creation of joints perpendicular to the direction of intrusion. However, mapping these dikes can be challenging due to their thin horizontal extent.

MASW has emerged as one of the most useful near-surface seismic methods. MASW utilizes the dispersive nature of surface waves, such as ground rolls, in heterogeneous subsurface conditions. By analyzing the phase-velocity-frequency spectrum of these waves, MASW allows for the mapping of geological features. In the Ghatia region of India, Kumar et al. (2010) used MASW imaging to study the lava flows and their weathering zones. They identified three subsurface flows: weathered basalt, massive basalt, and weathered basalt again. The accuracy of their findings was confirmed by an exposed section of a nearby well. Srinivas et al. (2020), used shear velocity imaging for mapping the groundwater. Kumar (2022) showed that MASW can be used to image weathered zones and volcano stratigraphy. These studies highlight the utility of MASW in mapping and understanding basalt sequences in the region.

In this study, we propose a modified MASW data analysis workflow required for imaging Dike like structures. The scheme is referred to as piecewise 2D inversion. We will present some results from the Dive Ghat region in Pune, India, utilizing the conventional and the proposed scheme for MASW technique. Our focus will be on comparing the effectiveness of above-mentioned methods with other seismically derived subsurface images in detecting the presence of a dike using the same dataset.

Method

The MASW is a geophysical method used to characterize subsurface using shear-wave velocity (v_s) (Olson Engineering, 2023). It involves i) recording seismic data using an array of geophones, ii) calculating phase-velocity-frequency spectrums, iii) using the spectrums, the dispersion curves are obtained, iv) and finally a simultaneous inversion of all the dispersion curves is performed to obtain the shear-wave velocity profile. The workflow of the MASW technique is illustrated in Figure 1.

Data Acquisition and Processing

The data was acquired along a 2D profile, approximately perpendicular to the dike, using a 48-channel engineering seismograph. Figure 2 displays the exposed section of Dike near the survey area. The receiver spacing was set to 1 meter, and the shot point interval was kept at 2 meters, with a sledgehammer used as the seismic source. A sample shot-point gather is shown in Figure 3.

During the processing of the data, the first step involves deriving the cross-correlation for every pair of traces in each shot gather. Cross-correlated traces with common-mid-point (CMP) are gathered and then the traces with equal spacing are stacked together (Hayashi and Suzuki, 2004). The resulting gathers are called CMP cross-correlated (CMPCC) gathers. These CMPCC gathers are transformed into phase-velocity-frequency spectrum as shown in Figure 4. The phase-velocity-frequency pairs are specifically picked for the fundamental mode of frequencies (see red dots in Figure 4). Collectively these pairs are called phase-velocity-frequency curves, which serves as the input data for the inversion process. The conventional inversion involves inverting all the curves simultaneously employing a 1D forward modeling to obtain a 2D subsurface image.

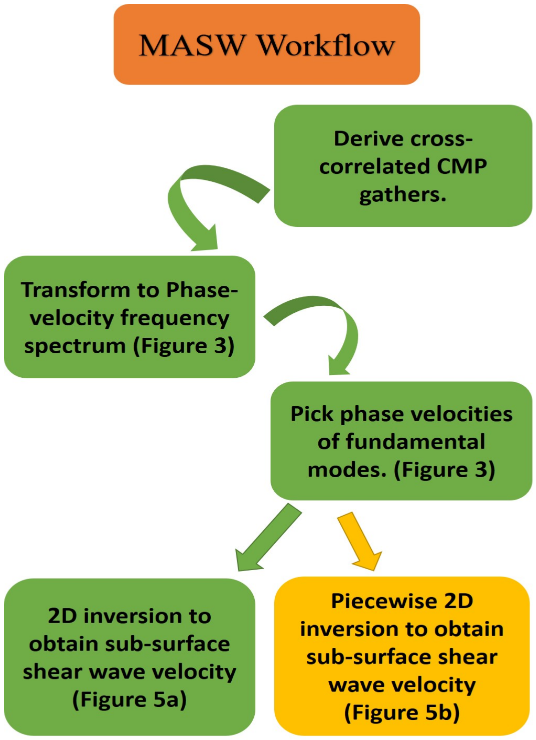

Figure 1. Flowchart for the MASW technique with an improvised step shown in yellow box.

This process generally produces a horizontally smoothened image. The smoothness is the consequence of objective-function regularization that is optimized during the inversion. The regularization stabilizes the solution; however, it introduces the bias in the solution, which leads to smoothness. Therefore, the conventional inversion is not suitable for imaging thin vertical anomalies. Consequently, an unconventional approach is adopted, where step iv) mentioned above in the Method section is modified. Here, the inversion is performed on individual CMPCC gathers, which gives the information below the corresponding CMP position. Then the subsurface velocity information is collectively put in their natural order. This procedure has been applied to the data of Dive Ghat region and results are discussed further.

Results

We analyzed the recorded surface wave data using the conventional and piecewise 2D inversion schemes; additionally, the refraction method is also used for P-wave velocity imaging. Figure 5(a) shows the inverted shear-velocity subsurface model for the proposed piecewise 2D inversion scheme. The field picture (2D map view) is kept below it to better understand the results from a field perspective. The inverted image looks blocky due to the 1D inversion performed individually on each CMP location. A low-velocity anomaly around CMP 21 is observed from 20 meters depth till the bottom of the image. The anomaly coincides with the dike, as observed in the survey area image and shown at the bottom of the inverted velocity model (Figure 5(a)). For better visualization, the dike is partly marked by the yellow line; furthermore, the surface expression of the dike is also visible beyond the yellow line. Hence, the piecewise 2D inversion scheme is able to image the dike that crosses the 2D seismic profile line around 21 meters CMP location. The S-wave velocity of the dike below 20 m depth is observed around 1200-1300 m/s, whereas the S-wave velocity of the host flow is around 2100 m/s. The low velocity arises due to the cooling joints present in the dike. However, in the shallower part (< 20 meters), the velocity of the dike and the host flow are very similar. It is primarily due to the weathering process, which has affected both the dike and host rock, leading to a similar seismic character of the shallower part. From the field observation, the dike has a diameter of approximately 2.5 meters, and it's boundaries have been marked by two dashed black color parallel lines. However, the inverted model shows the low-velocity variations between CMP locations 18 to 28. It is due to the smearing of the image caused by the much longer wavelength of low-frequency Rayleigh wave compared to the thickness of the dike. However, the lower-most velocity anomaly is very well aligned with the dike location and thickness. Another attribute of low-velocity anomaly associated with the dike is that the vertical velocity variations from 10 m depth onwards till the bottom of the image are minimal, which is expected of the dike as it is likely to have smooth changes in its physical property with depth.

Figure 2. Exposed dike in the field where data was recorded.

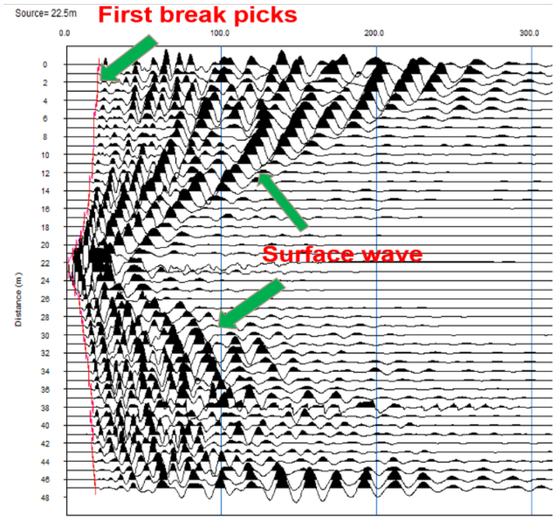

Figure 3. This is a shot gather for a source located at 22.5 meters. It shows the recorded data with offset and time up to 300ms. Surface waves are marked with green.

The shear-wave velocity profile obtained through the conventional 2D inversion is shown in Figure 5(b). It delivered a horizontally smooth model, as expected due to the regularization influence. Consequently, it does not image the dike present in the subsurface. Nonetheless, Figure 5(a) and (b) exhibit a good correlation if we compare the top 10 meters, 10 - 20 meters and below 20 meters regions of the subsurface S-wave velocities of both models except for a dike in Figure 5(a) below 20m depth. Using the refraction method workflow, we have also analyzed the data to obtain the P-wave velocity image. Figure 5(c) illustrates the P-wave velocity profile estimated using inversion of the first break data. The depth of investigation for the refraction method is up to 20 meters only; after that, there is an extrapolation done for comparison. The refraction method is also not able to image the dike. However, making a concrete observation is not possible because the imaging is accomplished only at the top 20 meters, where the dike and host may not seismically differ significantly. Nevertheless, the refraction method is generally suitable for the subsurface, where velocity increases with depth, causing critically refracted waves that are recorded at the surface. In nutshell, examining the results obtained using the analysis of the recorded data, we can say that the piecewise 2D inversion is able to detect the thin vertical dike; therefore, it can be a valuable scheme for analyzing the near-surface data in the presence of thin-vertical anomalies.

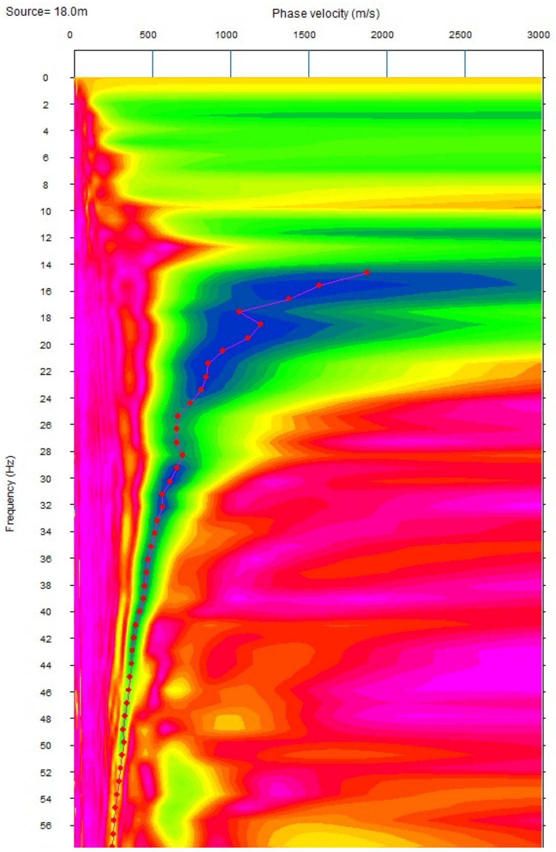

Figure 4. Phase-velocity-frequency spectrum along with picked frequency-phase velocity curve (red dots).

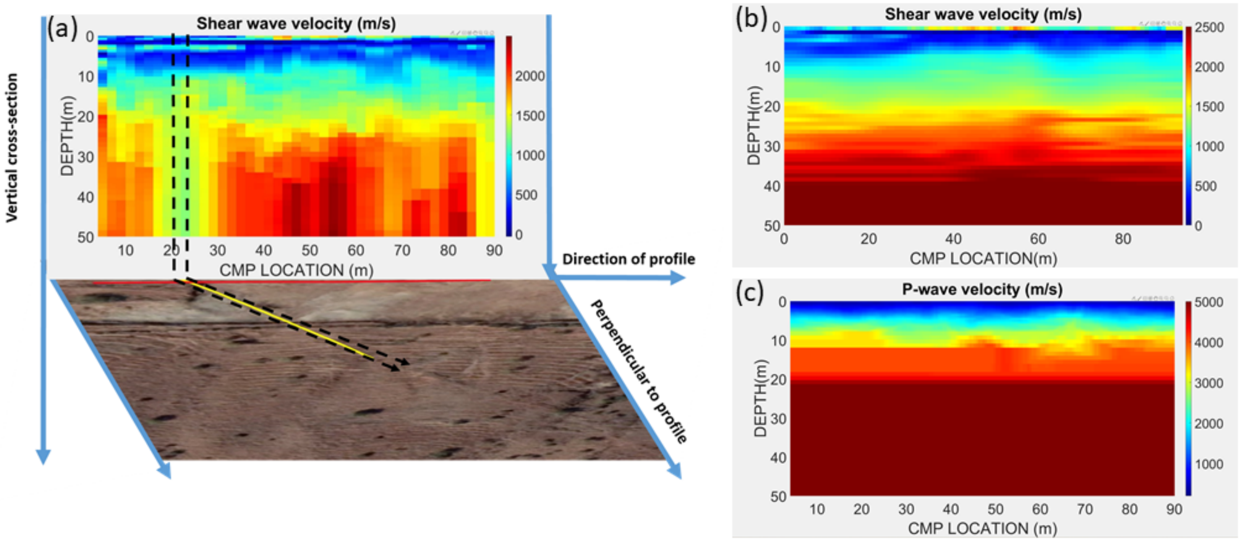

Figure 5. Inverted velocity models; (a) Shear velocity model obtained using Piecewise 2D inversion illustrated above the field image of the survey area, the boundaries of dike are marked with parallel dashed black lines on inverted model and the field image. The imprints of dike are visible in the field image kept below it where data was acquired with red line marked as acquisition profile and yellow line showing the direction of dike cross-cutting the 2D seismic line. (b) Shear wave velocity model estimated using conventional 2D and (c) P-wave velocity model derived using refraction method. Please note the scale of P-wave and S-wave velocities are different.

Conclusions

I present an application of the MASW technique to image a dike using two inversion schemes. A conventional 2D inversion and the proposed piecewise 2D inversion are employed to examine their imaging capabilities for mapping a thin vertical dike. Conventional 2D inversion is unable to map dike in the subsurface due to its inherent nature of producing horizontally smeared images. In contrast, piecewise 2D inversion confirms its presence, supported by corresponding field observations. Therefore, I propose a modified workflow for MASW data analysis for imaging thin-vertical anomalies.

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