Exploring Seismic Phenomena: A Comprehensive Investigation Into Seismology and the Dynamics of Seismic Wave Propagation

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Abstract

This review paper explores the field of seismology and the complex behavior of seismic wave propagation through various geological media. The study summarizes the fundamental concepts of earthquakes and seismology, tracing their historical development and scientific relevance. A comprehensive analysis of seismic waves, including body and surface waves is presented. Particular emphasis is placed on understanding how different material properties such as isotropy, anisotropy, homogeneity, and porosity influence wave dynamics. The study consolidates existing theoretical and applied research, offering insights valuable for earthquake prediction, engineering design, and geophysical exploration. This work aims to serve as a foundational reference for early-stage researchers in seismology and related disciplines.

Keywords: Seismology, earthquake, seismic waves, surface wave, body wave.

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1 Introduction

The science of earthquake is termed as seismology. The word "seismology" is the combination of the Greeks "seismos" which means "earthquake" and "logos" which means "science". Seismology, like nearly every other science, has grown beyond its initial limits. Seismology is the science of different type of vibrations in the internal part of earth. The comprehending of the Earth inner structure and keeping track of the seismic activity is greatly aided by seismology. Seismology is divided into three sections:

1. Observational Seismology: The seismology that records earthquakes and studies their effects. Understanding the source, size, and components of an earthquake are all part of this seismology.
2. Engineering Seismology: This field of study focuses on identifying seismic risks and dangers. Examining and designing a structure to withstand the stress caused by an earthquake's ground movement is known as Earthquake Engineering.
3. Physical Seismology: This field of study examines the physical attributes of the seismic source as well as the internal features of the Earth.

An earthquake is a natural disaster that happens when the Earth shakes for a short period of time, causing damage to both natural and human made structures such as bridges, buildings etc. Hence, for seismologists, studying earthquakes is crucial because, during an earthquake, a significant quantity of energy is released spontaneously inside the ground in form of waves, called seismic waves. Seismology plays a crucial role in minimizing the impact of earthquake on our society, as accurate predictions of earthquake would certainly be beneficial in minimizing the damage caused by earthquake. Before the beginnings of humanity, the Earth had experienced hundreds of millions of earthquakes during its formative stage. Like other natural disasters, earthquakes were once thought to be a curse of God. The earthquake was not recognized as a geological process until the seventeenth century, or the middle of the seventeenth century. From that point on, methodical data and observations were kept, and by using these, researchers have attempted to comprehend the earthquake phenomena that are a part of Earth's geological process. Additionally, this data aids in the provision of methods for the rational evaluation and planning of structures resistant to earthquakes. Real time seismology [1] is another useful technique for using seismology for efficient damage mitigation. When we talk about real time seismology, we typically mean the process of gathering and evaluating seismic data as soon

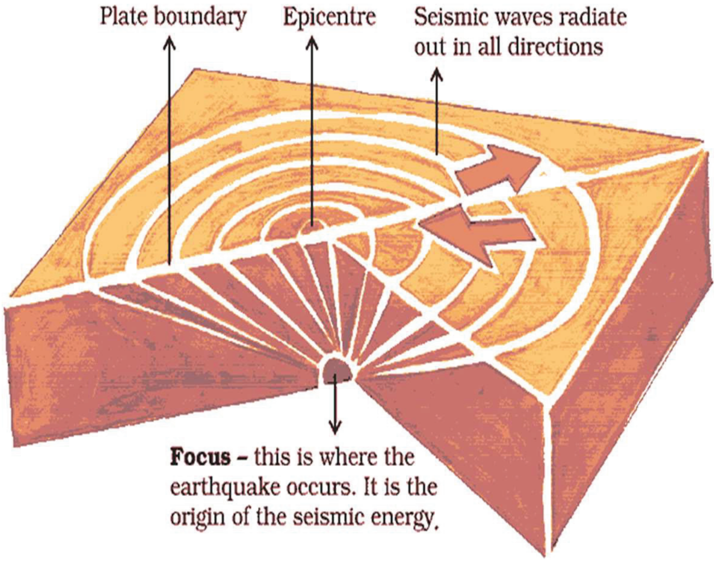

Figure 1 Representation of earthquake (from [2]).

as possible following a large-scale seismic event. This allows us to use the data for efficient post-earthquake emergency response and in the best case, early warning. An earthquake is a sudden, brief motion or disturbance on Earth's surface brought on by a geological disturbance within the planet. The tectonic plates of the Earth that made of elastic and brittle rocky material keeps sliding, very slowly against each other. The plates break when they can no longer hold the energy. Earthquakes are caused by this abrupt slip and the stored elastic energy releases. The enormous amount of released energy travels in all directions. The point of an earthquake where this energy is released is called the focus or hypocentre. The epicentre is a region of the Earth's surface that is found above the focus as shown in the figure. The penetrating devices thousands of miles from the centre can detect these seismic waves. The top layer of the Earth is shaken by the earthquake, and other effects include ground rupture, soil liquefaction, landslides, fires, tsunamis, floods, and so forth.

Despite the wealth of existing literature on seismic wave propagation and seismology, there remains a noticeable gap in the integration of historical, theoretical, and practical perspectives in a single review. Most studies tend to focus either on the mathematical formulation of wave motion or on applied seismology, often neglecting the broader interdisciplinary context.

Additionally, limited attention is given to the combined impact of anisotropy, heterogeneity, and porosity on wave behavior, particularly in fluid-saturated and layered media. This review addresses these gaps by synthesizing classical knowledge, modern advancements, and mathematical models to offer a comprehensive resource that bridges theory and practice in seismic wave research. The structure of this review is organized as follows: Section 2 discusses the historical development and evolution of seismology. Section 3 introduces different types of seismic waves, including body and surface waves, along with their classification and characteristics. Section 4 presents the seismic wave propagation in different media under different conditions, emphasizing the role of various material properties. Section 5 highlights key observations and research insights derived from seismic studies, followed by the references. This review aims to provide a comprehensive understanding of seismology by exploring the historical evolution of the field, the classification and propagation characteristics of seismic waves, and the mathematical modeling of wave motion under different geological conditions. The objective is to consolidate foundational knowledge and recent developments in seismic wave dynamics, particularly in isotropic, anisotropic, and heterogeneous media and to present their practical relevance in geophysics, earthquake engineering, and seismic hazard analysis.

2 Development of Seismology

Around the turn of the last century, seismology was recognized as a separate scientific field. The theoretical basis had been developed much earlier, such as the concepts of elasticity and wave propagation. In particular, Cauchy and Poisson had developed the elasticity theory as early as the first half of the 1800s. Since ancient times, people have been observing earthquakes and their effects in populated areas. About a century after Christ, China was using the seismoscope [3], a specific tool for observing earthquakes. However, until the end of the 20th century, the observations and the theoretical underpinnings were entirely unrelated to one another. Seismology has become a science thanks to the use of high-quality seismographs [4], which also contributed to the significant advances in our understanding of the interior of the Earth over the past century. We will next look at the history of seismology, beginning with the theory of material strength and the theory of elasticity [5]. This relates to the behaviour of bodies, particularly solids, under force that is, how they deform and finally break under sufficiently high stresses. In 1638, Galileo became the first mathematician to study such problems [6]. He investigated how a beam that was loaded and had one end fastened to a wall behaved. He noticed that the beam rotates around a central axis. that is in the plane of the wall and perpendicular to its length as the load increases. Galileo's problem is the name given to the task of identifying this axis. Despite the lack of mathematical relationships between load and deformation, Galileo's contributions to elasticity theory were ground-breaking. The creation of Hooke's law (1660) and the fundamental equations of elasticity by the French scientist Navier in 1821 are two of the most significant developments in the evolution of elasticity theory [7]. According to Hooke's law, a body's deformation is directly correlated with the amount of stress it experiences. It acts as the foundation for the elasticity mathematical theory and is taken for granted in the research of the interior of the Earth. In any case, it remains a useful initial approximation of the Earth's elastic conditions. During this comparatively early phase, the primary concerns of the elasticity scientists were the extension of Galileo's problem. Two others highly regarded French mathematicians, Cauchy and Poisson, were also drawn to the elasticity theory, and specifically the question of how elastic waves travel through media. Through their research, the issue of light propagation became intimately associated with the advancement of elasticity theory. The majority of the elasticity theory's foundations were introduced by Cauchy in 1822, and he later expanded his research to include crystalline bodies. Around 1830, Poisson discovered two types of waves while researching the propagation of waves in elastic media. When these are farther from the source, they are both longitudinal and transverse in effect, with a 13:1 ratio between their velocities. Later, in 1849, Stokes [8] in England agreed this. This is the first time we encounter the primary and secondary waves, which are so well-known in the field of seismology. Another kind of elastic wave was found in 1887 by Lord Rayleigh; this one moves along a body's surface. It was discovered that this wave type's velocity, or speed of propagation, was slower than that of the first two mentioned. It wasn't until 1911 that another significant kind of seismic surface wave was discovered, known as love waves after the Englishman Love. In a paper he published in 1888, German scientist A. Schmidt addressed how waves travel through the interior of the Earth. He pointed out that, usually, the velocity of waves must increase with Earth's depth; as a result, wave paths will be curved rather than rectilinear. The curved wave patterns will have to concave in the direction of the Earth's surface. The majority of the early elasticity research team's efforts were focused on fundamental studies. Their findings, however, have since become extremely important in many practical fields, including technology and seismology. As we have seen, mathematicians made the discovery of the primary seismic wave types that are now frequently found on our seismograph records long before any seismic records were acquired. It is true that, until the turn of the century, our understanding of earthquakes was fairly incomplete, but this is also true of our understanding of the interior of the Earth. Since the beginning of time, people have enjoyed assuming about and using their imaginations freely in relation to the interior of the Earth. The fact that volcanoes occasionally erupt molten lava was likely the basis for the first, more scientific beliefs, which held that this was proof that the Earth's interior was molten and red-hot. When it was discovered more than a century ago that Earth's temperature increases with depth, this theory was deemed to be proven. Lord Kelvin asserted in 1863 that the Earth is more rigid generally than glass based on findings of the tidal effect of the rigid Earth. Later evidence has supported this opinion; the only distinction is that steel provides a more accurate comparison. The Earth's mean density was roughly calculated around the eighteenth century, notably in 1799 by the English scientist Cavendish. The inference was that the density had to rise with Earth's depth as it was higher than the density of rocks at the surface. It was believed to reach its maximum near the Earth's centre. By using theoretical calculations, the German geophysicist Wiechert discovered in 1897 that an iron core is surrounded by a mantle of silicates that is roughly 1500 km deep. This was the original iron-core hypothesis idea, to which most people are still loyal. In 1906, the English seismologist Oldham [9] confirmed the existence of the Earth's core. The American geophysicist Gutenberg [10] updated the depth to the core's border to its current value (2900 km) in 1913. Seismographs were the unifying factor that brought exactness to the study of the earthquakes. These made seismology a science and a mathematical-physical discipline as opposed to merely a descriptive one. Installing seismographs is without a doubt the most significant advancement in the research of earthquakes and the interior of the Earth. A seismograph is a device that continuously records ground motion. A seismometer is defined as a seismograph whose physical parameters are well understood enough to allow the measurement of the actual ground motion from the seismogram. A seismoscope is a tool or equipment that does not record data; it only signals when an earthquake has happened. The seismometer, however, also has a more common meaning. An electromagnetic seismograph is composed of an electromagnetic sensor, usually a pendulum instrument, and a galvanometer that includes an electronic recording apparatus. In an installation like this, the entire device is referred to as a seismograph, whereas the pick-up is typically called a seismometer. Furthermore, we must note that today, the numerical properties of almost all seismographs (seismograph constants) are known with sufficient accuracy to allow for the precise computation of ground motion. Using the later definition of seismometer is beneficial for this reason as well.

3 Seismic Waves

A wave is a type of energy that moves from one location to another across a medium, occasionally causing minimal to no permanent displacements of the medium's particles. Wave propagation is the process by which waves move through any kind of media. Consequently, the particles oscillate about their mean position during wave propagation without changing from their initial positions. We can distinguish between various types of waves based on the direction of oscillation with relation to the propagation's direction. The study of elastic waves spread out from an earthquake possesses the highest level of reliability and conclusions regarding the Earth's internal constitution. Earthquakes, volcanic eruptions, magma movement, and man-made blasts are all causes of seismic waves, which are vibrations that flow through the Earth's layer. Earth has enormous amounts of stored energy, that released as elastic waves known as seismic waves. Large scale devastation is caused by this released energy, including the destruction of individual properties and buildings. Robert mallet made the discovery of seismic waves in 1857, while Kennett [11] conducted further studies on the movement of seismic waves through different materials. According to British geologist Richard Oldham, seismic waves can be classified as either body waves or surface waves. Body waves exist in the interior of the Earth. Primary and secondary waves are examples of body waves, While Rayleigh, Love, and Stoneley waves are recognized as surface waves. These are described in detail below:

A wave that moves across the interior of the Earth is called a body wave. In comparison to surface waves, body waves typically travel faster and have smaller amplitudes and shorter wave distances. Body waves produce less damage than surface waves since these waves contain less particle motion. Based on particle motion, body waves can be divided into two groups: primary body waves and secondary body waves.

3.1 Primary Waves

Primary waves, commonly referred as p-waves, are the initial class of body waves. P-waves are push-pull, compressional waves, which implies that

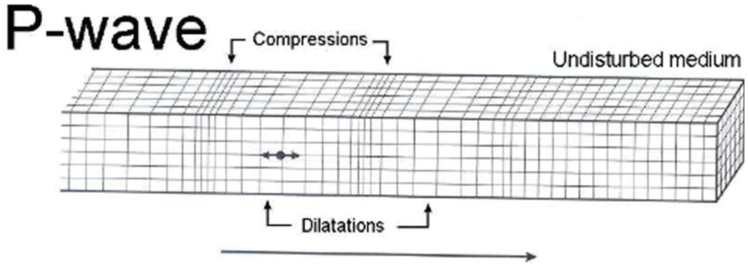

Figure 2 Particle motion of primary waves (from Kearey et al. [12]).

molecules in a solid move in the same direction as the seismic waves travel through the materials as shown in the figure. Because these waves travel faster than other wave types, they are the first to arrive at seismographic stations, hence the name “primary”. P-waves are characterized primary by their sound-speed propagation. Primary waves are able to pass through all kinds of things, including gases, liquids, and solids. In the case of primary waves, materials are not important. These waves travel at a speed of roughly five kilometres per second through the materials. Dogs are among the animals that can sense p-waves well in advance of an earthquake. Only the effects it exerts on the crust are felt by humans. Waves in a stretched spring and sound waves are two examples of p-waves.

3.2 Secondary Waves

Often referred to as s-waves or shear waves, secondary waves are the second type of body waves. The particles’ motion within the material is actually perpendicular to their direction of propagation as shown in the figure. S-waves are referred to as secondary because they consistently arrive at seismographic substations seconds, following p-waves. They resemble transverse waves in certain ways. Shear horizontal waves (‘Sh-waves’) and shear vertical waves (‘Sv-waves’) are the names given to these waves when they are polarized into horizontal and vertical orientations respectively. These waves have a wavelength and a speed of three to four kilometres per second. These waves can only pass through solid media and move more slowly than p-waves. Scientists predicted that the outer core is a pure liquid medium by examining s-waves. The examples of s-waves are water and light waves.

In surface waves, energy transmitted along the surface of the Earth move from one side to the other like a snake and in a rolling pattern like an ocean wave. Surface waves propagate across the Earth’s surface from the

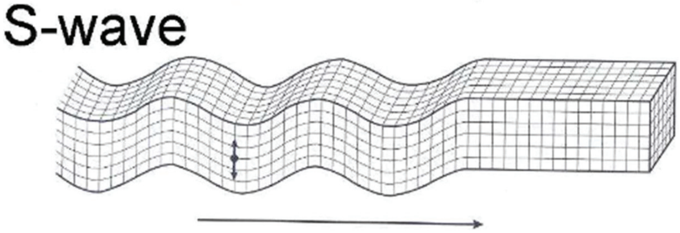

Figure 3 Particle motion of secondary waves (from Kearey et al. [12]).

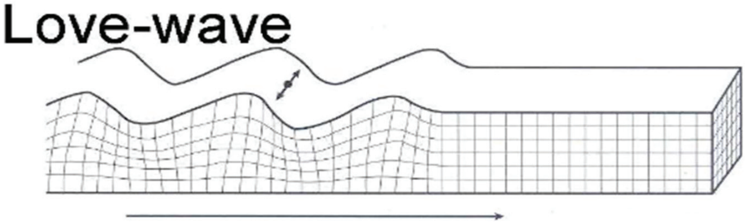

Figure 4 Particle motion of Loves waves (from Kearey et al. [12]).

epicentre. They are also accountable for most of the damage done during an earthquake. The surface waves will be less destructive as the depth of earthquake increases; this is due to the fact that these waves only exist on the Earth's surface. Compared to body waves, surface waves move more slowly. The surface waves are further subdivided into three well-known waves: the Love, Reyleigh, and Stoneley waves.

3.3 Love Waves

Named on a British mathematician A.E.H. Love [13], the first kind of surface wave is known as Love wave or Q wave. Love waves are made up of both transverse and longitudinal waves. In Love waves particles travel back and forth horizontally in a zigzag pattern as shown in the figure. Love waves are slower than any other type of body wave, but these cannot spread into water like s-waves. Love waves usually travel slightly quicker than Rayleigh waves. Love devised a mathematical model of surface waves that he called the Love wave.

3.4 Rayleigh Waves

Rayleigh waves are another form of surface waves. Lord Rayleigh [14] predicted these waves for the first time in 1885. Rayleigh waves are backwards

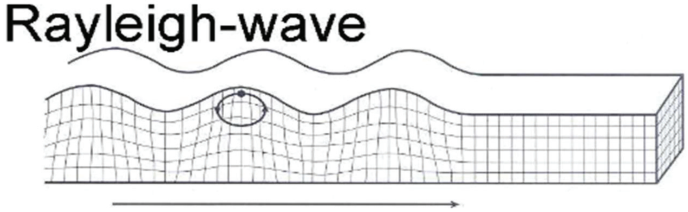

Figure 5 Particle motion of Rayleigh waves (from Kearey et al. [12]).

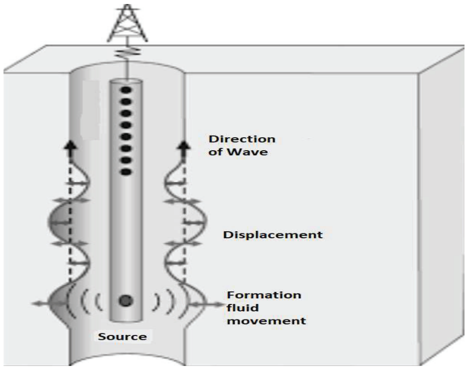

Figure 6 Particle motion of Stonley waves (from [16]).

moving particles that move elliptically like ripples in a pond as shown in the figure. Rayleigh waves move in a unique way; it is rolling. The majority of the damage caused by earthquakes is caused by Rayleigh waves, which is subsequently higher compared to other types of waves. Observer must observe Rayleigh waves in vast open spaces, such as parking lots. Rayleigh waves are less quick than body waves and they usually travel at a 10% slower speed than s-waves.

3.5 Stonley Waves

Stoneley waves, commonly referred to as Scholte waves, are the third type of surface wave that propagates primarily along solid-solid interfaces. Robert Stoneley [15], a British seismologist, discovered these waves in 1924. These waves have a large amplitude interface, and they were generated in a borehole by a sonic tool. These waves are used to estimate the location of fractures and the formation's permeability.

The waves in which the particle oscillates in a direction similar to the direction in which the wave travels are known as longitudinal waves.

Longitudinal waves are those in which the particles in the medium oscillate back and forth on both sides in the direction that the wave is moving. The direction of the particle vibration in transverse waves is normal to the wave's propagation motion. To put it another way, the particles are vibrating up and down in their mean position even while the disturbance is moving forward. The Earth's structure is revealed to us by all these different kinds of waves.

4 Seismic Wave Propagation

Earth is thought to be a multilayered medium made up of layers that have different mechanical properties and differing thicknesses. The seismic wave propagation is very highly influenced by the Earth's heterogeneous composition, which contains a particularly hard layer, the stiff interface, and the medium porosity. The propagation of seismic waves through different geological media has been a subject of considerable research in geophysics and applied mathematics. Understanding how seismic waves behave in varied materials such as isotropic, anisotropic, homogeneous, non-homogeneous, porous, and thermoelastic media is essential for accurate modeling of the Earth's interior and for improving seismic hazard assessment. These properties of the medium have a major impact on their behavior, each influencing wave velocity, amplitude, dispersion, and attenuation in different ways.

4.1 Seismic Wave Propagation in Isotropic and Anisotropic Media

In isotropic media, the material properties are the same in all directions. The governing equations are simplified versions of the Navier-Cauchy equations of motion. Biot [17] was instrumental in describing wave motion in such settings. The primary waves and secondary waves propagate through these media with constant velocities. P-waves, being compressional, are the fastest, while S-waves are shear waves that travel slower. Rayleigh and Love waves, which are surface waves, also exhibit simplified behavior in isotropic media, with well-defined dispersion relations when layered structures are involved. Chattopadhyay and Kar [18] used Green's function methods to study the propagation of Love-type waves from a point source in isotropic elastic media under initial stress. This approach added more depth and detail to traditional wave propagation models. Anisotropy arises in geological media due to the presence of aligned cracks, minerals, or layering. In such materials, the elastic constants vary with direction, causing seismic wave velocities to depend on the wave's orientation. Thomsen [19] introduced a set of parameters (epsilon, delta, and gamma) for weak anisotropy that help describe P-wave and S-wave velocity variations in vertical transverse isotropy models. In anisotropic media, shear waves can split into fast and slow components, a phenomenon known as shear wave splitting. This is critical in the study of crustal deformation and tectonic stress fields. Love waves, which are horizontally polarized shear waves, show marked dispersion in anisotropic media. Similarly, Rayleigh waves in anisotropic materials demonstrate elliptical particle motion influenced by directional stiffness coefficients. Kumar and Saini [20] studied how Love waves propagate through a fluid-saturated porous layer placed between a top isotropic layer and a non-homogeneous base. Using Biot's theory and Fourier transform methods, their analysis showed that anisotropy have a strong effect on the phase velocity of the waves. Sharma and Kumar [21] investigated the propagation behavior of shear horizontal waves in a multilayered system composed of a fluid-saturated porous layer that is transversely isotropic, situated between a homogeneous upper layer and a non-homogeneous elastic half-space.

4.2 Seismic Wave Propagation in Homogeneous and Non-Homogeneous Media

Homogeneous media have uniform physical properties (density, elasticity), allowing for closed-form analytical solutions to wave equations. P-waves and S-waves maintain consistent velocity and amplitude unless boundary conditions are introduced. Love and Rayleigh waves in homogeneous layered media display classic dispersion due to geometric layering. In contrast, non-homogeneous (or inhomogeneous) media feature spatial variation in properties such as shear modulus or density. This variation causes seismic waves to bend (refract), reflect, or scatter. Seismic velocities increase with depth, implying curved ray paths. This led to the development of ray theory and wavefront tracking methods. Sato et al. [22] provided an extensive discussion on wave scattering and attenuation in heterogeneous Earth models, revealing how randomness in material properties can lead to coda waves and amplitude decay. Kundu et al. [23] investigated Love waves in a micropolar layer overlying a non-homogeneous elastic half-space, showing how material heterogeneity and microstructural effects alter phase velocities. Chattopadhyay et al. [24] explored how the inhomogeneity parameter and other variables impact Love wave dispersion, reinforcing the importance of spatial gradients in subsurface materials. Chattaraj and Samal [25] conducted a theoretical investigation into the dispersion of Love-type surface waves in an anisotropic porous layer with a non-uniform periodic boundary.

4.3 Seismic Wave Propagation in Porous Media

Porous media, often encountered in sedimentary basins, consist of a solid skeleton and interstitial fluid. Materials in the skeletal segment are commonly referred to as frames or networks of pores. Generally speaking, the pores are filled with liquid or gasses. Porosity and permeability are the two primary characteristics used to classify porous media. The ratio of a material's pore space, or holes, to its volume is called its porosity. Rocks solid sentiment remained in the soil, as well as their real size, degree of packing, shape, and sorting, all have an impact on porosity. Water's ability to permeate the surface of the Earth is known as permeability. A fluid saturated medium is a phenomenon in fluid mechanics that consists of an incompressible fluid phase combined with elastic solids. Biot [26] developed the first comprehensive theory describing elastic wave propagation in fluid-saturated porous solids. His equations predict three wave types: fast P-wave, slow P-wave, and S-wave. The slow P-wave is especially unique to porous media and is highly attenuated. Porous media are crucial in hydrocarbon exploration, groundwater studies, and subsurface geotechnical evaluation. Surface waves like Stoneley and Scholte waves are particularly responsive to fluid-solid interfaces, making them effective for detecting fractures and estimating permeability in porous formations. Kumar et al. [27] examined shear wave behavior in an anisotropic porous layer with a triangular-shaped irregularity and inhomogeneity, demonstrating how these factors alter dispersion characteristics. Saini and Kumar [28] studied multilayered media subjected to parabolic-shaped irregularities and initial stress, highlighting their impact on the Love wave dispersion equation in anisotropic porous layers over heterogeneous half-spaces.

4.4 Seismic Wave Propagation in Thermoelastic Media

Thermoelasticity considers the coupling between mechanical deformations and temperature changes. In such media, seismic waves not only cause displacement but also thermal diffusion, altering wave speed and attenuation. Love and Rayleigh waves exhibit thermal dispersion in thermoelastic layers. The classical wave equation is augmented with a heat conduction term, leading to complex-valued velocities. These models are useful in understanding thermally stressed zones near magma chambers or in engineered geothermal systems. The field of thermoelasticity has grown significantly over time. Early contributions by Biot [29] and Nowacki [30] introduced theories based on the assumption of instantaneous heat conduction, which led to the development of classical (parabolic) heat equations. These models explained how changes in volume (dilatation) are related to both thermal and mechanical effects. Lord and Shulman [31] proposed a generalized thermoelastic theory by adding a relaxation time to the heat equation. This change converted the equation into a hyperbolic form, which allows heat waves to travel at a finite speed, making the theory more physically accurate. Building on this, Green and Lindsay [32] introduced a more advanced model using two relaxation times for better accuracy. Green and Naghdi [33] further enhanced the theory by proposing a model that allows undamped thermal waves, which is especially useful for high-frequency or low-damping scenarios. Kumar et al. [34] studied how thermal stresses affect dispersion of Love waves in thermoelastic layers, highlighting the direct impact of heat conduction and relaxation time on wave characteristics. Chirita [35] explored Rayleigh waves in anisotropic thermoelastic half-spaces, incorporating thermal dissipation effects.

Since the Earth's structure is complicated and differs across its strata, seismologists are primarily interested in studying how waves propagate in different media. Many researchers have examined the propagation of seismic waves in multilayered media with varying degrees of success. This phenomenon has significant applications in seismology and geophysics. Theoretical research on seismic waves and elastic layering mediums is highly valuable due to its numerous potential applications in soil mechanics, structural and earthquake engineering, geophysical science, and seismology. Rich insights into the Earth's interior have been obtained via a variety of research projects and experiments involving the seismic wave propagation through the layers of the Earth.

The basic equations are

- The basic equation of motion with body forces

$$\rho \ddot{u}_i = \sigma_{ij,j} + \rho F_i.$$

- The equation of motion without body forces

$$\rho \ddot{u}_i = \sigma_{ij,j}.$$

- Strain-displacement relation

$$e_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}).$$

- Generalized Hooke's law

$$\tau_{ij} = c_{ijkl}e_{kl}.$$

- Hooke's law for isotropic elastic medium

$$\tau_{ij} = \lambda\delta_{ij}v + 2\mu e_{ij}.$$

- Basic equations of motion for fluid saturated medium

$$\sigma_{ij,j} = \rho_{11}\ddot{u}_i + \rho_{12}\ddot{U}_i - b_{ij}(\dot{U}_j - \dot{u}_j),$$
$$\sigma_{,j} = \rho_{12}\ddot{u}_i + \rho_{22}\ddot{U}_i - b_{ij}(\dot{U}_j - \dot{u}_j).$$

- The primary wave equation

$$\nabla^2\phi - \frac{1}{\beta^2}\frac{\partial^2\phi}{\partial t^2} = 0$$

- The secondary wave equation

$$\nabla^2\psi - \frac{1}{\beta^2}\frac{\partial^2\psi}{\partial t^2} = 0$$

- The Love wave equation

$$\frac{\partial^2 u}{\partial t^2} = \beta^2\frac{\partial^2 u}{\partial y^2}.$$

- The Love wave dispersion equation in a two-layer system

$$tan(kh) = \frac{2k_1k_2}{k_1^2 - k_2^2}.$$

- The Rayleigh wave equation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)(u, w) = 0$$

5 Discussions and Future Scope

Scientific research has focused on better understanding of the Earth's interior for many years. Studying the composition and materials of the Earth's interior is greatly aided by earthquakes. We thoroughly reviewed seismology, earthquake, types of seismic waves, and propagation of seismic waves in different mediums under different conditions in this review article. Thus, this paper gives a platform for new researchers to easily understand the fundamental concepts associated with this significant subject, which makes it very helpful for them to conduct research regarding seismology and seismic wave propagation and study about the internal structure of Earth.

This review leads to several key findings. First, the behavior of seismic waves, particularly Love and shear waves is significantly influenced by the nature of the medium, including factors such as isotropy, anisotropy, heterogeneity, and porosity. Second, mathematical modeling using classical elasticity and Biot's theory provides a robust framework for analyzing seismic wave motion in various geological settings. Third, transversely isotropic and fluid-saturated porous layers exhibit complex wave dynamics that are essential for accurate subsurface imaging. Lastly, this synthesis of classical foundations and recent research helps bridge theoretical seismology with practical applications such as earthquake hazard mitigation and structural design. The paper's unique contribution lies in presenting a cross-sectional review that not only revisits classical theories but also discusses their application in contemporary problems such as wave propagation through anisotropic and fluid-saturated porous structures, thereby filling a critical educational and research-oriented gap in the current literature.

While this review presents a comprehensive overview of seismic wave phenomena and their propagation through various geological media, it is not without limitations. The study primarily focuses on theoretical and classical modeling approaches and does not delve into detailed numerical simulations or recent machine learning applications in seismology. Future research should explore multi-physics models combining thermal, elastic, and fluid interactions, as well as real-time data assimilation techniques for seismic hazard prediction. Expanding the discussion to include 3D heterogeneous and viscoelastic media, along with in-situ experimental validations, would further enrich the field.

Nomenclature

u_j: Components of displacement vector for a solid
U_j: Components of displacement for a fluid
σ_{ij}: Components of stress tensor
c_{ijkl}: Elastic constants
ϱ: Mass density of the medium

F_i: Components of the vector of the electromagnetic force directed to the body
λ, μ: Lame's coefficients
δ_{ij}: Kronecker delta
τ_{ij}: Components of the stress tensor
e_{ij}: Strain tensor
v_i: Components of the displacement vector
ϕ: Scalar displacement potential
α: P-wave velocity
ψ: Vector displacement potential
β: S-wave velocity
k: Wave number
h: Layer thickness
c: Rayleigh wave velocity

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