Seismic Evidence for Earth's Layered Structure and Its Relevance to Earthquake and Geotechnical Engineering

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Abstract—

The layered structure of the Earth is understood mainly through indirect geophysical observations, particularly the propagation of seismic waves generated by earthquakes. Changes in the arrival time, velocity, amplitude, reflection, refraction and attenuation of seismic phases provide evidence for boundaries between materials with different elastic and physical properties. This review summarizes the principal seismic-wave types and explains how travel-time observations, shadow zones, normal modes, receiver functions and seismic tomography constrain the crust, mantle and core. It discusses the Mohorovičić discontinuity, major mantle transition-zone boundaries, the core–mantle boundary and the inner-core boundary, while distinguishing compositional layering from mechanical layering. The review then considers the engineering significance of seismic structure. Regional crustal structure and wave-propagation paths influence ground motion, whereas near-surface soil and rock profiles, sedimentary basins and groundwater conditions strongly affect local site response. These effects are relevant to seismic hazard assessment, foundation design, liquefaction evaluation and soil–structure interaction. The paper also identifies limitations arising from incomplete seismic coverage, non-unique inverse problems, model assumptions and uncertainty in subsurface characterization. The discussion is a literature-based synthesis and does not present new field measurements or original numerical simulations.

Index Terms—Earth structure, seismic waves, seismic discontinuities, seismic tomography, site response, ground motion, seismic hazard, geotechnical engineering.

I. INTRODUCTION

The Earth is not a uniform solid sphere. Its interior is organized into layers that differ in composition, density, temperature, pressure and mechanical behaviour. In the broad compositional model, the crust forms the outer rocky shell, the mantle consists predominantly of silicate minerals, and the core is mainly metallic. A second classification describes the lithosphere, asthenosphere and deeper mechanically distinct regions according to how materials deform over short and geological timescales. These models are complementary: one describes what the layers are broadly made of, while the other describes how they respond to stress. Understanding both is important for explaining plate motion, earthquake generation and the transmission of seismic energy [1], [2].

Direct observation of most of the deep Earth is not possible with conventional drilling or excavation. The deepest boreholes reach only a small fraction of the distance to the mantle, while the core lies thousands of kilometres below the surface. Scientists therefore infer internal structure by combining seismic observations with gravity, magnetic, heat-flow, mineral-physics and laboratory evidence. Among these methods, seismology is especially important because earthquake waves travel through the planet and respond to changes in elastic properties and material state. Their recorded arrival times and waveforms provide constraints on internal boundaries that cannot be observed directly [1], [3].

The engineering relevance of this subject occurs at several scales. Deep Earth structure and regional crustal properties influence the paths, travel times and attenuation of seismic waves. At the scale of an engineering site, the thickness and stiffness of soil and rock layers, groundwater conditions, topography and sedimentary-basin geometry can modify the shaking that reaches a foundation. Consequently, the same earthquake source may produce different ground motions at nearby locations. For earthquake and geotechnical engineering, seismic knowledge is therefore useful not only for understanding the planet but also for assessing site conditions, selecting appropriate ground-motion inputs and evaluating hazards such as liquefaction [9]–[11], [13].

This paper reviews the seismic evidence for Earth's principal layers and discontinuities and explains the physical basis of the main seismic observations. It then examines the relationship between internal and near-surface structure and selected engineering applications, including site response, ground motion, seismic hazard assessment and geotechnical design. The review is narrative rather than a systematic meta-analysis: it synthesizes undergraduate-level textbooks, peer-reviewed review articles and authoritative technical material. No new seismic records, laboratory measurements or numerical simulations are presented.

II. SEISMIC WAVE BASICS

A. Generation and classification of seismic waves

Earthquakes occur when accumulated stress causes sudden slip or deformation along a fault or within a volume of rock. The released elastic energy radiates away from the source as seismic waves. The point inside the Earth where rupture begins is the hypocentre or focus; the point directly above it at the surface is the epicentre. Seismometers record ground motion as a time series called a seismogram. The sequence of arrivals, their amplitudes and their frequency content are used to identify seismic phases and infer the structure through which they travelled [1], [2].

Body waves travel through the Earth's interior and are commonly classified as primary (P) and secondary (S) waves. P waves are compressional waves: particles oscillate approximately parallel to the direction of propagation. They are generally the fastest seismic body waves and can travel through solids and fluids. S waves are shear waves, in which particle motion is perpendicular to the direction of propagation. Their propagation requires a non-zero shear rigidity, so they travel through solid materials but do not propagate through a fluid with no static shear strength. This difference is central to the inference that the Earth's outer core is liquid [1], [3].

In an isotropic elastic material, idealized body-wave speeds depend on elastic moduli and density: $V_p = [(K + 4\mu/3)/\rho]^{(1/2)}$ and $V_s = (\mu/\rho)^{(1/2)}$, where K is the bulk modulus, μ is the shear modulus and ρ is density. These relations show that wave speed is not controlled by density alone. Composition, temperature, pressure, porosity, fractures, fluid content and stress may all alter effective elastic properties. Real rocks may also be anisotropic and heterogeneous, so the equations are useful idealizations rather than complete descriptions [1].

Surface waves travel along or near the Earth's surface and can contribute strongly to recorded shaking. Rayleigh waves involve coupled vertical and horizontal particle motion, while Love waves involve horizontal transverse motion. They are dispersive because different frequencies sample different depths and may travel at different speeds. Surface-wave dispersion is therefore useful for estimating crustal velocity structure and near-surface shear-wave profiles [1], [5], [6].

B. Reflection, refraction and travel-time observations

At a boundary between materials with different elastic properties, seismic energy may be reflected, transmitted or refracted. The proportions depend on impedance contrast, incidence angle, wave type and boundary geometry. In a layered Earth, velocity changes bend seismic rays and produce characteristic travel-time curves. Reflected and converted phases can be identified from their arrival times and waveforms [1], [2].

Travel-time analysis compares observed arrivals at seismograph stations with times predicted by a velocity model. Models are tested against many source–receiver paths rather than a single record. Travel times, normal-mode observations and other constraints contributed to the Preliminary Reference Earth Model (PREM), a one-dimensional average description of radial density, elastic velocity and attenuation [4]. PREM is a reference model, not a map of every local structure.

C. Seismic shadow zones and other observations

A seismic shadow zone is a region where a particular direct seismic phase is absent or strongly reduced because of the geometry and physical properties of the interior. S waves do not pass directly through the liquid outer core, so direct S-wave arrivals are absent at stations beyond the relevant angular distance from an earthquake. P waves can cross the core, but they are strongly refracted at the core–mantle boundary, creating a broad P-wave shadow zone. These patterns were among the key observations used to identify a liquid outer core [2], [3]. The exact limits of a shadow zone depend on the seismic phase being considered and on the Earth model.

Other observations provide complementary constraints. Normal modes are whole-Earth oscillations whose frequencies depend on global density and elasticity. Receiver functions use converted phases, such as P-to-S conversions, to identify velocity contrasts beneath a station. Seismic tomography combines travel times or waveforms from many paths to estimate three-dimensional velocity variations. Together, these methods reveal lateral heterogeneity and anisotropy beyond a simple layered-sphere model [5]–[7].

III. EARTH'S LAYERS AND SEISMIC DISCONTINUITIES

A. Crust and the Mohorovičić discontinuity

The crust is the Earth's outermost compositional layer. Continental crust is generally thicker and compositionally more varied than oceanic crust, which is typically thinner and denser. The boundary between the crust and the mantle is called the Mohorovičić discontinuity, or Moho. It is identified seismically by a rapid increase in P-wave velocity, often accompanied by an increase in S-wave velocity. The Moho is not a visible surface boundary; it is inferred from refraction, reflection and converted phases recorded by instruments at the surface [2]. Its depth varies between tectonic settings, and local crustal structure may be complicated by faults, intrusions, sedimentary basins and crustal deformation.

The Moho illustrates that a seismic discontinuity is defined by a change in properties affecting wave propagation, not necessarily by one simple change in rock type. It broadly separates crustal from mantle rocks, but may be sharp, gradational or complex. Controlled-source surveys, receiver functions and wide-angle reflection/refraction data help estimate crustal thickness and lower-crustal geometry. These models matter because crustal velocity variations affect regional wave paths [2], [3], [7].

B. Lithosphere, asthenosphere and mantle transition zone

The mantle is a thick shell of predominantly silicate material extending from the base of the crust to the core–mantle boundary, at a depth of approximately 2,890 km in the PREM reference model [3], [4]. Although mantle rocks are solid under ordinary seismic-wave timescales, they can deform and flow slowly over geological timescales. The lithosphere consists of the crust and the mechanically strong uppermost mantle and forms the moving tectonic plates. Beneath much of the lithosphere lies the asthenosphere, a relatively weak region of the upper mantle that can deform more readily. The lithosphere–asthenosphere boundary is not a single globally uniform plane; its seismic expression varies with temperature, composition, water content, frequency and tectonic setting [1], [6].

Within the mantle, seismic velocities show important changes near depths commonly identified at about 410 km and 660 km in reference Earth models [4], [6]. These are usually interpreted as phase transitions in mantle minerals under increasing pressure, rather than as boundaries between entirely different compositional shells. The transition zone between them is therefore a region of mineralogical change that affects density and seismic-wave speed. The lower mantle extends below the transition zone to the core–mantle boundary. Tomographic studies reveal that mantle velocity variations are laterally heterogeneous, reflecting differences associated with temperature, composition, phase, anisotropy and mantle dynamics [1], [4], [6]. These depths are approximate reference values; regional conditions can shift the observed discontinuities.

Global mantle tomography combines records from earthquakes and seismic stations to image velocity variations. Subducted slabs may appear as relatively high-velocity structures, while warmer or compositionally different regions may have lower velocities. A velocity anomaly does not uniquely identify temperature or composition; interpretation requires mineral-physics, geological and geodynamic constraints. Recent reviews emphasize data quality, coverage and uncertainty [5]–[7].

C. Core–mantle boundary and outer core

The core–mantle boundary, historically associated with the Gutenberg discontinuity, occurs at approximately 2,900 km depth. At this boundary, P-wave velocity changes markedly and S-wave propagation through the outer core ceases. The outer core is interpreted as liquid because it does not transmit ordinary shear waves and because P-wave travel paths and velocities change in a way consistent with a fluid metallic layer. The outer core is composed mainly of iron with nickel and lighter elements; the precise proportions remain a subject of geophysical and mineral-physics research [1]–[3].

The liquid outer core is important beyond seismic-wave transmission. Motion of electrically conducting liquid metal is associated with generation of the geomagnetic field. For seismology, the core is detected through phases that travel through, reflect from or convert at the core boundaries. The strong refraction of P waves at the core–mantle boundary and the absence of direct S waves through the outer core form a coherent set of observations, rather than relying on one isolated measurement [2], [3].

D. Inner core and inner-core boundary

The inner core lies within the liquid outer core and is inferred to be solid. Its existence was proposed by Inge Lehmann in 1936 after she examined unexpected P-wave arrivals that could not be explained adequately by a model containing only a liquid core. The inner-core boundary is associated with a change in seismic velocity and the appearance of phases that have travelled through or interacted with the inner core. The inner core is commonly described as predominantly solid iron–nickel alloy, although its detailed composition, anisotropy and structure remain active research topics [5], [6], [8].

Together, the crust, mantle, outer core and inner core form the principal compositional model of Earth's internal structure. Seismic evidence does not simply produce a picture of concentric shells; it constrains the depth, sharpness and physical character of interfaces and reveals departures from a perfectly radial Earth. The same evidence also demonstrates why the inner and outer core must be distinguished mechanically: one is solid and the other liquid under the pressure and temperature conditions at their respective depths [1]–[6], [8].

TABLE I. SUMMARY OF MAJOR INTERNAL LAYERS AND SEISMIC EVIDENCE (APPROXIMATE REFERENCE DEPTHS) [1]–[4], [6]

Region / boundary	Approximate position	Key seismic evidence
Crust / Moho	Surface to variable crustal base	Velocity increase at the crust–mantle boundary; depth varies with tectonic setting
Upper mantle	Below the Moho to about 410 km	Velocity gradients, upper-mantle low-velocity behaviour and anisotropy; lithosphere–asthenosphere boundary varies regionally
Mantle transition zone	Around 410–660 km	Velocity and density changes linked to pressure-induced mineral phase transitions
Lower mantle	About 660–2,890 km	Increasing seismic velocities with depth; tomography shows lateral velocity anomalies
Core–mantle boundary / outer core	About 2,890–5,150 km	Strong P-wave refraction at the core–mantle boundary; direct S-wave transmission stops in the liquid outer core
Inner-core boundary / inner core	About 5,150–6,371 km	Core phases and changes in compressional-wave behaviour support a solid inner core

IV. RELEVANCE TO EARTHQUAKE AND GEOTECHNICAL ENGINEERING

A. Site response and near-surface structure

Site response describes how local geological and geotechnical conditions modify incoming seismic motion before it is recorded at the ground surface or transmitted to a structure. The key controls include the thickness and geometry of soil layers, shear-wave velocity, density, damping, stiffness, plasticity, saturation and the depth to competent rock. A soft sediment layer over much stiffer bedrock can trap and reverberate seismic energy. Depending on the frequency content of the input motion and the properties of the deposit, the surface motion may be amplified, reduced or shifted in frequency. Thus, the common statement that soft soil always amplifies every component of shaking is too simple; the response depends on strain level, frequency and the soil profile [9], [10].

A simple one-dimensional model illustrates the role of layer thickness and shear-wave velocity. For a uniform soil layer of thickness H over much stiffer rock, the fundamental site period is often approximated as $T0 \approx 4H/Vs$, where Vs is the representative shear-wave velocity of the layer. The corresponding frequency is $f0 \approx Vs/(4H)$. This quarter-wavelength approximation helps explain why thick, soft deposits tend to have longer predominant periods than thin, stiff deposits. It is not a complete site-response model: real deposits are layered, damped and laterally variable, and strong shaking can produce nonlinear changes in stiffness and damping [9], [10].

A key site-response mechanism is resonance. If incoming shaking contains frequencies close to a soil deposit's natural frequency, motion may be amplified over that frequency range. The response depends on layer thickness, shear-wave velocity, damping and stiffness contrast with underlying rock. At strong shaking levels, nonlinear behaviour may reduce stiffness and increase damping as cyclic strain grows. Amplification is therefore not a fixed multiplier and may change with shaking intensity and frequency content [9], [10].

The average shear-wave velocity in the upper 30 m, commonly denoted Vs30, is widely used as a practical site descriptor in ground-motion models and seismic design frameworks. It provides a convenient basis for broad site classification, but it cannot fully represent deep sediment thickness, basin geometry, topographic effects or all nonlinear soil behaviour. Trifunac's review highlights the limitations of reducing a complex subsurface volume to a single shallow parameter, while studies of sedimentary basins show that basin shape and edge geometry can influence wave trapping, focusing, duration and frequency content [10], [11]. For important infrastructure, the site model should therefore be selected according to the required level of engineering analysis rather than relying on a single proxy value.

Site characterization combines geological mapping, boreholes, laboratory testing and in-situ geophysics. Seismic refraction/reflection help identify velocity contrasts and bedrock depth; surface-wave methods such as MASW estimate near-surface shear-wave profiles; downhole and crosshole tests measure velocities between boreholes. These results are interpreted with SPT, CPT and laboratory data to develop a ground model that represents the profile and its uncertainty, not merely a single Vs value [1], [9], [10].

Geophysical estimates should be interpreted alongside borehole logs and in-situ tests because shear-wave velocity alone does not describe soil strength, compressibility, plasticity, groundwater conditions or cyclic resistance. MASW, for example, provides a near-surface shear-wave velocity profile, whereas SPT and CPT provide complementary indicators of penetration resistance and stratigraphy. An integrated interpretation should identify weak or contrasting layers, groundwater level and depth to competent material. The level of investigation should match the foundation system, project scale and consequences of failure [9], [10], [13].

B. Ground-motion characteristics and propagation path

Recorded ground motion reflects the combined influence of earthquake source, propagation path and local site conditions. Source factors include magnitude, rupture dimensions, depth and directivity. Path effects include geometric spreading, attenuation, scattering, reflection and conversion through crustal structures. Site effects arise from soil, rock, basin geometry and topography. These components can overlap, especially for near-fault earthquakes [9], [10].

Ground motion is described using measures such as peak ground acceleration (PGA), peak ground velocity (PGV), response spectra, duration and frequency content. Response spectra show the maximum response of idealized oscillators with different periods and damping. A single peak value cannot describe all shaking effects: duration and frequency content also influence cumulative deformation and structural demand [9]–[11].

Ground-motion records are commonly examined in both the time and frequency domains. A time history shows how acceleration, velocity or displacement changes during shaking, while a response spectrum summarizes the maximum response of idealized single-degree-of-freedom systems over a range of natural periods. Duration is also important: two records with similar peak acceleration can produce different cumulative demands if their duration and number of strong cycles differ. Engineers therefore select and scale records with attention to spectral shape, duration, source characteristics and site conditions [9]–[11].

Regional crustal structure can affect the way seismic energy travels from the source to a site. Strong velocity contrasts, sedimentary basins and lateral heterogeneity can cause reflected, refracted or trapped phases. In a basin, waves may reverberate within low-velocity sediments, and basin edges may generate additional surface waves or spatially variable motions. Numerical studies of the Kathmandu basin during the 2015 Gorkha earthquake demonstrate how simplified basin geometry and material contrasts can help explain some long-period ground-motion characteristics, although idealized models cannot capture every feature of a real three-dimensional basin [11].

C. Seismic hazard assessment

Seismic hazard assessment estimates the likelihood or level of earthquake ground motion at a location over a specified period. Probabilistic seismic hazard analysis combines earthquake-source information, earthquake occurrence models, ground-motion models and uncertainty treatment to estimate the frequency with which specified shaking levels may be exceeded. The method does not predict the exact date, location or magnitude of a future earthquake. Instead, it provides a framework for representing uncertainty and supporting decisions in building design, infrastructure planning, land-use management and emergency preparedness [12].

Earth models contribute to hazard assessment by describing earthquake sources and wave-propagation paths. Local site conditions matter because the same reference rock motion can produce different surface motions depending on soil stiffness, sediment depth and basin structure. Hazard estimates therefore need to account for both regional propagation and local amplification or basin effects [12], [16].

Hazard and risk should not be used interchangeably. Seismic hazard concerns the likelihood or level of shaking at a site; seismic risk additionally considers the people and assets exposed, their vulnerability and the consequences of damage. A location with a given hazard level can therefore have very different risk depending on its population, building stock and infrastructure [12], [16].

For engineering practice in India, the applicable national provisions should be checked before selecting design ground motions and detailing structures. The cited IS 1893 (Part 1):2016 publication is identified as the sixth revision [15]. In an April 2026 parliamentary reply, the Ministry of Earth Sciences stated that the seismic-zoning map published under IS 1893 (Part 1):2016 remained the current map after the revised zonation was withdrawn in March 2026 [17]. Engineers should confirm the applicable edition and amendments directly with the Bureau of Indian Standards before using design parameters. A review paper can explain the scientific basis of seismic design, but it cannot replace the governing code or a site-specific engineering investigation [15], [17].

D. Geotechnical engineering: foundations, liquefaction and soil–structure interaction

Geotechnical earthquake engineering examines soil and rock deposits, slopes, foundations and buried infrastructure during shaking. In soil–structure interaction, the foundation and supporting soil form a coupled system. Foundation flexibility, soil stiffness, damping, embedment and radiation of waves can modify structural response compared with a perfectly fixed-base assumption. Seismic provisions therefore distinguish free-field motion from the motion that excites the foundation [14].

Liquefaction is a geotechnical hazard in susceptible deposits. During cyclic shaking, loose saturated sand or silt may develop excess pore-water pressure; as effective stress and stiffness decrease, the soil may lose strength and deform. Consequences include settlement, foundation tilting, lateral spreading, ground cracking and damage to buried services. Susceptibility depends on soil density and history, groundwater and shaking intensity and duration, so it requires site investigation [13].

The connection between seismic evidence and geotechnical design is consequently indirect but important. Seismology supplies the physical understanding and ground-motion inputs; engineering geophysics and geotechnical investigation describe the local ground; and numerical or empirical methods estimate the response of the soil–foundation–structure system. A defensible engineering assessment integrates these sources rather than assuming that a global Earth model can directly predict the behaviour of a particular foundation.

V. LIMITATIONS AND CHALLENGES

Seismic interpretation is an inverse problem: scientists observe waveforms and attempt to infer the structure and material properties that produced them. Different combinations of velocity, density, anisotropy, attenuation and boundary geometry may explain similar observations. As a result, seismic models are not always unique. The degree of resolution depends on the number and distribution of earthquakes and stations, the range of frequencies recorded, the signal-to-noise ratio, the quality of phase identification and the paths sampled by the waves. Regions with sparse station coverage may remain poorly resolved even when the global dataset is large [5]–[7].

Simplified one-dimensional reference models such as PREM are valuable for describing average radial structure, but they cannot represent every lateral variation in the mantle, crust or core. Three-dimensional tomography improves spatial representation, yet it is affected by smoothing, parameterization, regularization and trade-offs among model parameters. A low-velocity anomaly, for example, may reflect temperature, composition, partial melt, fluids or combinations of these factors. The resulting image should therefore be interpreted with independent geological and mineral-physics constraints [4]–[7].

The distinction between seismic discontinuities and engineering boundaries must also be maintained. A global discontinuity such as the core–mantle boundary is crucial for understanding the Earth but has little direct influence on the selection of a shallow foundation at a particular site. Conversely, a thin weak soil layer or shallow groundwater table may strongly affect a foundation even though it is not a globally significant seismic discontinuity. The engineering scale of interest determines which parts of the subsurface model need to be measured and represented.

Near-surface site-response models have their own limitations. One-dimensional equivalent-linear methods assume simplified layering and wave incidence; they may be inadequate where strong lateral changes, basin edges, topography, near-fault effects or large nonlinear strains are important. A single Vs30 value can conceal deep basin geometry and local weak layers. Liquefaction predictions are also sensitive to uncertainty in groundwater level, soil stratigraphy, in-situ test interpretation and earthquake loading. The cited USGS liquefaction-susceptibility layer is specific to the San Francisco Bay region and is intended as an educational resource; it illustrates regional screening but cannot establish susceptibility at an Indian project site [13]. These limitations support the use of multiple data sources and sensitivity analyses for critical projects [10], [11], [13].

These limitations also affect how seismic information is transferred into engineering analysis. A global reference model summarizes broad average Earth properties; it is not a substitute for a local ground model beneath a proposed structure. Engineering investigations should resolve the soil and rock layers that influence a foundation, slope or buried facility, using geophysical profiles checked against boreholes and in-situ tests. Where layer depths or wave velocities are uncertain, alternative ground profiles and sensitivity checks can show how that uncertainty affects predicted response. The investigation should be matched to the project scale and the consequences of failure [9], [10], [13], [14].

Numerical values quoted for internal boundaries and layer thicknesses should be treated as approximate reference values rather than universal constants. Crustal thickness varies with tectonic setting, and the depths and seismic expressions of mantle transitions vary with regional temperature, composition and other physical conditions. The depths in Table I summarize a reference radial model such as PREM and do not constitute a detailed model for every location [4], [6]. Engineering parameters must likewise be selected using the applicable standard and project-specific site investigation.

VI. CONCLUSION

Seismic observations provide the principal evidence for the layered structure of the Earth. The different propagation properties of P and S waves, travel-time variations, reflections, refractions, shadow zones, normal modes and tomographic images reveal the

crust, mantle, liquid outer core and solid inner core, together with major internal discontinuities. Reference models such as PREM summarize average radial properties, while modern tomography identifies three-dimensional variations and highlights the continuing need to quantify uncertainty.

For earthquake and geotechnical engineering, the practical importance of this knowledge is found in the way seismic energy travels through regional geology and interacts with local soil and rock profiles. Site response, basin effects, ground-motion characteristics and seismic hazard estimates influence engineering decisions, while liquefaction and soil–structure interaction require detailed knowledge of near-surface conditions. Deep Earth structure provides the physical framework, but reliable site-specific design depends on measured ground conditions, appropriate analysis methods and current engineering standards. Integrating seismological evidence with geotechnical investigation therefore supports more informed assessment of earthquake effects and more resilient infrastructure.

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