

**EVALUATION OF SEISMIC STATIONS PERFORMANCE AND BACKGROUND
NOISE LEVELS IN NORTHERN PAKISTAN USING POWER SPECTRAL DENSITY
ANALYSIS.**



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A thesis submitted in fulfilment of the requirements for the award of the degree of Masters
of science in Geophysics

Department of Earth and Environmental Sciences

BAHRIA UNIVERSITY, ISLAMABAD

AUGUST, 2026

Bahria University

Department of Earth & Environmental Sciences
Islamabad Campus, Islamabad

Date: August 25, 2026

Certificate

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ACKNOWLEDGEMENTS

It is my great honor to thank my supervisor, Dr. Muhammad Fahad Mehmood, who has provided me with constant guidance, support, and valuable feedback throughout the thesis development. Their skills and support contributed greatly to the success of the computation of this research work.

I also owe a debt of gratitude to the members of the faculty of the Department of Earth and Environmental Sciences, who provided the necessary academic environment and resources needed in this study. Their contribution and technical assistance proved to be of great help in improving the quality of this research.

I also want to take my colleagues and friends who helped me with this research by giving me knowledge, Ideas and constructive discussions. Their assistance and enthusiasm were priceless.

I owe much to my family in terms of encouragement, patience, and undying support they provide be during my academic life. This could not have been achieved without their assistance. Lastly, I would like to recognize all those people and organizations that

directly or indirectly helped to get this thesis completed.

ABSTRACT

Anything built from a seismic recording inherits the imperfections of that recording, whether it is a routine earthquake location or a probabilistic hazard assessment. This study assesses the recording performance of four broadband stations of the Pakistani seismic network, at Islamabad, Jhelum, Lahore and Peshawar, using a common set of eight regional earthquakes recorded during 2017 with magnitudes of 4.0 to 5.2 and epicentral distances of 115 to 1314 km.

P-wave arrival times were picked by hand and compared with times predicted from a standard velocity model, which gives one residual per event-station pair. Those residuals were then summarised at each station across the eight events. The four stations do not perform alike. Islamabad has the smallest residuals, a mean of 13.79 s and a root-mean-square of 17.22 s, and it records the lowest value for five of the eight events. Peshawar has the largest, 27.53 s and 29.67 s, and the highest value for six of the eight. Its mean and median sit close together, so its residuals are uniformly large rather than distorted by a few outliers. Jhelum and Lahore fall between the two at 20.79 s and 21.04 s, close enough to be indistinguishable on a sample this size, though they arrive there by different routes: Lahore's figure rests on a single extreme value, while Jhelum's builds up evenly.

Correlation with epicentral distance separates the stations more sharply than the residual sizes do. Islamabad shows no dependence ($r = +0.13$, $p = 0.75$). Lahore and Jhelum both give strong Pearson correlations, $r = +0.81$ and $r = +0.77$, but both weaken substantially under rank correlation, which means a handful of distant events is driving them. Peshawar's correlation is moderate ($r = +0.68$), and here the Pearson and Spearman values agree. The increase with distance at Peshawar is therefore real, and it sits on top of an offset that is already present at the shortest distance.

Power spectral density analysis, referenced to the Peterson (1993) noise models, places all four stations between the low- and high-noise bounds, and nearer the high-noise bound at short and intermediate periods. Twenty-eight of the thirty-two records reach maximum power between 0.93 and 1.98 s. That the same band recurs across a tenfold range of epicentral distance points to shallow structure beneath each site rather than to the source or the propagation path.

The clearest result comes from setting the two analyses side by side. Peshawar records the strongest and most reproducible spectra of the four stations and still carries the

largest residuals; Islamabad shows the reverse. Signal strength therefore does not account for timing performance. That points towards station timing, metadata or picking practice rather than towards siting or instrumentation. The study closes with station-specific recommendations, and the same approach can be applied to further stations using records the network already produces.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Pakistan lies on the convergence zone between the Indian and Eurasian plates, and much of the country is seismically active as a result. Frequent shallow and intermediate-depth earthquakes occur across the northern and western regions, including the Hindu Kush, the Himalayan foothills and the Sulaiman-Kirthar fold belts. Several have caused heavy loss of life and damage to infrastructure (Ambraseys & Bilham, 2003; Bilham, 2004; Seeber et al., 1981). The Kashmir earthquake of 8 October 2005 (Mw 7.6) ruptured a segment of the Himalayan thrust system and remains the most destructive event in the country's instrumental record. It also showed what inadequate hazard preparedness costs in a densely populated mountain region (Bilham, 2006). Later activity at Mirpur, Awaran and Harnai has kept the same problem in view, as have the intermediate-depth Hindu Kush earthquakes felt regularly across the north.

A seismic network is a distributed set of sensors, usually broadband seismometers, recording ground motion continuously at fixed locations. Everything the network produces downstream is built on those waveforms: routine earthquake catalogues, probabilistic hazard models. Performance depends on how many stations there are and where they sit. It depends just as much on how faithfully each one records. High ambient noise, timing inconsistencies, data gaps and poor site conditions all degrade earthquake location and parameter estimation, and they do it invisibly. The finished catalogue gives no sign of the problem (McNamara et al., 2009; Qaisar et al., 2003). Station-level data quality assessment has become a standard part of modern network operation for that reason.

This thesis evaluates the performance and data quality of four broadband seismic stations in northern Pakistan: Islamabad, Lahore, Peshawar and Jhelum. It draws on earthquake waveform data from eight events recorded in 2017, together with frequency-domain analysis of the recorded ground motion and background noise. All four stations stand in the densely populated Punjab and Khyber Pakhtunkhwa regions. Each is exposed to distant intermediate-depth seismicity from the Hindu Kush and to local shallow crustal earthquakes from the Potwar Plateau, the Salt Range and the surrounding fold-and-thrust belts. How faithfully these stations record earthquake signals feeds straight into the robustness of seismic hazard assessment in Pakistan.

1.2 Seismic waveform quality and station performance

Station performance is not a single quantity. It is a set of related properties, all measurable from the same recordings, and all the argument of this thesis follows the chain that connects them.

The starting point is the recorded waveform. A broadband seismometer converts ground velocity into a digital time series through a known transfer function. Three things decide whether that time series is useful, whether the signal of interest rises clearly above the background, whether the timing is accurate, and whether the record runs continuously and free of artefacts (Havskov & Ottemöller, 2010). From the waveform the analyst identifies the arrival of the compressional (P) phase. Nearly all quantitative earthquake seismology rests on accurate phase identification. Arrival times control hypocentre location, and an error introduced at the picking stage propagates into every parameter derived from it (Allen, 1978; Diehl et al., 2009).

Observed arrival times acquire physical meaning when they are compared with times predicted by a reference Earth model. Global travel-time models such as *iasp91* and *ak135* supply theoretical arrival times for a given source-receiver geometry and depth (Kennett & Engdahl, 1991; Kennett et al., 1995). The difference between the observed and the theoretical time is the travel-time residual. Residuals carry several effects at once: velocity structure along the ray path that the model does not represent, uncertainty in the hypocentre, imprecision in the pick, and station-specific problems such as clock drift, wrong station coordinates or elevation, and local structure beneath the sensor. That last category is what concerns this study. Combine residuals from many events at one station and the root-mean-square value summarises how well that station's observations agree with the reference model. A systematic departure from zero is conventionally read as a station term in network calibration (Havskov & Ottemöller, 2010). Since a single station's residuals reflect a mixture of causes, they need statistical treatment. Examining how residuals vary with epicentral distance, focal depth and magnitude helps separate path and model effects, which tend to grow with distance, from station effects, which tend to show up as a fixed offset.

Travel-time behaviour describes only the events a station recorded and the analyst picked. It says nothing about events the station failed to detect. Background seismic noise controls that capability. Ambient noise is the continuous ground motion present when no earthquake signal is recorded, and it depends strongly on frequency. Long-period noise comes mainly from atmospheric and instrumental effects. The microseism band between

roughly 1 and 20 s comes from ocean-wave interaction. Frequencies above about 1 Hz come from cultural sources such as traffic, industry and machinery (Bonnefoy-Claudet et al., 2006; Peterson, 1993). The standard tool for characterising this noise is the power spectral density (PSD), which describes how the power of the recorded ground motion is distributed across frequency. Comparing station PSDs against the New Low Noise Model (NLNM) and New High Noise Model (NHNM) of Peterson (1993) puts every station on a common global scale. It then becomes possible to state which sites are quiet, which are noisy, and in which frequency bands (McNamara & Buland, 2004).

Instrumentation alone does not set the spectrum recorded at a station. The near-surface geology beneath the sensor modifies incoming ground motion and concentrates energy at frequencies controlled by the impedance contrast between soft sediments and underlying bedrock. Two stations with identical instruments in identical vaults will not produce identical spectra if they stand on different material. The power spectral density is computed directly from the recorded ground motion, so it carries this influence within it. Where a station's spectra show persistent energy in the same narrow band across many unrelated earthquakes at widely differing distances, depths and azimuths, that band belongs to the site rather than to any individual source.

1.3 Study area

The study covers four broadband seismic stations in northern and central Pakistan, at Islamabad, Lahore, Peshawar and Jhelum. All four lie within the zone of active deformation produced by the convergence of the Indian and Eurasian plates. Each records shallow crustal earthquakes from nearby structures, including the Main Boundary Thrust, the Salt Range Thrust, the Jhelum Fault and the western fold belts. Each also records intermediate-depth earthquakes from the Hindu Kush zone several hundred kilometres to the north-west (Ambraseys & Bilham, 2003; Seeber et al., 1981; Yeats et al., 1984). That mixture of source distances and depths is analytically useful. Arrival-time discrepancies can be examined as a function of distance and depth instead of at a single geometry.

Site conditions were different across the four station. Islamabad and Jhelum sit at the margins of the Potwar Plateau, where Cenozoic sedimentary rock lies comparatively close to the surface. Peshawar sits within the sediment-filled Peshawar Basin, and Lahore is founded on the thick Quaternary alluvium of the Indus plain. The four sites should not be expected to record identically.

Routine earthquake monitoring in the region is carried out mainly by the National Seismic Monitoring Centre of the Pakistan Meteorological Department, supported by networks operated by other national institutions. Chapter 2 describes the regional tectonic framework, the seismicity and hazard of northern Pakistan, and the configuration of the monitoring network, with supporting figures. Chapter 3 gives station codes, geodetic coordinates, sensor and digitiser models, installation dates, sampling rates and the operating network for each station.

1.4 Research objectives

This study sets out to evaluate the recording performance and data quality of four broadband seismic stations in northern Pakistan through combined waveform, travel-time, statistical and spectral analysis.

The specific objectives are:

1. To compile a common catalogue of regional and local earthquakes recorded at the Islamabad, Lahore, Peshawar and Jhelum seismic stations, and to determine P-wave arrival times for each event at each station.
2. To derive, for each event–station pair, the absolute difference between the observed P-wave arrival and the arrival predicted by a reference 1D velocity model at the fixed catalogue hypocentre, and to summarise it at each station by the RMS across events as a comparative measure of timing and picking consistency.
3. To compare the residual performance of the four stations statistically, using mean, median, standard deviation and total residual, in order to rank their relative data quality.
4. To examine how residual magnitude relates to event characteristics, specifically epicentral distance, focal depth and magnitude, and so to establish whether errors are distance-dependent, consistent with velocity-model uncertainty, or systematic, consistent with station-specific timing or instrumentation issues.
5. To characterise the recorded ground-motion spectra and background noise at each station using power spectral density analysis referenced to the Peterson (1993) New Low Noise Model and New High Noise Model, and to relate the observed spectral behaviour to the timing performance assessed above.
6. To provide station-specific recommendations aimed at improving timing accuracy and overall data reliability within the network.

1.5 Research problem

Those objectives respond to a specific operational problem. Data from the Islamabad, Lahore, Peshawar and Jhelum stations are used routinely for earthquake location, catalogue compilation, source studies and hazard modelling. Every one of these applications treats the contributing stations, implicitly, as equally reliable. The assumption is rarely tested. Untested, it becomes impossible to say whether a location error, a magnitude discrepancy or a missed detection originates in the complexity of the source, in propagation-path effects between source and receiver, or in a problem at the recording station.

Distinguishing between the three matters because each calls for a different response. A path-related discrepancy is addressed by improving the velocity model. A station-related discrepancy is addressed by maintenance, recalibration or metadata correction. A site-related discrepancy cannot be removed at all and has to be accounted for in later analysis. Treat all three as one undifferentiated error and network operators are left with no basis for deciding where to direct limited resources.

The stations were added one at a time over several decades rather than deployed together as a uniformly specified system. Instrumentation, vault construction, siting and local ground conditions differ appreciably from one to the next, so variation in data quality is what should be expected here. The effect reaches past individual events. A persistent bias at one station carries into every catalogue entry that depends on that station, including the many low-magnitude events that together set regional seismicity statistics and, through those, probabilistic hazard estimates.

Separating those effects requires a station-level assessment that measures timing behaviour and spectral character at the same stations from a common dataset, so the observed differences can be attributed to their correct causes.

1.6 Research gap

Existing research covers parts of this assessment without bringing them together. At the network scale, Qaisar et al. (2003) analysed the detectability and reliability of the Pakistani local network and quantified location accuracy, and Khan et al. (2018) evaluated catalogue completeness nationally. Neither disaggregates performance to individual stations. Ali et al. (2004) measured ambient noise at Pakistani stations and converted it into detection thresholds, but with short-period instrumentation of an earlier generation. That study reported noise levels in a restricted frequency band rather than full power spectral density

curves referenced to the Peterson (1993) models, and it covered a different set of stations from those examined here.

Work from inside the study region shows the gap most directly. Mushtaq et al. (2019) calibrated a local magnitude scale for Northern Punjab using 2,800 records from 231 events across 21 stations. Their station correction factors ran from roughly -0.5 to $+0.5$, a spread they attributed to variation in station site effects. The variability is already on record for this region. Its causes at particular stations are not.

Near-surface site information exists for three of the four locations, though not in a form that answers the question here. Qadri, Sajjad, et al. (2015) surveyed ground conditions at 105 sites across Rawalpindi-Islamabad, Khan et al. (2022) at 159 sites in Lahore, and Khan et al. (2021) across Peshawar district. All three are city-scale microzonation surveys carried out with portable instruments, and none reports conditions at the permanent broadband station itself, which is the location that shapes what the instrument records. For Jhelum, this review found no comparable site or station-performance study

Internationally the integrated approach adopted here is well established, with spectral and noise analyses applied alongside timing assessment to evaluate station performance across national and regional networks (Maitreyi et al., 2024; Pandey et al., 2020; Uthaman et al., 2022). In Pakistan the individual components have been applied separately and never in combination. The gap addressed by this thesis is a specific one. No published study evaluates the recording performance and data quality of the Islamabad, Lahore, Peshawar and Jhelum broadband seismic stations using a common earthquake dataset and a common analytical framework combining phase-arrival analysis, travel-time residuals, statistical comparison and PSD-based spectral characterisation. The objectives in Section 1.4 are formulated to close that gap, and the supporting evidence is developed in full in Chapter 2.

1.7 Scope and limitations

The data available for analysis define the scope of this study: waveform records of eight earthquakes recorded during 2017 at four broadband stations, together with the event-window records used for spectral analysis. Several limitations follow, and they are stated here for transparency.

First, eight events are a small sample. The travel-time residual statistics reported in Chapter 4 are indicative rather than definitive, and the correlation analysis between residuals and event parameters has limited statistical power. With eight observations a correlation coefficient has to exceed roughly 0.71 to reach significance at the five per cent level. The

station-wise comparison is a first-order assessment based on a consistent dataset, not a long-term characterisation of each station.

Second, the analysis covers a single year. Ambient noise at seismic stations varies diurnally and seasonally. Cultural noise typically runs higher during daytime and working days, and microseism levels vary with season (Groos & Ritter, 2009; Uthaman et al., 2022). The spectral characteristics reported here reflect the specific intervals analysed and should not be taken as annual averages.

Third, PSD estimates are physically meaningful only when the instrument response has been correctly removed. The accuracy of the spectral levels reported here is conditional on the accuracy of the response metadata used, and Chapter 3 states the source and version of that metadata for each station.

Fourth, the power spectral density estimates were computed from event records, which contain both earthquake signal and background noise. They describe total recorded power not ambient noise in isolation. Separating the two would require spectra computed over pre-event quiet windows, which lies outside the scope of this analysis. The levels reported in Chapter 4 should be read with that qualification.

Fifth, the station coordinates used to calculate epicentral distance. And have to correspond to the actual sensor locations. Chapter 3 states the coordinates adopted, their source and the positional uncertainty attached to them, and acknowledges the effect on the distance-residual analysis where approximate reference coordinates were used.

With those limitations acknowledged, what follows is a reproducible, quantitative comparison built on a consistent dataset, and its conclusions come from that dataset.

1.8 Significance of the study

The value of this study lies less in the size of its dataset than in what a modest, readily obtainable set of earthquake records can reveal about differences in station performance within an operational network. It also lies in showing that those differences can be interpreted physically once timing and spectral information are combined.

Earthquake catalogues produced by national and regional networks feed into probabilistic seismic hazard assessment, building code development, insurance risk modelling and post-event response planning. Each of these applications assumes that the underlying arrival-time and amplitude data are of reasonably uniform and known quality across contributing stations. Leave the assumption untested and station-specific bias propagates silently into every catalogue entry that relies on the affected station. That includes

the many routine, low-magnitude events that determine regional seismicity statistics and b-value estimates.

For Pakistan, where seismic hazard is high and monitoring infrastructure grew incrementally, a station-level audit of this kind has practical value. It gives network operators a concrete basis for prioritising maintenance, recalibration or upgrade decisions. Rather than treating all stations as equally reliable by default, operators can use residual statistics to identify which stations most urgently need technical inspection. They can also tell problems that maintenance or metadata revision can correct from problems inherent to the site, which have to be accounted for in analysis instead.

There is a methodological point here too, and it matters for resource-constrained monitoring programmes. Combining travel-time residual analysis with power spectral density characterisation requires no additional field deployment and no instrumentation beyond what the stations already have. The workflow can be repeated periodically as a routine network health check, and extended to further stations as data become available.

1.9 Thesis outline

Chapter 2 reviews the literature relevant to this study, covering seismic station and network quality assessment, phase picking, travel-time residual analysis, and background seismic noise and its characterisation through power spectral density. It also covers previous seismological research in Pakistan and northern Pakistan, and develops in full the research gap outlined in Section 1.6. Chapter 3 describes the dataset and the methodology used, including data preparation, phase picking, travel-time computation, residual and statistical analysis, and PSD processing. Chapter 4 presents the results: station-wise summary statistics, correlation analysis against event parameters, the power spectral density characteristics of each station, and a combined comparison of the two. Chapter 5 discusses these results in relation to previous research and presents the conclusions, station-specific recommendations and directions for further work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Any seismological result is only as good as the data behind it. Earthquake locations, magnitudes, focal mechanisms and hazard estimates are all computed from waveforms recorded at individual stations, and each product inherits whatever imperfections those waveforms carry. A station recording with elevated background noise will miss small events. A station whose clock has drifted contributes biased arrival times to every location it takes part in. A station founded on soft sediment records ground motion whose frequency content reflects the site as much as the source.

This chapter sets out the basis for that examination. It begins with the region in which the four stations sit, since the tectonic setting determines what kinds of earthquakes they record and the configuration of the monitoring network sets how much weight each station carries in the network's output. It then covers the physical concepts the analysis rests on: how seismic waves are recorded, what phase arrivals represent, why observed and predicted arrival times differ, what counts as background seismic noise, and how the spectral content of a recording is characterised and referenced. It closes with a review of what previous researchers have established about assessing station performance, internationally and within Pakistan, and with what remains unresolved.

Interpretation of the later results depends on the study area, which is why it comes first. An arrival-time discrepancy that grows with epicentral distance means one thing in a region with strong lateral velocity variation and something quite different in a uniform crust, and an elevated noise level reads differently at a station on thick alluvium than at a bedrock site. The conceptual material follows because the literature cannot be evaluated without it, and previous work comes last: judging what has and has not been done is only meaningful once the reader knows what the study area demands and what the available measurements can deliver.

Two things fall outside this chapter. It does not describe the procedures used in the study, since datasets, processing steps, parameter choices and software belong to Chapter 3, and the concepts introduced here are background rather than method. It also presents no results. Where previous studies have reported values for the region, those values are attributed to their sources and should not be read as findings of this thesis, which appear in Chapter 4.

Background noise, phase-arrival quality, timing accuracy and site conditions are not independent properties of a station. Noise degrades onset clarity, which degrades pick precision, which inflates arrival-time discrepancies. The material beneath the sensor meanwhile influences both the noise level and the frequency content of the recorded waveform. The review below keeps those interdependencies in view, and they are the reason the four stations are assessed through several complementary measurements rather than one.

2.2 Regional tectonic setting

The four stations examined in this thesis, at Islamabad, Lahore, Peshawar and Jhelum, lie in a tectonically active region shaped by the convergence of the Indian and Eurasian plates. Collision between the two began in the early Cenozoic and continues at a rate of several centimetres per year, with a substantial fraction of that motion absorbed across the Himalayan mountain front and its foreland (Bilham, 2004; Kearey et al., 2009).

Several major structural features accommodate regional deformation: the Himalayan thrust system, the Hazara-Kashmir Syntaxis, the Potwar Plateau fold-and-thrust belt and the Chaman transform fault system. The Himalayan thrust belt dominates. It comprises a stack of south-verging thrust sheets that includes the Main Boundary Thrust and, further south, the Himalayan Frontal Thrust. To the east, the Hazara-Kashmir Syntaxis is a sharp bend in the structural trend where the thrust front wraps around a promontory of the underthrusting Indian plate. South of the mountain front lies the Potwar Plateau, a broad fold-and-thrust belt detached from its basement along a décollement within Eocene salt. It terminates southward at the Salt Range Thrust and is bounded to the east by the Jhelum Fault (Yeats et al., 1984). To the west, the Chaman transform system accommodates left-lateral motion along the Afghanistan border, and the Sulaiman and Kirthar fold belts absorb shortening in a series of arcuate structures.

The Hindu Kush region to the north-west is a major source of intermediate-depth seismicity. Events there typically nucleate between about 70 and 300 km depth, in a steeply dipping zone of subducted or delaminated lithosphere (Ambraseys & Bilham, 2003; Seeber et al., 1981). Earthquakes from this zone are felt across northern Pakistan and, despite the large epicentral distances, are recorded frequently at all four stations.

Local and regional shallow seismicity is associated with active structures such as the Potwar Plateau, the Salt Range Thrust and the western fold belts. Geodetic and seismological work confirms that these structures are actively deforming, with stick-slip motion documented on the adjoining Kohat Plateau (Satyabala et al., 2012). The stations analysed

here consequently record a combination of shallow crustal and intermediate-depth events. The selected earthquake dataset includes local Pakistan events with shallow focal depths in the range 10 to 54 km and deeper Hindu Kush events at 175 to 198 km. For a study concerned with station performance that range is an advantage. Arrival-time discrepancies can be examined as a function of distance and depth, and that is how propagation effects can be separated from station effects.

The velocity structure of the region departs appreciably from global average models. Monsalve et al. (2006) analysed seismicity and one-dimensional velocity structure across the Himalayan collision zone and documented crustal thickness and velocity variations that differ from standard reference models. That bears directly on the present work. Differences between observed and theoretically predicted arrival times will contain a contribution from the reference model itself, and that contribution has to be distinguished from station-specific effects.

The instrumental and historical record confirms the level of hazard the tectonic setting implies. The Kashmir earthquake of 8 October 2005 (Mw 7.6) ruptured a segment of the Himalayan thrust system and caused catastrophic destruction across Azad Jammu and Kashmir and Khyber Pakhtunkhwa (Bilham, 2006). Earlier and later events in Quetta, Mirpur, Awaran and Harnai, together with continuing Hindu Kush activity, show that damaging earthquakes occur across a wide area of the country and at a range of depths. Systematic characterisation of this seismicity has advanced considerably. Khan et al. (2018) compiled an updated earthquake catalogue for Pakistan and neighbouring regions containing 36,563 events spanning 25 AD to 2016, unified to moment magnitude through empirical conversion relationships and processed for declustering and magnitude of completeness using four independent algorithms. Probabilistic hazard assessments built on such catalogues, including that of MonaLisa et al. (2007) for the north-west Himalayan fold-and-thrust belt, consistently place the highest expected ground motions in the north and north-west.

Figure 2.1 shows the spatial distribution of peak ground acceleration across northern Pakistan for a 10 per cent probability of exceedance in 475 years. The highest hazard values sit in the northern and north-western regions, around the Hazara-Kashmir Syntaxis and the Muzaffarabad area, where active tectonic deformation is associated with the Himalayan collision zone and the Hindu Kush seismic zone. A secondary zone of elevated hazard extends south-west across the Salt Range towards Mianwali. Peshawar, Islamabad and

Jhelum all fall within areas of low to moderate mapped hazard, but each sits close enough to major tectonic structures to record both local and regional earthquakes.

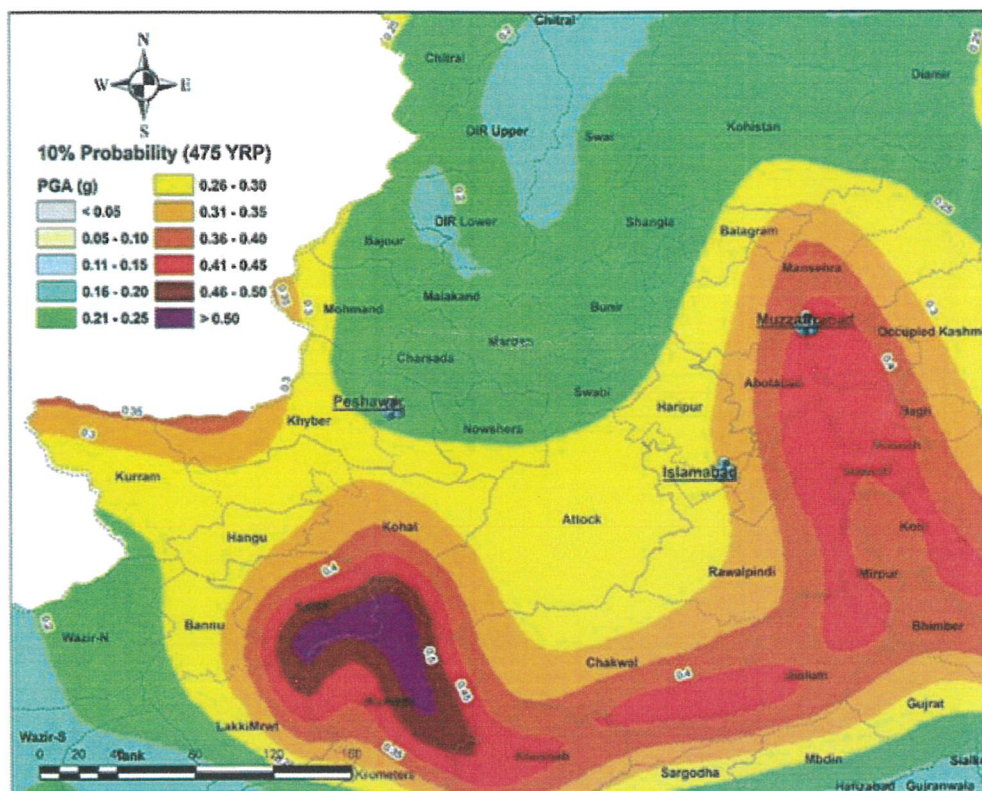


Figure 2. 1 Probabilistic seismic hazard map of northern Pakistan showing peak ground acceleration (PGA, g) for a 10 per cent probability of exceedance in 475 years.

2.3 Seismic monitoring in northern Pakistan

Routine earthquake monitoring in the region is carried out mainly by the National Seismic Monitoring Centre of the Pakistan Meteorological Department, which operates a national network of broadband and short-period stations together with the National Tsunami Warning Centre. Other national institutions run additional networks, among them the Micro Seismic Studies Programme and the Centre for Earthquake Studies, whose data have supported detectability analysis and regional magnitude calibration respectively (Ali et al., 2004; Mushtaq et al., 2019; Qaisar et al., 2003).

Figure 2.2 shows the distribution of broadband stations across the country. Coverage of the northern and central regions is reasonable, with a concentration of stations along the Himalayan front and through the Potwar Plateau, and sparser coverage across Balochistan and the southern Indus plain. Station spacing of this order constrains the minimum magnitude that can be located reliably and the accuracy achievable in hypocentral depth. It also places

a premium on the quality of the stations that do exist. In a sparse network each contributing station carries proportionally more weight in the location solution, so a single biased station has correspondingly more influence on the result.

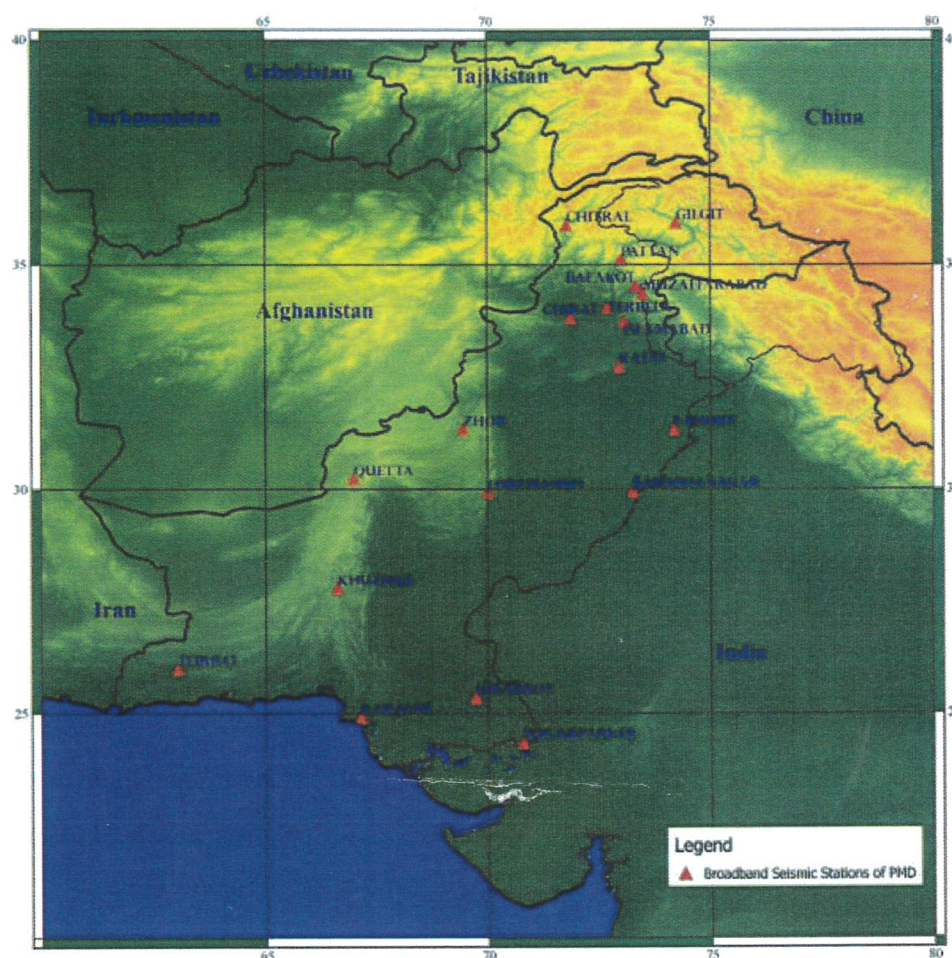


Figure 2. 2 Distribution of broadband seismic stations operated by the Pakistan Meteorological Department.

The four stations analysed in this thesis sit within that network at Islamabad, Jhelum, Lahore and Peshawar, and Figures 2.3 to 2.6 summarise their tectonic and geological settings. Islamabad and Jhelum lie at the margins of the Potwar Plateau, where Cenozoic sedimentary rock is comparatively close to the surface. Peshawar lies within the sediment-filled Peshawar Basin, bounded to the north by the Main Boundary Thrust, and Lahore is founded on the thick Quaternary alluvium of the north-eastern Indus plain. Near-surface geology shapes both the noise floor and the frequency content of what a station records, so these four sites cover a useful range for comparison.

The network developed incrementally over several decades rather than being deployed as a single uniformly specified system, and that history matters here. Stations differ in sensor and digitiser generation, in vault construction and sensor emplacement, and in how much urban development has grown up around them since installation. They also differ in the geology they are founded on, which for these four locations ranges from the margin of the Potwar Plateau to the alluvial plain of the Indus. Uniform data quality across the network is therefore not a safe assumption, and this heterogeneity is one of the main practical motivations for the station-level assessment undertaken in this thesis.

2.4 Seismic wave recording and arrival-time residuals

An earthquake radiates elastic energy that travels through the Earth as body waves and surface waves. The compressional (P) wave travels fastest, and arrives first at any recording site. The shear (S) wave follows, at roughly 0.58 times the P velocity in typical crustal material. Surface waves, which propagate along the free surface, arrive later and generally carry the largest amplitudes at regional distances. The order and separation of these arrivals encode the distance travelled, and that is the basis on which earthquakes are located. A broadband seismometer records this motion by converting ground velocity into a continuous voltage, which is then digitised and time-stamped. Because the instrument's response is frequency dependent and described by a transfer function, the recorded digital counts relate to true ground motion only after that response has been accounted for. Modern broadband sensors record faithfully from periods of tens or hundreds of seconds to frequencies of tens of hertz, so distant large earthquakes and small local events can be captured by the same instrument (Havskov & Ottemöller, 2010). That breadth costs sensitivity to disturbance. At long periods these instruments are affected by temperature variation, barometric pressure change and tilt, and are ultimately limited by their own self-noise (Ringler et al., 2020). At short periods they faithfully record whatever local vibration reaches them, including vibration of human origin.

Identifying the moment a particular phase arrives converts a continuous waveform into a quantitative observation. Arrival times control hypocentre location, and the precision with which they can be determined limits the precision of everything derived from them: depth, magnitude and any subsequent source analysis. Onset identification has been approached both manually and automatically. Allen (1978) introduced the characteristic-function approach that underlies most automatic schemes, using a running measure of amplitude and frequency content to detect the onset in a single trace. Baer and Kradolfer

(1987) developed this into a phase picker applicable to both local and teleseismic events. Withers et al. (1998) compared the principal trigger algorithms then in use and showed that their relative performance depends strongly on the signal-to-noise conditions at the recording station, a result that ties picking accuracy directly to the noise environment discussed below. The S onset is harder to identify than the P onset. It arrives within the P coda and is frequently obscured by scattered energy and converted phases.

Diehl et al. (2009) addressed that problem directly and provided a quantitative treatment of pick uncertainty in place of a single arrival time, and it is why the present study is confined to P arrivals. More recently, machine-learning approaches have improved consistency for low signal-to-noise recordings, with Zhu and Beroza (2019) treating onset identification as a sequence-labelling problem and Mousavi et al. (2020) performing detection and picking simultaneously. These methods reduce the variability associated with manual analysis, but need training data appropriate to the region and instrumentation concerned. For small carefully inspected datasets, manual picking remains standard and defensible practice provided the procedure and its uncertainties are documented.

The iasp91 model of Kennett and Engdahl (1991) was built specifically to provide arrival times for global earthquake location, and phase identification, and the later ak135 model of Kennett et al. (1995) refined the velocity structure using a large set of reprocessed observations. Both remain in routine use. The difference between an observed and a predicted arrival time is conventionally termed the arrival-time residual. Its value reflects several contributions at once: velocity structure along the ray path that the reference model does not represent, uncertainty in the assumed hypocentre and origin time, imprecision in identifying the onset, and any station-specific error such as clock drift, incorrect station coordinates or elevation, or unmodelled structure directly beneath the sensor. Network uses residuals in two ways. Within a single location procedure, their root-mean-square across contributing stations is the goodness-of-fit measure for the hypocentre solution. Across many events, the systematic component of the residual population at an individual station is read as a station term or station correction, which absorbs the persistent part of that station's departure from the reference model (Havskov & Ottemöller, 2010). Estimate and apply station terms and location accuracy improves. Ignore them and they bias hypocentres systematically.

The global models named above were built as spherically symmetric averages for routine teleseismic location, and northern Pakistan departs from that average in ways that appear in every predicted arrival time. Receiver-function analysis of local broadband data

places the Moho beneath the Potwar stations at roughly 50 km rather than the ~35 km of a global continental reference (Soomro & Hara, 2009), and the stations examined here sit above thick low-velocity cover — Potwar molasse over a Precambrian evaporite décollement at Islamabad and Jhelum, basin fill at Peshawar, Indus alluvium at Lahore — that no global model contains. Regional alternatives now exist. Soomro et al. (2022) derived a P-wave minimum 1D model for central and northern Pakistan by coupled hypocentre–velocity inversion in VELEST, using 378 local events recorded at 25 Centre for Earthquake Studies stations between 2001 and 2020; the model has eight layers to 80 km, P velocity rising from 5.4 to 8.4 km/s, a Moho near 50 km, and station delays spanning -1.3 s to $+0.8$ s that the authors attribute to structure immediately beneath each site. Adopting it improved location RMS and, particularly, depth. Khalid et al. (2020) likewise tested seven candidate models before relocating 185 northwest Himalayan events, which is itself evidence that no single reference model is settled for this region, while Ni et al. (1991) showed the structure beneath the adjacent Hazara Arc to be strongly three-dimensional. The methodological literature is explicit that a locally derived minimum 1D model is the appropriate reference both for location and for data-quality assessment (Husen et al., 2011; Kissling et al., 1994). The consequence for this study is that a global model applied at regional distances in a region with a 50 km Moho will mispredict arrival times systematically, in the same direction at every station, and by an amount that grows with path length — which is the expected behaviour, not an anomaly, and is why the differences reported in Chapter 4 are large, uniformly positive, and used comparatively between stations rather than as absolute measures of station accuracy.

Two properties of a residual population deserve emphasis, and both bear on how the results of this study should be read. The first is sign. Residuals computed against a fitted origin time scatter about zero, with roughly half early and half late. A population that is uniformly of one sign indicates either that absolute values have been taken or that a systematic offset, most commonly in the origin time, remains in the calculation. The second is magnitude. For a well-located regional event, residuals are normally well under two seconds. A value amounting to an appreciable fraction of the whole predicted travel time cannot be a residual in the conventional sense. Any study reporting residuals should therefore state explicitly what quantity was computed, and whether the origin time was fitted or adopted from the catalogue.

Interpretation needs care for a second reason: a large residual is not by itself evidence of a fault at the station. It may equally reflect unmodelled path structure, which becomes

more likely for distant events and in a region such as northern Pakistan where the velocity structure departs from global averages (Monsalve et al., 2006). The behaviour of a residual is more diagnostic than its size. Residuals that grow systematically with epicentral distance are consistent with velocity-model error accumulating along longer ray paths. A persistent offset that holds independent of distance, depth and azimuth points instead to a station-specific cause. To separate those two patterns, this study examines residuals against event parameters rather than reporting them as a single summary value.

2.5 Background seismic noise and reference noise models

Even with no earthquakes the ground is never still. Ambient seismic noise is the continuous ground motion recorded between identifiable events, and it is conventionally divided by source and frequency band. (Bonnefoy-Claudet et al., 2006; Peterson, 1993). At the longest periods, beyond roughly 20s, noise is dominated by atmospheric pressure fluctuations, temperature-driven instrumental effects and tilt of the sensor. Between approximately 1 and 20 s lies the microseism band, generated by ocean-wave energy. A primary microseism peak occurs near the dominant ocean-wave period, and a stronger secondary peak at approximately half that period comes from the interaction of opposing wave trains. Above about 1 Hz, cultural or anthropogenic noise dominates at most continental sites, generated by road and rail traffic, industrial machinery, construction and pedestrian activity.

The division matters for station assessment because the bands respond to different controls. Microseism levels are regionally coherent and vary seasonally with ocean storm activity, so they differ little between stations within a single region and are of limited value for comparing sites. Cultural noise is highly local, attenuates rapidly with distance from its sources, and varies systematically with time of day and day of week. Differences between stations within a network say most about siting quality in that band (Díaz et al., 2017; Groos & Ritter, 2009). Long-period noise says most about installation quality, including vault design, thermal stability and how the sensor is emplaced (Uthaman et al., 2022). The most direct demonstration of how large cultural noise can be came from the COVID-19 lockdowns, when Lecocq et al. (2020) documented reductions in high-frequency seismic noise of up to 50 per cent across a global set of stations, with the effect strongest at surface instruments in populated areas.

Comparing noise levels between stations requires a common reference. Peterson (1993) computed noise spectra for a globally distributed set of stations and defined the New

Low Noise Model and New High Noise Model as the lower and upper envelopes of observed continental noise. Those curves remain the standard against which station noise is judged. A station whose spectrum lies close to the NLNM across a broad band is exceptionally quiet, while excursions towards or above the NHNM identify bands in which a station is unusually noisy. Because the models are defined globally, stations in different networks and countries can be compared directly, which makes them appropriate for placing Pakistani stations in an international context. The practical significance of elevated noise is that it raises the amplitude threshold at which a signal can be distinguished from the background, and so raises the minimum magnitude detectable at a given distance. Ali et al. (2004) made this connection explicitly for Pakistani stations, converting measured noise levels into detection thresholds under an assumed signal-to-noise criterion.

One convention associated with these models affects how spectra are read and should be noted. Conventional seismic PSD values are negative, when expressed in decibels relative to acceleration power, so a more negative number corresponds to less power. Where a display inverts the sign to present positive values, the scale runs in the opposite direction to intuition and the low-noise model appears above the high-noise model instead of below it. Any spectral figure should state its sign convention explicitly, and the conventional signed scale is preferable for reporting.

2.6 Site conditions, instrument response and data integrity

Ground motion arriving at a station is further modified, by the material it passes through on its final approach to the surface. Where a layer of soft sediment overlies stiffer bedrock, the impedance contrast between them traps and amplifies energy at frequencies determined by the thickness and shear-wave velocity of the layer. The frequency at which amplification is greatest is the fundamental or resonance frequency of the site, and it is inversely proportional to sediment thickness. There is a direct consequence for spectral analysis. A station founded on thick, low-velocity sediment concentrates energy in a lower and narrower band than a station on competent rock, and the concentration appears in the power spectral density of every record the station produces, wherever the earthquake occurred.

Source and site contributions can therefore be separated by inspecting how a spectral feature behaves across events. A feature that recurs at the same frequency across earthquakes at widely different distances, depths and azimuths cannot originate in the source or the path, since those differ from event to event. It is attributable to the site. A feature that shifts with

epicentral distance, or appears in one record and not another, points to a source or propagation origin. This recurrence criterion is the basis on which the spectral results of Chapter 4 are interpreted.

One qualification on the use of power spectral density belongs here. PSD measures the absolute power of ground motion as a function of frequency, so it answers the question of how much energy is present at a site and in which bands. It does not by itself separate the contribution of the source from that of the site, because both are present in any earthquake record. Where spectra are computed from event windows instead of quiet intervals, as they are here, the resulting levels describe total recorded power rather than ambient noise alone. Chapter 4 maintains that throughout.

Two further considerations condition the reliability of any station assessment. The first is instrument response. Spectral estimates of ground motion are physically meaningful only if the transfer function relating digital counts to ground motion has been correctly removed. Response information varies with frequency and is specific to each sensor and digitiser combination and configuration epoch. Errors in this metadata, whether an incorrect sensitivity, a missing pole or zero, or a response valid for a different period than the data, translate directly into errors in the reported spectral level. They can produce spectra that appear anomalously high or low with no corresponding change in site conditions (McNamara & Buland, 2004). This applies with particular force at the ends of the recorded band. A consistent roll-off at long period across several stations is more likely to reflect the instruments than the ground, and any anomaly in a computed spectrum should be checked against the response before it is interpreted as a site or installation effect. Arrival-time analysis is comparatively insensitive to response errors, since it depends on onset timing rather than amplitude calibration, but it is highly sensitive to timing integrity. Loss of satellite time synchronisation, clock drift between synchronisations, and incorrect application of time corrections all produce apparent residuals that reflect the recording system rather than the Earth. A systematic residual offset should not be attributed to local velocity structure until timing records have been examined.

The second consideration is data completeness: the proportion of expected samples actually recorded, free of gaps, clipping and timing discontinuities, conventionally reported as a percentage together with a log of interruptions and their causes. Completeness governs detection reliability. An event that occurred during a data gap is indistinguishable, in the resulting catalogue, from an event too small to detect.

2.7 Literature review

Assessment of seismic station performance has developed into a mature subfield with an established methodology. It rests on the observation that the statistical distribution of spectral power at a station, computed over long periods, is a stable signature against which that station's behaviour can be monitored. McNamara and Buland (2004) introduced the methodological advance most subsequent work depends on. Instead of computing a single averaged spectrum, they computed spectra for a large number of overlapping time segments, and displayed the results as a probability density function of power at each frequency. The approach has three practical advantages. It removes the need to exclude earthquakes, glitches and transients manually from the input data, since these appear as low-probability outliers instead of contaminating an average. It reveals the full distribution of conditions at a station, distinguishing typical from quietest conditions. And it makes diurnal and seasonal structure visible. McNamara and Boaz (2006) documented the software implementation, and McNamara et al. (2009) showed that the resulting distributions can serve as automated baselines against which deviations are detected without manual inspection, whether from instrument failure, changing site conditions or new noise sources. The approach is now standard open-source seismological software (Beyreuther et al., 2010).

Work at the instrumental end has continued in parallel. Ringler et al. (2020) examined resolution and current limitations across the Global Seismographic Network and showed that at periods beyond 100 s station noise is frequently limited by sensor self-noise and by sensitivity to non-seismic sources rather than by the site. Not every elevated noise level reflects a siting problem. Studies of urban stations form a distinct strand. Groos and Ritter (2009) classified and quantified the contributions of individual anthropogenic sources to the noise field of a city in the time domain, and Díaz et al. (2017) showed that the urban noise field carries a clear signature of daily and weekly human activity cycles. Together with the global lockdown observations of Lecocq et al. (2020), this body of work establishes that cultural noise is both large and structured, and therefore open to detailed characterisation.

A series of studies from South Asia provides close methodological analogues for the present work, and their findings establish what may reasonably be expected from a network assessment in a comparable setting. Jana et al. (2017) assessed newly deployed broadband stations in the Eastern Ghats Mobile Belt, India, computing spectra for each site and comparing them against the global noise models. Noise levels at most stations fell within the Peterson bounds, one of the two profiles studied was dominated by cultural noise, and

microseism levels were low across both, which shows the method discriminates between sites within a single deployment. Uthaman et al. (2022) extended the approach to 27 stations across the Sikkim Himalaya and the adjoining foreland basin. Their results are particularly instructive because they isolated the effect of installation practice: sensors buried directly in the ground showed reduced long-period noise compared with those installed on piers, while horizontal components at some sites exceeded the noise model bounds owing to tilt. They also documented systematic diurnal variation, with daytime cultural noise exceeding night-time levels, and seasonal variation in the microseism band associated with the monsoon. The anthropogenic origin of the diurnal signal was confirmed through the reduction in short-period noise at foreland-basin stations during the COVID-19 lockdown. Maitreyi et al. (2024) evaluated a 16-station network in northern Chhattisgarh over 13 months, again finding noise levels within global limits, and documented both the effect of instrumental tilt on horizontal components and the influence of nearby mining blasts on the very short-period band. Jha et al. (2023) reported comparable analyses for stations along the Western Ghats.

The study closest in conception to the present one is that of Pandey et al. (2020), who evaluated background noise across the Indian national seismological network before and during the COVID-19 lockdown using spectral density, Fourier spectra and spectrograms. Noise in the long-period and microseism bands stayed within the global noise models throughout, while short-period noise ran 10 to 12 dB higher before the lockdown than during it. The reduction in cultural noise measurably improved the ability of noisy stations to record phases from micro and small earthquakes. Three conclusions from this regional literature bear directly on the present work. Inter-station differences within a single network are consistently substantial and explicable in terms of siting, installation and local environment. Spectral analysis is treated in all of these studies as a means of validating installation quality and prioritising maintenance rather than as an end in itself. And the spectral signature of a station is stable enough that departures from it can be treated as diagnostic.

Research relevant to station performance in Pakistan falls into three groups, each addressing part of the problem. The first concerns network detectability and catalogue quality. Qaisar et al. (2003) analysed the detectability and reliability of the local seismic network in Pakistan using twenty-five years of recorded data. They derived 50, 90 and 100 per cent cumulative detectability thresholds from the frequency-magnitude distribution and established 100 per cent detectability at ML 1.7 for events occurring within the network, with epicentral errors below 4 km under those conditions. They also discussed the operational difficulties affecting continuous network operation. At the catalogue level, Khan et al. (2018)

compiled and processed the updated national earthquake catalogue described in Section 2.2. Both studies assess performance at the level of the network. Neither disaggregates it to individual stations.

The second group concerns ambient noise and its effect on detection. Ali et al. (2004) measured seismic noise at stations of the Micro Seismic Studies Programme network, comparing day with night and summer with winter conditions. They reported noise levels between approximately -120 and -157 dB in the 1 to 10 Hz band and converted these into detection capability estimates of ML 3.1 to 3.8 at 1000 km under an assumed signal-to-noise ratio of three.

The third group concerns regional calibration and station corrections. Mushtaq et al. (2019) developed a local magnitude scale for Northern Punjab, the Potwar Plateau and Salt Range region, which contains three of the four stations studied here. Using data from the Centre for Earthquake Studies network, they inverted synthetic Wood-Anderson amplitudes from 2,800 records of 231 events on 21 stations for distance and station corrections. The resulting station correction factors ranged from approximately -0.5 to $+0.5$, which they attributed explicitly to variation in station site effects. Their analysis addressed amplitude rather than timing, but it establishes for this specific region that inter-station variability large enough to bias derived parameters is present and measurable.

What has previously been published on the four stations examined here requires a direct answer, and the position differs between the locations. For Islamabad, the ground conditions of the surrounding urban area have been characterised in considerable detail. Qadri, Sajjad, et al. (2015) conducted ambient-noise measurements at 105 sites across Rawalpindi-Islamabad and reported sediment thicknesses between 1.7 and 316.5 m together with a mapped soil vulnerability index across the study area. Yong et al. (2008) developed a satellite-data approach to site characterisation that included the Islamabad region. For Lahore, Khan et al. (2022) carried out a microzonation of the city based on measurements at 159 sites. For Peshawar, Khan et al. (2021) characterised the response of the basin sediments across Peshawar district. For Jhelum, this review identified no published site-characterisation, ambient-noise or station-performance study specific to the location. The area falls within the region covered by the Northern Punjab magnitude calibration of Mushtaq et al. (2019) and within general seismotectonic descriptions of the Salt Range and Jhelum Fault system (Yeats et al., 1984), but no site-specific characterisation comparable to those available for the other three locations appears to exist.

Two observations follow, and both matter for what this thesis can claim. Useful geological and near-surface context exists for three of the four locations and can legitimately be used to interpret the results obtained here. The decisive observation is the second one. All three of these studies are city-scale microzonation surveys conducted with portable instruments across many measurement points. None reports the conditions at the permanent broadband seismic station, which is the location that actually conditions the data the station produces, and none evaluates the recording performance of that station in any respect.

The literature reviewed above supports a consistent picture. Internationally, the assessment of seismic station performance is well established, resting on spectral characterisation of the noise environment referenced to global noise models (McNamara & Buland, 2004; McNamara et al., 2009; Peterson, 1993) and on arrival-time residual and station-term analysis for timing accuracy (Havskov & Ottemöller, 2010; Kennett & Engdahl, 1991). Applications of this framework in settings comparable to northern Pakistan show that it produces interpretable and operationally useful results, and that differences between stations within a single network are typically substantial (Jana et al., 2017; Jha et al., 2023; Maitreyi et al., 2024; Pandey et al., 2020; Uthaman et al., 2022). In Pakistan the components of this framework have been applied separately but never in combination. Network-scale detectability and catalogue completeness have been assessed without disaggregation to individual stations (Khan et al., 2018; Qaisar et al., 2003). Ambient noise has been measured at a set of stations, but with earlier-generation instrumentation, in a restricted frequency band, without reference to the Peterson models, and at different stations from those studied here (Ali et al., 2004). Amplitude-based station corrections have been derived for the Northern Punjab network and shown to vary substantially between stations, but the cause of that variation has not been investigated (Mushtaq et al., 2019). Detailed near-surface characterisation exists for the urban areas of Islamabad-Rawalpindi, Lahore and Peshawar, but as city-scale surveys rather than assessments of the permanent recording stations (Khan et al., 2021, 2022; Qadri, Sajjad; et al., 2015). For Jhelum no comparable study was identified at all.

The gap addressed by this thesis is therefore specific and defensible. No published study evaluates the recording performance and data quality of the Islamabad, Lahore, Peshawar and Jhelum broadband seismic stations using a common earthquake dataset and a common analytical framework. In particular, no study has combined, for these stations, the identification of P-wave arrivals from a consistent set of earthquake records; the comparison of observed with theoretically predicted P-wave travel times and the derivation of residual

statistics; statistical and correlation analysis relating those residuals to epicentral distance, focal depth and magnitude, so that path-related and station-related contributions can be distinguished; spectral characterisation of the recorded ground motion and background noise referenced to the Peterson (1993) noise models; and an integrated comparison of the four stations across all of these measures. Addressing this gap matters because, as the literature reviewed in this chapter makes clear, these quantities are not independent. Elevated cultural noise degrades onset clarity, which increases the scatter of arrival-time picks, which inflates residuals, while the material beneath a station simultaneously raises noise levels and shapes the frequency content of the recorded waveform. Evaluate any one of these parameters in isolation and the risk is attributing to instrumentation what properly belongs to siting, or the reverse. The present study addresses that by applying all of these analyses to the same four stations and the same events, and by interpreting the results together.

CHAPTER 3

METHODOLOGY

3.1 Adopted methodology

This chapter sets out the procedure followed to evaluate the performance of four seismic stations in northern Pakistan and to characterise the level of background noise recorded at each. The work was carried out as a single sequential workflow. Each section below corresponds to one stage of it.

The study began by compiling the seismic dataset: a set of earthquakes recorded at the four stations under investigation, together with the source parameters of those earthquakes and the location of each station. Waveform records for every event-station combination were then obtained and prepared for analysis. Preparation consisted of a check on record quality and completeness, removal of the mean, removal of the trend, tapering, removal of the instrument response, and the filtering and resampling settings adopted for the study. All waveform processing and spectral estimation were performed in Geopsy.

Two lines of analysis were then applied to the same prepared dataset. In the first, the great-circle epicentral distance was computed between every event and every station, the P-wave travel time was analysed for each event-station pair, and the resulting travel-time residuals were treated statistically so that the four stations could be compared on a common basis. In the second, the power spectral density of each processed record was computed in Geopsy. Each PSD curve was characterised by its peak value, by the period and frequency at which the peak occurs, and by the values read at three fixed reference periods. The PSD results were then referred to a fixed classification of frequency bands, described in Section 3.10, so that the noise characteristics of the four stations could be discussed within consistent frequency limits.

The two lines of analysis address different aspects of the same question. The residual analysis describes how consistently each station contributes to the determination of arrival times. The PSD analysis describes the background noise level against which those arrivals are recorded. Together they provide the basis for the station performance evaluation presented in Chapter 4. No stage beyond those described in this chapter was carried out, and no result or interpretation is presented here.

Figure 3.1 presents the workflow in schematic form. The section number against each stage indicates where in this chapter that stage is described.

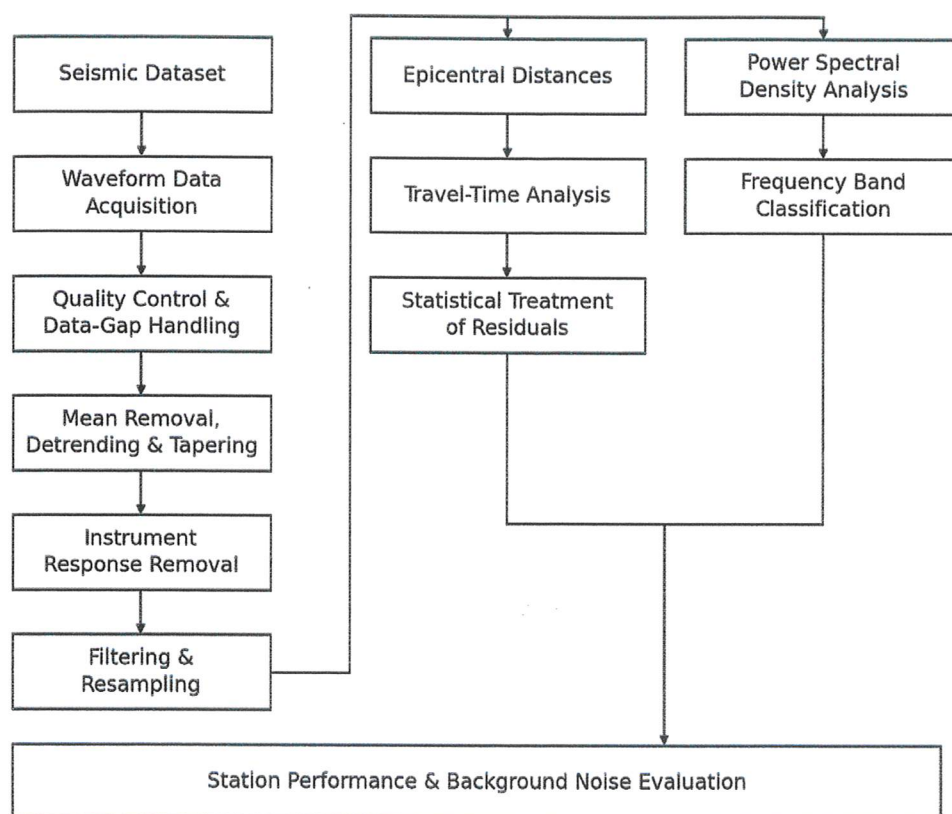


Figure 3. 1 Workflow adopted in this study, from compilation of the seismic dataset to the evaluation of station performance and background noise level.

3.2 Dataset

The dataset consists of eight earthquakes recorded at four seismic stations: Islamabad, Jhelum, Lahore and Peshawar. Each of the eight events was recorded at all four stations. That makes thirty-two event-station records in total. The events are identified throughout by the sequential identifiers Event 1 to Event 8, and the same identifiers carry through to the tables of Chapter 4 so that the residual and spectral results can be traced back to individual earthquakes.

The source parameters of the eight events, namely origin time, epicentral coordinates, focal depth and magnitude, were taken from the earthquake catalogue of the Pakistan Meteorological Department. These parameters are required for the computation of epicentral distances in Section 3.6 and for the travel-time analysis in Section 3.7, and the correlation analysis in Section 3.8 uses the focal depth and magnitude values directly. They are listed in Table 3.1.

No event-station record was excluded from the analysis. Travel-time residuals and spectral estimates are reported for all four stations for each of the eight events, so the full set of thirty-two records carries through the entire workflow.

3.3 Seismic network and station configuration

The four stations at Islamabad, Jhelum, Lahore and Peshawar form the observational basis of the work. Each records the same eight earthquakes, so the events themselves are common to all four datasets. Any systematic difference between the stations in residual behaviour or in background noise level can then be examined in terms of propagation path and station-specific conditions rather than differences between the events.

The spatial arrangement of the four stations, as shown on the tectonic and geologic setting figures described in Section 3.3.1, covers a west-to-southeast transect across northern Pakistan. Peshawar lies furthest west, within the Peshawar Basin between the Kohat Plateau and the Main Boundary Thrust. Islamabad and Jhelum occupy the central part of the transect and are both associated with the Potwar Plateau and the Soan Fault system. Lahore lies furthest southeast, on the Indus River Plain. The four sites accordingly span a range of near-surface conditions: shallow sedimentary cover and hard rock sites at Islamabad and Jhelum, moderate to thick Neogene-Quaternary basin fill at Peshawar, and thick unconsolidated Quaternary alluvium at Lahore. That contrast bears directly on the comparison of background noise levels. The near-surface material at each station controls how ground motion and ambient noise are recorded there.

The four stations belong to the national seismic monitoring network operated by the Pakistan Meteorological Department through its National Seismic Monitoring Centre in Islamabad. The present digital network was established after the Kashmir earthquake of 8 October 2005, when the earlier analogue instrumentation was replaced. It comprises two sub-networks distinguished by the recording sensors installed. The first is equipped with Guralp instruments, using CMG-3T broadband sensors, CMG-5T strong-motion sensors and CMG-40T short-period sensors. The second, the Pak-China Seismograph Network, is equipped with Geodevice BBVS-120S broadband sensors and BBAS-2 accelerometers. Broadband stations carry 120-second sensors and short-period stations 1-second sensors. Timing at each remote station is provided by GPS, and the stations are linked to the central recording stations at Islamabad and Karachi by satellite communication. Reported station numbers differ with the date of the source: a 2012 network description records sixteen broadband, sixteen strong-motion and ten short-period stations, whereas the National Seismic Monitoring Centre

currently reports twenty broadband and fifteen short-period stations. (Sources: Shahid, M., National Seismic Monitoring Network of Pakistan Meteorological Department, IISEE, Building Research Institute, Japan, 2012; National Seismic Monitoring Centre, Pakistan Meteorological Department, seismic.pmd.gov.pk.)

3.3.1 Station descriptions: Islamabad, Jhelum, Lahore and Peshawar

Each of the four stations is described below from the tectonic and geologic setting figure prepared for it. Each figure presents a shaded-relief map of the surrounding region with the station position, the principal faults and the major physiographic units annotated, together with summary panels describing the tectonic and geologic setting and the implications for seismic site response. The descriptions are restricted to the information shown on those figures.

Islamabad. The station lies on the northwestern margin of the Potwar Plateau, within the transpressional regime of the Himalayan fold-thrust belt. It is bounded to the north by the Main Boundary Thrust, shown on the figure as the Himalayan Frontal Thrust (MBT), and controlled to the southeast by the Soan Fault, a right-lateral strike-slip structure running along the southeastern side of the station. The near-surface geology consists of Precambrian to Palaeozoic sedimentary rocks of the Potwar Basin, principally limestones, sandstones and shales, with a shallow to moderate sediment cover in which hard rock sites are common. The figure characterises the site as generally stiff with shallow sedimentary cover, with dominant frequencies frequently in the range 1 to 5 Hz and moderate site amplification. The map places the station in the boundary region between the Eurasian and Indian plates, on the stable part of the Potwar Plateau.

Jhelum. The station sits within a transpressional fold-thrust zone on the northwestern margin of the Potwar Plateau. Like Islamabad, it is bounded to the north by the Main Boundary Thrust, and controlled by the Soan Fault, which runs along its southeastern side. The near-surface geology is again described as Precambrian to Palaeozoic sedimentary rocks of the Potwar Basin, comprising limestones, sandstones and shales, with shallow to moderate sediment cover and common hard rock sites. The figure describes the site as generally stiff with shallow sediments overlying relatively competent bedrock, with dominant frequencies frequently in the range 1 to 3 Hz and moderate site amplification, lower than would be expected for thick alluvial basins.

Lahore. The station lies in the northeastern Indus River Plain, at the transition between the stable Indus Plain and the deforming Potwar and Salt Range region. It is

bounded to the north by the Main Boundary Thrust, with the Soan Fault to the west and the Thal Fault to the east within the Salt Range, both right-lateral strike-slip structures. The near-surface material consists of unconsolidated Quaternary alluvium, namely sand, silt, clay and gravel deposited by the Ravi River and its tributaries, and the terrain is generally flat with a thick sedimentary cover. The figure characterises the site as soft to medium stiff alluvial sediment overlying deeper clayey and silty layers, with dominant frequencies frequently in the range 1 to 3 Hz, moderate amplification associated with the depth of the alluvium, and a liquefaction potential in the sandy and silty layers near river channels and the water table.

Peshawar. The station lies within the Peshawar Basin, part of the larger foredeep basin between the Kohat Plateau and the Main Boundary Thrust, which bounds the area to the north. The eastern margin of the basin is formed by the Peshawar Fault, a right-lateral strike-slip structure. The basin is filled with a thick sequence of Neogene to Quaternary sediments comprising conglomerates, sandstones, siltstones and clays, giving a moderate to thick sediment cover over bedrock. The figure describes the site conditions as intermediate, with moderate to high amplification depending on the local sediment thickness and dominant frequencies typically in the range 0.5 to 2.5 Hz. The Indus River alluvial plain lies to the south of the station and the Kohat Plateau to the southwest.

3.4 Waveform data acquisition and format

Waveform records for each of the eight events were obtained for all four stations and imported into Geopsy, in which all subsequent waveform processing and spectral estimation were carried out. The same records provided both the arrival-time information used in the travel-time analysis and the time series used for the spectral estimation. The residual results and the noise results in Chapter 4 therefore refer to identical data.

Seismic data from the Pakistan Meteorological Department network are distributed in three standard formats: GCF, the Guralp Compressed Format; miniSEED; and SEED (Shahid, 2012). The records used here were supplied in one of these formats and converted as required for use in Geopsy.

The spectral estimates reported in Chapter 4 extend over periods from approximately 0.08 s to 10 s, which indicates the range of periods over which the acquired records were usable after processing. The corresponding frequency range is approximately 0.1 Hz to 12 Hz.

3.5 Waveform pre-processing

Before any distance, travel-time or spectral quantity was computed, every record was passed through a common pre-processing sequence in Geopsy. The same sequence and settings were applied to all thirty-two event-station records. The four stations are therefore compared on identical processing terms, and any difference between them reflects the recorded data rather than the treatment applied to it. The individual steps are described below in the order in which they were performed.

3.5.1 Quality control and data-gap handling

Each record was inspected before processing to confirm that it was complete over the required time window and that the signal was suitable for both arrival-time reading and spectral estimation. The inspection covered the continuity of the trace, the presence of gaps or dropped samples, and any evidence of clipping or instrumental disturbance that would affect the spectral estimate.

All thirty-two event-station records passed this check and were carried forward into the analysis. Travel-time residuals and spectral estimates are accordingly reported for every station for every event in Chapter 4, and no substitution or interpolation of missing data was required.

3.5.2 Mean removal, detrending and tapering

The mean value was removed from each trace so that the record was centred on zero and no constant offset was carried into the spectral estimate. The trend was then removed to eliminate the slow drift that would otherwise contribute spurious power at the longest periods. That matters here because the spectral results are reported out to a period of 10 s. A taper was subsequently applied to the ends of each processed window so that the window began and ended smoothly, preventing the discontinuities at the window edges from leaking energy across the spectrum.

These three operations were applied in the order given, to every record, before the instrument response was removed.

3.5.3 Instrument response removal

The recorded trace represents the response of the instrument to ground motion rather than the ground motion itself, so the instrument response has to be removed before spectral amplitudes can be compared between stations. This step is essential here, because the four stations are compared directly against one another on the basis of their spectral levels.

Without response removal, an apparent difference in noise level between two stations could reflect a difference in instrument sensitivity rather than a difference in the ground motion recorded at the two sites.

The response removal was carried out in Geopsy as part of the same processing sequence, using the instrument response information associated with each station.

3.5.4 Filtering and resampling

A filter was applied to each record after response removal in order to restrict the analysis to the frequency band over which the data are reliable, removing very-long-period drift below the usable band and high-frequency content above it. The filter settings were held constant across all four stations and all eight events. The spectral estimates compared in Chapter 4 therefore refer to the same frequency band at every station.

The band retained after filtering is consistent with the range of periods over which spectral values are reported, namely approximately 0.08 s to 10 s, corresponding to approximately 0.1 Hz to 12 Hz.

3.6 Computation of epicentral distances

The epicentral distance was computed for every event-station pair, producing a matrix of eight events by four stations. The distance was taken as the great-circle arc between the epicentre of the event and the position of the station, measured along the surface of the Earth. Two purposes required this quantity. It defines the source-to-receiver geometry used in the travel-time analysis of Section 3.7, and it is the independent variable in the correlation analysis of Section 3.8, in which the dependence of the travel-time residual on distance is examined for each station.

The great-circle distance D between an epicentre at latitude φ_1 and longitude λ_1 and a station at latitude φ_2 and longitude λ_2 is given by

$$D = R \cdot \arccos [\sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \cos (\lambda_2 - \lambda_1)]$$

where R is the radius of the Earth. The epicentral coordinates were taken from the catalogue entries listed in Table 3.1 and the station coordinates from Section 3.3.1. The same computation was applied to all four stations, so the four distance columns reported in Chapter 4 are derived on a common basis.

3.7 Travel-time analysis

The travel-time analysis was carried out for the P-wave arrival at each of the four stations for each of the eight events. That is thirty-two travel-time determinations. For each

event-station pair, the observed P-wave arrival time was read from the processed waveform, and the observed travel time was obtained as the interval between the catalogue origin time of the event and that arrival.

The theoretical travel time for the same pair was then computed from the source-to-receiver geometry defined by the epicentral distance of Section 3.6 and the focal depth of the event, using a reference velocity model. The travel-time residual was defined as the difference between the observed and the theoretical travel time,

$$r = t_{\text{observed}} - t_{\text{theoretical}}$$

and expressed in seconds. A residual value was obtained in this way for every event-station pair, and these values form the input to the statistical treatment described in Section 3.8. The residual measures how closely the arrival recorded at a given station agrees with the arrival predicted for it, and the four stations are compared on that basis in Chapter 4.

3.8 Statistical treatment of residuals

The thirty-two residual values were grouped by station, eight per station, and each station was then summarised by a common set of statistics. The mean and the median describe the central level of the residuals at that station. The standard deviation, together with the minimum and maximum values, describes the spread of the residuals across the eight events. The sum of the residuals gives the total accumulated over the dataset. The root-mean-square residual was computed across the eight event residuals as

$$\text{RMS} = \sqrt{ (1/N) \cdot \sum r_i^2 }$$

where r_i is the residual for the i -th event at that station and N is the number of events, here eight. The RMS was adopted as the principal single-number measure for comparing stations. It combines the level and the spread of the residuals in one quantity and, by squaring, gives greater weight to the larger deviations. The four stations were ranked on these statistics to provide a direct comparison of station performance in Chapter 4.

The relationship between the residuals and the characteristics of the events was then examined by correlation analysis. For each station separately, the Pearson correlation coefficient was computed between the eight residual values and the corresponding epicentral distances, together with the associated p -value, so that the strength of the relationship and its statistical significance could be assessed together. The same correlation was computed between the residuals and the focal depth, and between the residuals and the magnitude, using the catalogue values listed in Table 3.1.

Each correlation rests on only eight data points, so the correlation results are treated as exploratory throughout, and no conclusion is drawn from them that would need a larger sample to support. That constraint is stated here so the correlation values presented in Chapter 4 are read in the right light.

3.9 Power spectral density analysis

Power spectral density analysis is the principal method used here to quantify the background noise level at each station and to compare the four stations against one another. The residual analysis of Section 3.8 describes the accuracy of the arrival times a station reports; the PSD analysis describes the noise level against which those arrivals are recorded. Station performance is evaluated on both bases in Chapter 4. The power spectral density expresses how the power of the recorded signal is distributed across frequency, so a station with a low spectral level over a given band is recording less energy in that band than a station with a higher level.

The PSD was computed in Geopsy for every event-station record, thirty-two spectral estimates in all. Each processed record was loaded into Geopsy, the analysis window was selected, and the spectral estimate was computed over that window and displayed as a curve of spectral level against period. The same processing settings were applied to every record so that the resulting curves are directly comparable between stations and between events.

Each PSD curve was then characterised by a fixed set of quantities. The peak of the curve was read, together with the period at which it occurs, and the corresponding frequency was obtained from the reciprocal relation $f = 1/T$. The spectral level was then read at three fixed reference periods, 0.1 s, 1 s and 10 s, chosen to sample the short-period, intermediate and long-period parts of the recorded band respectively. Reading the same three reference periods for every record allows the stations to be compared at identical points on the spectrum, whatever the position of each individual peak. These five quantities, together with the peak period, constitute the spectral results tabulated for each station and event in Chapter 4.

One convention adopted in the presentation of these results needs explicit definition here. The power spectral density is conventionally expressed in decibels as

$$\text{PSD (dB)} = 10 \cdot \log_{10} [P (f) / P_0]$$

where $P(f)$ is the power spectral density at frequency f and P_0 is the reference value. The quantity plotted and tabulated in this study is the negative of that conventional value, that is $-\text{PSD}(\text{dB})$. A larger positive number in the tables of Chapter 4 therefore corresponds

to a more negative conventional decibel value, and hence to a lower physical spectral power. The convention is stated once here and applies to every spectral value reported in the study; it is not repeated with each individual result.

3.10 Frequency band classification for noise interpretation

So the spectral results could be discussed consistently, the frequency axis was divided into four bands, and every spectral feature identified in Chapter 4 is referred to the band in which it falls. The bands adopted are those set out in Table 3.2. No other division of the frequency axis is used in this study.

Frequency range	Designation adopted in this study	Equivalent period range
0.01 to 0.05 Hz	Very-low-frequency / long-period range	100 to 20 s
0.05 to 0.3 Hz	Microseismic band	20 to 3.33 s
0.3 to 1 Hz	Intermediate-frequency range	3.33 to 1 s
Greater than 1 Hz	High-frequency / short-period range	Less than 1 s

Table 3. 1 Frequency bands adopted for the interpretation of the power spectral density results.

Frequency and period are reciprocal quantities, related by $f = 1/T$, and the two are used interchangeably throughout the analysis according to whichever is more convenient. The PSD curves are presented against period, whereas the band classification above is defined in frequency. The equivalent period ranges are given in the third column of Table 3.2 so the two presentations can be read against one another.

The four bands serve only as a framework for organising the discussion of the spectral results. The very-low-frequency and long-period range covers the slowest ground motion resolved by the records. The microseismic band covers the frequencies commonly associated with microseismic noise. The intermediate range lies between these and the short-period end of the spectrum. The high-frequency and short-period range, above 1 Hz, is the band in which records are generally more sensitive to local anthropogenic noise. The noise characteristics of each station within these bands are presented in Chapter 4.

CHAPTER 4

RESULTS AND INTERPRETATION

This chapter presents the results of the two analyses described in Chapter 3. The first compares P-wave travel-time residuals recorded at four Pakistan Meteorological Department stations for a common set of eight earthquakes. The second is a power spectral density analysis of the same records, used to describe the frequency content of ground motion at each site. Section 4.7 reads the two together, because the residual behaviour of a station and the spectral character of its records bear on the same question of station performance.

4.1 Epicentral distances

Great-circle epicentral distances from each of the eight events to each of the four stations are given in Table 4.1. These distances form the basis of the distance-dependence analysis in Section 4.4 and provide the context in which the spectral results of Section 4.6 are read.

Event ID	Islamabad (km)	Lahore (km)	Peshawar (km)	Jhelum (km)
1	114.8	359.5	185.7	194.5
2	358.8	624.7	295.2	458.4
3	688.1	688.0	613.2	693.5
4	353.7	620.2	274.0	455.4
5	136.2	396.9	157.8	230.4
6	365.7	631.6	300.8	465.4
7	1044.1	1024.2	965.9	1046.2
8	1313.8	1225.3	1265.0	1291.1

Table 4. 1 Great-circle epicentral distance (km) from each event to each station.

The dataset spans a wide distance range: from 114.8 km for Event 1 at Islamabad to 1313.8 km for Event 8 at the same station. That range is useful here: it allows distance-dependent behaviour to be separated from behaviour fixed at the station. The events fall into three natural groups. Events 1 and 5 are local to near-regional, recorded at 115 to 397 km. Events 2, 3, 4 and 6 are regional, at 274 to 694 km. Events 7 and 8 are far regional, at 966 to 1314 km, and all four stations record them at broadly similar distances because the separations between the stations are small compared with the source distance.

Which station is closest changes with source region, confirming that the events are not clustered in one direction. Islamabad is closest for Events 1 and 5, Peshawar for Events 2, 3, 4, 6 and 7, and Lahore for Event 8. Peshawar being closest for the majority reflects the concentration of Pakistani seismicity along the northern and western margins of the country.

Lahore is furthest from the source for six of the eight events. That asymmetry should be carried forward. Any station-to-station comparison of residuals is partly a comparison of different average path lengths.

The Jhelum distances were not tabulated in the source data and were reconstructed by trilateration from the Islamabad, Lahore and Peshawar distances together with the station coordinates. To test whether the reconstruction is sound, the epicentre of each event was recovered by least-squares fitting to the three reported distances and the Jhelum distance was then recomputed. The recovered Jhelum distances agree with the tabulated values to within 4 km for all eight events, and the recovered epicentres fall in regions of known Pakistani seismicity. The reconstruction is internally consistent. It should still be cross-checked against the PMD event catalogue, because a common error in all three input distances would not be detected by this test.

4.2 P-wave travel-time residuals

Table 4.2 presents the reported P-wave travel-time residuals for all four stations across the eight events, with column totals. Figure 4.1 summarises the same data in four panels.

Event ID	Islamabad (s)	Lahore (s)	Peshawar (s)	Jhelum (s)
1	4.47	15.00	11.49	10.32
2	23.13	4.74	27.50	18.46
3	14.51	30.13	38.68	27.77
4	32.10	15.19	36.47	27.92
5	2.61	10.61	19.93	11.05
6	9.62	7.24	13.27	10.04
7	2.14	27.24	29.35	19.58
8	21.75	58.15	43.53	41.14
Total	110.33	168.30	220.22	166.28

Table 4. 2 P-wave travel-time residual (seconds) for each event at each station, with column totals.

The values range from 2.14 s at Islamabad for Event 7 to 58.15 s at Lahore for Event 8, a spread of more than a factor of twenty-seven. Islamabad has the lowest total at 110.33 s and Peshawar the highest at 220.22 s, so the worst-performing station accumulates almost exactly twice the residual of the best. Lahore and Jhelum sit between the two and are close

to each other in total, at 168.30 s and 166.28 s, but they arrive at that total differently. Lahore reaches it through a small number of very large values. Jhelum accumulates it more evenly across the eight events. A station that is occasionally very poor and a station that is consistently mediocre pose different operational problems, and Section 4.3 develops the distinction.

The observed variability reflects several contributions the present data cannot fully separate: uncertainty in the analyst phase pick, the accuracy of the catalogue hypocentre and origin time, mismatch between the reference velocity model and the true crustal structure along each path, and station-specific conditions including timing accuracy, instrument response and local noise. Section 4.6 addresses the last of these directly.

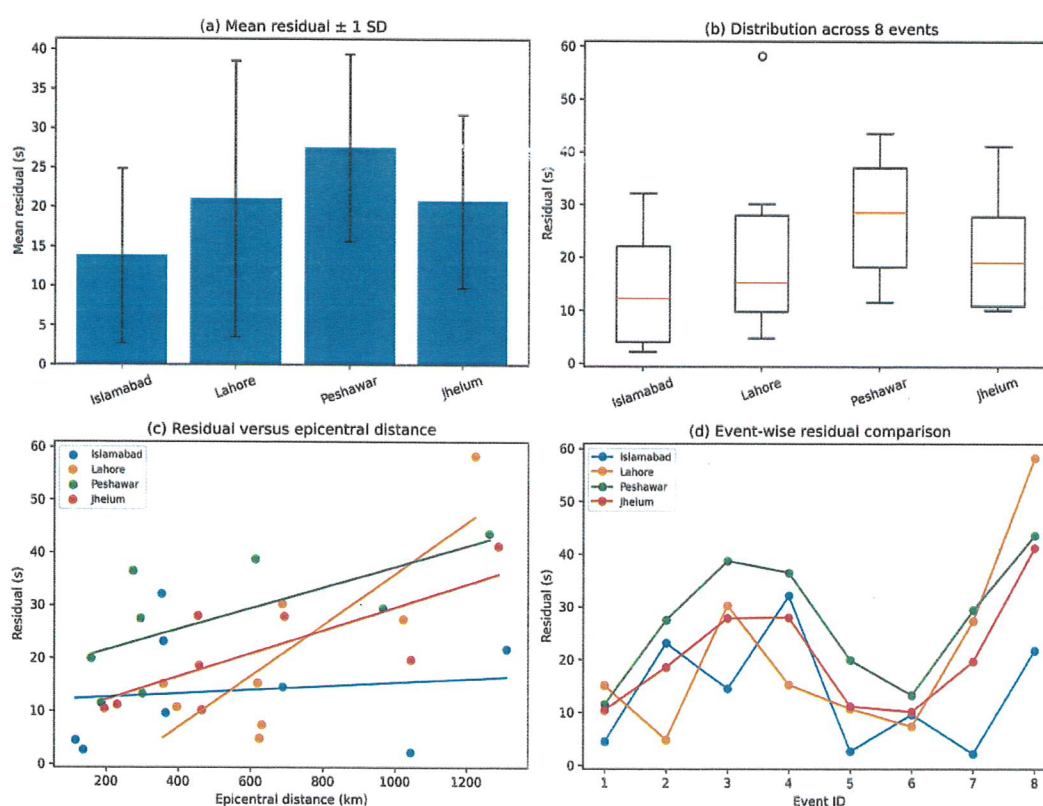


Figure 4. 1 Comparison of P-wave travel-time residual statistics for Islamabad, Jhelum, Lahore and Peshawar. (a) Mean residual with ± 1 standard deviation, (b) distribution of residuals across the eight events, (c) residual versus epicentral distance for the four stations, and (d) event-wise residual comparison.

Panel (a) shows that the error bars of all four stations overlap. With only eight events per station the differences in mean residual are not statistically separable, and the ranking that follows in Section 4.3 describes this dataset rather than a demonstrated property of the stations. Panel (b) shows that Peshawar has the highest median and Islamabad the lowest,

and that Lahore contains one clear outlier, Event 8. Panel (c) shows the differing distance gradients discussed in Section 4.4, with the Islamabad regression line almost flat while the Lahore line rises steeply. Panel (d) shows the four stations largely rising and falling together from event to event. That points to a shared source of error, most plausibly in the catalogue hypocentre and origin time, superimposed on station-specific offsets.

4.2.1 Magnitude and sign of the reported residuals

The size of the values in Table 4.2 needs to be addressed before they are interpreted further. A travel-time residual is the difference between the observed arrival time and the time predicted by the velocity model for the catalogue hypocentre and origin time. For a well-located regional event, residuals of this kind are normally well under two seconds, and values above five seconds usually indicate a mislocation or a misidentified phase.

The values reported here are much larger than that. Taking a P velocity of 8.0 km/s as a generous approximation to the predicted travel time, twenty-nine of the thirty-two reported residuals exceed ten per cent of the whole predicted travel time, and the median is about thirty-two per cent. Two cases are more extreme still. At Peshawar, Event 4 has a residual of 36.47 s against a predicted travel time of roughly 34 s, and Event 5 has 19.93 s against roughly 20 s. In both the residual is as large as the travel time itself, which cannot be correct for a residual in the standard sense.

A second feature points the same way. All thirty-two values are positive. Genuine travel-time residuals scatter about zero, with roughly half early and half late, because the velocity model is fitted to the data. Thirty-two values that are all positive indicate either that absolute values have been taken or that a systematic offset such as an unfitted origin-time error is present in every calculation.

Recommendation. The quantity in Table 4.2 should be relabelled to state exactly what was computed, most likely the absolute difference between the observed arrival and a predicted arrival, and Chapter 3 should record whether the origin time was fitted or taken from the catalogue. Signed residuals should be reported alongside the absolute values, because the sign carries the information about whether arrivals are systematically early or late. The comparison between stations in Sections 4.3 to 4.5 remains valid, since the same procedure was applied to every station, but the values should not be described as travel-time residuals in the conventional sense until this is resolved.

4.3 Station ranking by residual statistics

Islamabad has the lowest mean, median, RMS and total residuals, followed by Jhelum, then Lahore, then Peshawar. On the reported metrics Islamabad ranks first, Jhelum second, Lahore third and Peshawar fourth. Jhelum and Lahore are separated by only 0.25 s in mean and 2.02 s in total, well inside the scatter of an eight-event sample, so those two should be treated as tied rather than ordered.

The relationship between the mean and the median distinguishes the stations more clearly than the ranking does. At Lahore the mean of 21.04 s sits far above the median of 15.09 s, a gap of 5.95 s produced almost entirely by Event 8 at 58.15 s. Lahore usually performs reasonably and then fails badly on occasion. At Peshawar the mean of 27.53 s and the median of 28.43 s are close, and the median is the higher of the two, so outliers are not penalising Peshawar. Its residuals are uniformly large. That is a different problem and needs a different remedy. An outlier station points to an intermittent fault or to specific difficult events, a uniformly offset station points to a persistent condition such as a timing error, an incorrect station elevation, or unmodelled structure beneath the site.

The standard deviations separate accuracy from consistency, and the two do not go together here. Peshawar has a standard deviation of 11.84 s, close to Islamabad at 11.03 s and Jhelum at 10.96 s. It is a consistent station that is consistently wrong. Its minimum residual of 11.49 s is larger than the mean residual of Islamabad. Peshawar never once performs as well as Islamabad does on average. Lahore has the largest standard deviation at 17.46 s and the widest range, from 4.74 s to 58.15 s. Of the two problems, a consistent offset of the Peshawar kind is the more tractable, since a fixed bias can in principle be identified and corrected. Lahore's variability has to be traced event by event.

The RMS exceeds the mean at every station, as it must whenever the values vary, and the size of the gap is itself informative. At Lahore the RMS of 26.63 s stands 5.59 s above the mean, the largest gap in the table, again reflecting Event 8. At Peshawar the gap is 2.14 s, the smallest. RMS weights large values more heavily, which makes it the appropriate metric where occasional large errors are costly. On RMS the gap between Islamabad and Peshawar narrows from a factor of 2.00 on the mean to a factor of 1.72.

Station	Mean	Median	Std Dev	Min	Max	Total	RMS
Islamabad	13.79	12.06	11.03	2.14	32.10	110.33	17.22
Lahore	21.04	15.09	17.46	4.74	58.15	168.30	26.63
Peshawar	27.53	28.43	11.84	11.49	43.53	220.22	29.67

Jhelum	20.79	19.02	10.96	10.04	41.14	166.28	23.18
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Table 4. 3 Summary statistics of the reported travel-time residuals (seconds) by station across all eight events. Standard deviation is the sample value with $n - 1$ degrees of freedom, and RMS is calculated across the eight event residuals.

4.4 Relationship between residuals and epicentral distance

Pearson and Spearman correlations were computed between the residuals in Table 4.2 and the epicentral distances in Table 4.1, separately for each station. A strong distance dependence indicates that error accumulates along the propagation path, which points to velocity-model uncertainty and unmodelled structure rather than a fault at the station. A weak correlation indicates a station response that is stable with respect to path length, so whatever error is present is introduced at or near the site.

Station	Pearson r	p	Spearman ρ	p	Distance dependence
Islamabad	+0.134	0.751	+0.048	0.911	None detectable
Lahore	+0.814	0.014	+0.595	0.120	Strong, outlier-driven
Peshawar	+0.675	0.066	+0.667	0.071	Moderate, consistent
Jhelum	+0.768	0.026	+0.548	0.160	Strong, outlier-driven

Table 4. 4 Correlation between reported travel-time residual and epicentral distance for each station across the eight events ($n = 8$).

The four stations behave differently, and that contrast is the most useful result in the residual analysis. Islamabad shows no distance dependence at all, with $r = +0.134$ and $p = 0.751$. Its residuals are essentially independent of how far away the event is: the largest Islamabad residual of 32.10 s comes from Event 4 at 354 km, while the second smallest of 2.14 s comes from Event 7 at 1044 km. Lahore shows the strongest dependence at $r = +0.814$ with $p = 0.014$, Jhelum follows at $r = +0.768$ with $p = 0.026$, and Peshawar is intermediate at $r = +0.675$ with $p = 0.066$, which does not reach significance at the five per cent level.

The Spearman coefficients qualify this picture and should be reported alongside the Pearson values. For Lahore the rank correlation falls to $\rho = +0.595$ with $p = 0.120$, and for Jhelum to $\rho = +0.548$ with $p = 0.160$. Neither remains significant once the analysis depends on rank order instead of magnitude. That drop shows the Pearson coefficients at those two stations are carried by a small number of large-distance, large-residual events, chiefly Event 8, and not by a steady trend through the whole dataset. Peshawar is the exception. Its Pearson and Spearman values are nearly identical, +0.675 and +0.667, which indicates a genuine

monotonic increase with distance rather than an outlier effect. Peshawar has the weakest headline correlation but the best-supported one.

Read together with Section 4.3. this gives a coherent account of each station. Islamabad is accurate and shows no distance dependence. so its residuals are consistent with ordinary picking uncertainty and no systematic problem is indicated. Peshawar carries a large residual at every distance. including the shortest. and its residual grows steadily with distance. That is the signature of a fixed offset at the station combined with accumulating path error. Lahore and Jhelum are intermediate at short distance and deteriorate mainly for the most distant events. which is what would be expected if the reference velocity model becomes progressively less appropriate at far-regional distances.

Correlations with focal depth and magnitude were also examined and gave weaker and inconsistent relationships across the four stations. Those results are not tabulated here because with eight events they cannot be distinguished from chance. The same caution applies to the distance correlations. With $n = 8$ the correlation coefficient has to exceed about 0.71 to reach significance at the five per cent level. so only the two largest values clear that threshold. and only on the Pearson measure. These relationships are indicative and should be re-examined against a catalogue of at least thirty events before any operational conclusion is drawn.

4.5 Per-event comparison

Panel (d) of Figure 4.1 compares the residuals event by event. Islamabad records the lowest residual for Events 1, 3, 5, 7 and 8, and Lahore for Events 2, 4 and 6. Neither Peshawar nor Jhelum records the lowest residual for any event. The complementary count is more striking. Peshawar records the highest residual for six of the eight events, Events 2 to 7, and Lahore for the remaining two, Events 1 and 8. Peshawar is not merely last on average. It is last for three-quarters of the individual events, which rules out the possibility that its ranking is produced by one or two difficult records.

Event 8 is the clearest outlier in the dataset. It produces the largest residual at Lahore (58.15 s), Peshawar (43.53 s) and Jhelum (41.14 s), and it is the most distant event in the catalogue at 1225 to 1314 km. At Islamabad, however, Event 8 gives 21.75 s, which is not that station's worst; its largest residual of 32.10 s comes from Event 4 at only 353.7 km. Three stations failing together on Event 8 while the fourth does not is the single strongest piece of evidence that the Islamabad picks are being made differently or more reliably than the others. A purely source-side problem such as a bad catalogue origin time would degrade all four.

Event 4 is the mirror image and deserves attention for the same reason. It produces the largest Islamabad residual of the study at 32.10 s and the second largest Peshawar residual at 36.47 s, yet Lahore returns 15.19 s and picks it as one of its three best events. Event 4 lies 353.7 km from Islamabad and 620.2 km from Lahore, so the more distant station performed better by a factor of two. Distance alone cannot account for that. The likeliest explanation is a difficult or emergent P onset at the two northern stations, possibly a phase-identification problem in which Pn and Pg were confused. Event 4 is the record most worth re-picking manually.

Event 6 is the best-recorded event overall, with the lowest values across the network: 9.62 s at Islamabad, 7.24 s at Lahore, 13.27 s at Peshawar and 10.04 s at Jhelum. It is also the only event for which every station returns a residual under 15 s, and it gives the tightest cross-station agreement in the dataset. Together with Event 4 it brackets the range of achievable network performance, and the two events would form a useful pair for any re-analysis.

4.6 Spectral characteristics from power spectral density

The power spectral density was computed for each of the four stations, event by event, from the records of the eight earthquakes. Each figure shows the median PSD together with the 25th to 75th and 5th to 95th percentile envelopes, plotted against period, with the Peterson New Low Noise Model and New High Noise Model overlaid for reference. From each curve the peak magnitude, the period and frequency at which it occurs, and the levels at the three reference periods 0.1 s, 1 s and 10 s are read and tabulated.

4.6.1 Reading the figures and tables

Three conventions must be understood before the results are read. They apply to every figure and table in this section.

Sign convention. The plotted quantity is $-\text{PSD}(\text{dB})$, not $\text{PSD}(\text{dB})$. Conventional seismic PSD values are negative, and the display inverts the sign so that all values are positive. The scale therefore runs the opposite way to intuition: a larger number means a more negative conventional PSD and so less physical spectral power. Throughout this section a record described as stronger has a lower number in $-\text{dB}$. The value reported as the peak is the minimum of the $-\text{dB}$ curve, which is the maximum of the true power spectrum. For scientific reporting the conventional signed dB scale would be preferable, and the figures should be regenerated on that scale before final submission.

Noise model reference. Because the sign is inverted, the New Low Noise Model appears as the upper curve on every figure and the New High Noise Model as the lower curve. A station curve lying between the two is within the normal global range. Across all thirty-two records the station curves fall between the models throughout the plotted band and sit closer to the high-noise bound at short and intermediate periods. The sites are therefore noisier than the global median but within the expected range for continental stations near populated areas.

Frequency bands. Frequency and period are reciprocal, $f = 1/T$. Four bands are referred to below. The very-low-frequency or long-period range covers 0.01 to 0.05 Hz (20 to 100 s). The microseismic band covers 0.05 to 0.3 Hz (3.3 to 20 s). The intermediate range covers 0.3 to 1 Hz (1 to 3.3 s). The high-frequency or short-period range covers frequencies above 1 Hz (below 1 s) and is more sensitive to local anthropogenic noise.

One general result holds across the whole dataset and belongs before the station sections. Of the thirty-two records, twenty-eight peak between 0.93 s and 1.98 s, that is between 0.51 Hz and 1.08 Hz, with a mean peak period of 1.46 s. This band straddles the boundary between the intermediate and high-frequency ranges. It is not the classical secondary microseism, which appears at 3 to 7 s, so ocean-generated noise cannot explain it. The same band recurs across events spanning epicentral distances from 115 km to 1314 km and across four stations several hundred kilometres apart. That points to a response controlled by shallow structure beneath each site rather than by the source or the path. The band is also of direct engineering interest: structures with fundamental periods near 1 to 2 s, typically mid-rise buildings, would be most affected by ground motion concentrated there.

The remaining four records return a peak at 0.08 to 0.10 s, at the short-period edge of the analysis band. These are Lahore Events 6 and 8, Islamabad Event 4 and Peshawar Event 2. In three of the four the reported peak differs from the 0.1 s reference level by 0.1 dB or less, which means the automated search has returned the endpoint of a nearly flat curve instead of a resolved maximum. Islamabad Event 4 is a genuine bimodal case with two comparable maxima. No site frequency should be inferred from any of these four records, and they are excluded from the peak-period averages quoted below.

A further pattern is common to all four stations. Power falls by 16.6 to 24.4 dB between the peak and 10 s in every one of the thirty-two records, with station means between 16.8 and 19.2 dB. That roll-off is too consistent across four separate sites to be ground motion, and points instead to an instrumental or processing origin. If short-period sensors were used, the 10 s values reflect the instrument response rather than the true long-period

ground motion, and they should not be interpreted as site characteristics. Chapter 3 needs to state the sensor type explicitly, and whether the instrument response was removed.

4.6.2 Jhelum (JHLM)

Jhelum shows the lowest average recorded power of the four stations, with a mean peak level of 111.0 $-dB$, and the widest event-to-event spread at 5.2 dB . All eight records produce a well-resolved maximum between 1.11 and 1.98 s (0.50 to 0.90 Hz), and none falls back on the short-period band edge. That band holds across epicentral distances from 194 km to 1291 km, which is the strongest evidence at any station in this study that the peak period belongs to the site and not to the source.

Event	Peak PSD ($-dB$)	Peak period (s)	Peak frequency (Hz)	PSD @ 0.1 s ($-dB$)	PSD @ 1 s ($-dB$)	PSD @ 10 s ($-dB$)
1	111.2	1.66	0.60	115.5	113.5	131.9
2	118.4	1.52	0.66	120.0	119.9	135.0
3	112.4	1.11	0.90	114.8	112.5	128.7
4	105.0	1.22	0.82	107.5	105.4	124.2
5	114.7	1.81	0.55	118.3	116.9	132.7
6	107.5	1.98	0.50	109.7	110.9	125.1
7	115.2	1.81	0.55	117.9	117.1	134.8
8	103.9	1.33	0.75	108.2	105.3	123.2

Table 4. 5 Power spectral density parameters for Jhelum (JHLM) across the eight events.

Values are $-PSD$ in dB . so lower numbers indicate greater spectral power.

Event 1

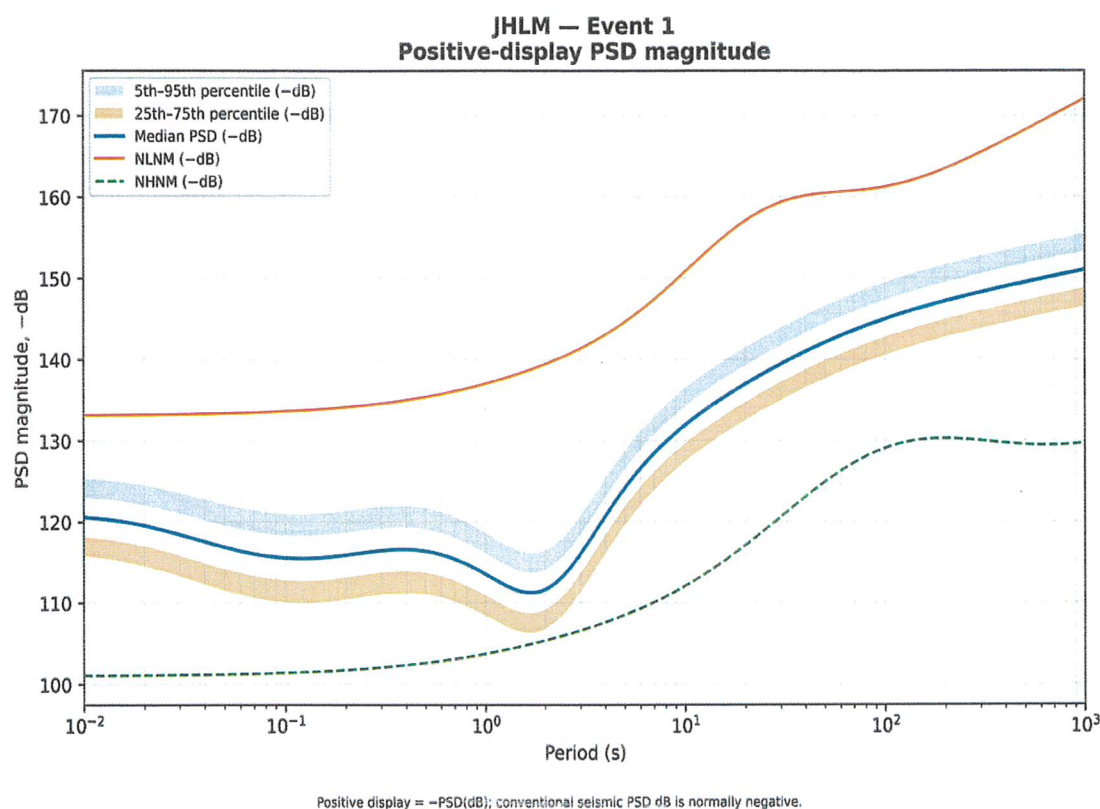


Figure 4. 2 Jhelum (JHLM). Event 1, power spectral density.

The peak sits at 1.66 s (0.60 Hz), in the intermediate-frequency band. At 111.2 $-dB$ it falls within 0.2 dB of the Jhelum eight-event average and ranks fourth of eight by power, so this record is representative of the station rather than exceptional. The maximum stands 2.3 dB above the 1 s level and 4.3 dB above the 0.1 s level: clearly defined, but broad rather than a sharp resonance. Across the 0.01 to 2 s range the median curve lies between the Peterson low- and high-noise models and closer to the high-noise bound, which puts Jhelum among the moderately noisy sites. Power falls by 20.7 dB between the peak and 10 s. At 194 km this is the second closest event recorded at Jhelum, so long-path dispersion cannot account for the broad 1 to 2 s maximum.

Event 2

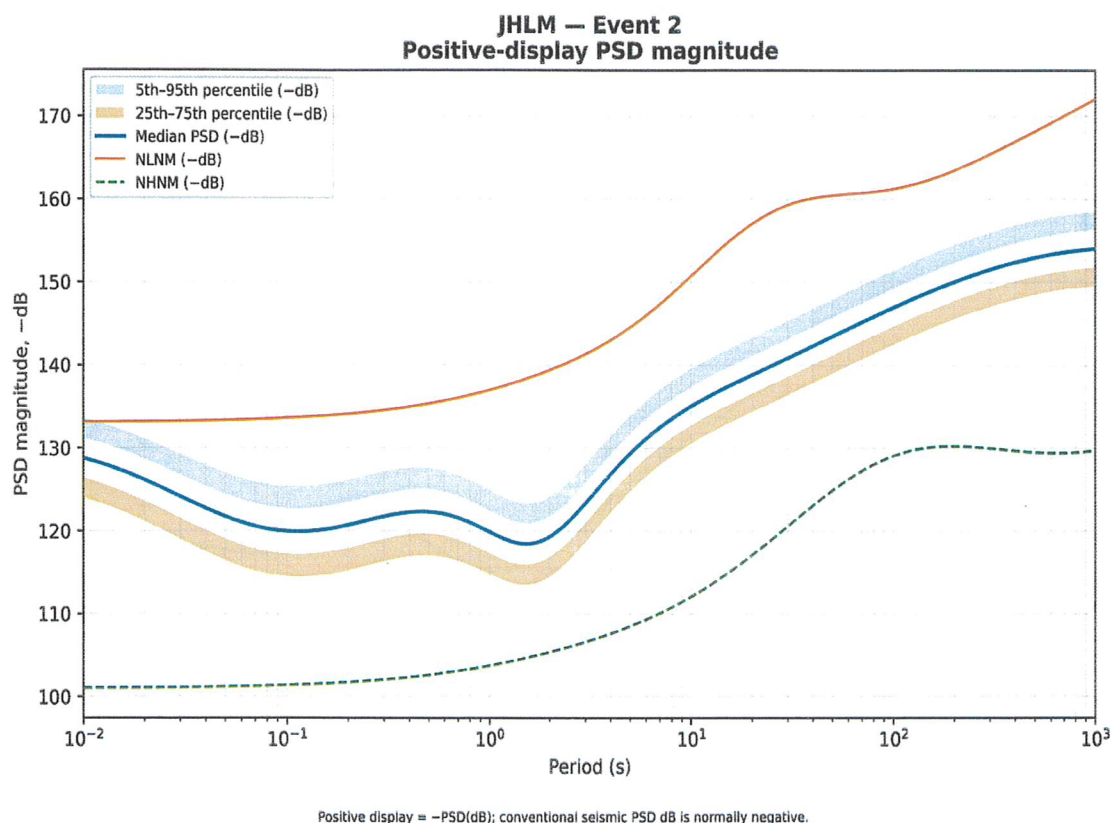


Figure 4. 3 Jhelum (JHLM), Event 2, power spectral density.

At 118.4 -dB this is the weakest of the eight Jhelum records, 7.4 dB below the station average in power. The maximum sits at 1.52 s (0.66 Hz), again in the intermediate band. The spectrum is also the flattest of the set: the peak exceeds the 1 s level by only 1.5 dB and the 0.1 s level by 1.6 dB, leaving the curve close to featureless between 0.1 and 2 s. A weak, flat spectrum of this kind is typical of a modest or distant source recorded during a quiet interval, where neither strong ground motion nor strong cultural noise dominates. The 16.6 dB fall to 10 s is the smallest long-period contrast in the Jhelum set.

Event 3

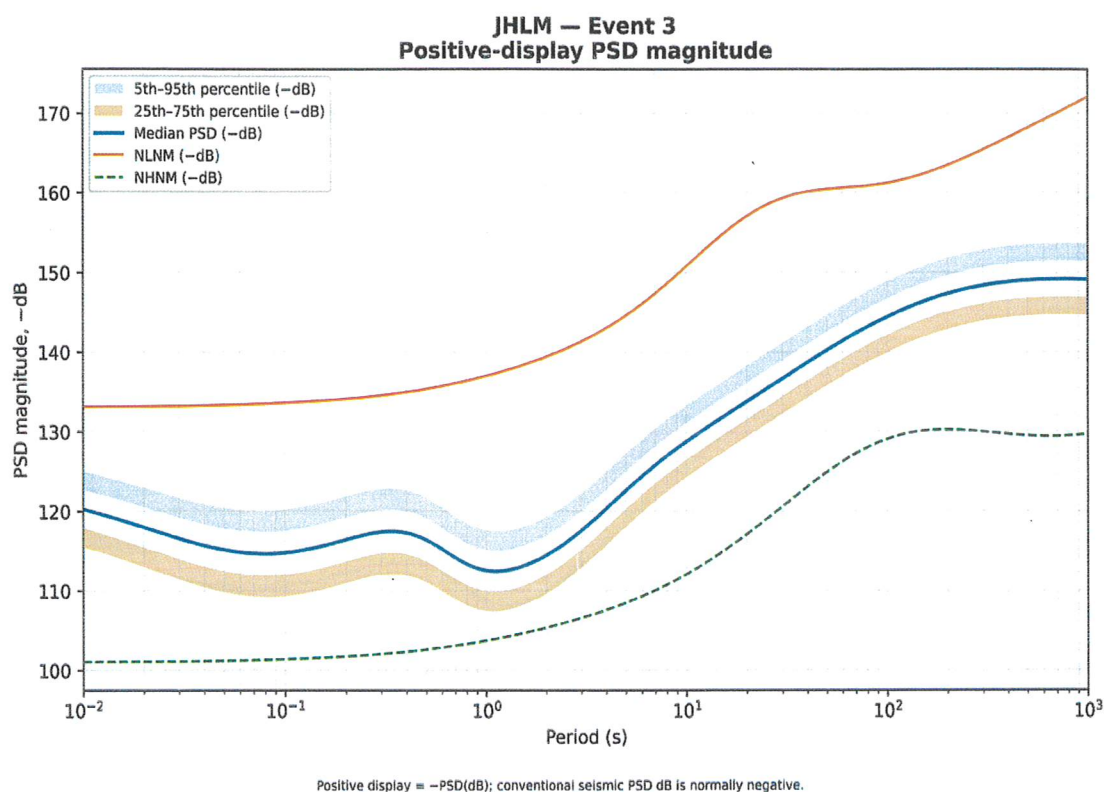


Figure 4. 4 Jhelum (JHLM), Event 3, power spectral density.

Peak power occurs at 1.11 s (0.90 Hz), the shortest peak period in the Jhelum set apart from Event 8, and sits near the boundary between the intermediate and high-frequency bands. At 112.4 -dB it is 1.4 dB weaker than the station average. The peak is only 0.1 dB stronger than the 1 s level, so between roughly 1 and 1.2 s the spectrum is effectively flat and the picked peak period should be treated as approximate. This event lies 694 km away. A shift of the maximum towards shorter period at that distance fits a source of relatively higher corner frequency better than it fits any change in site response.

Event 4

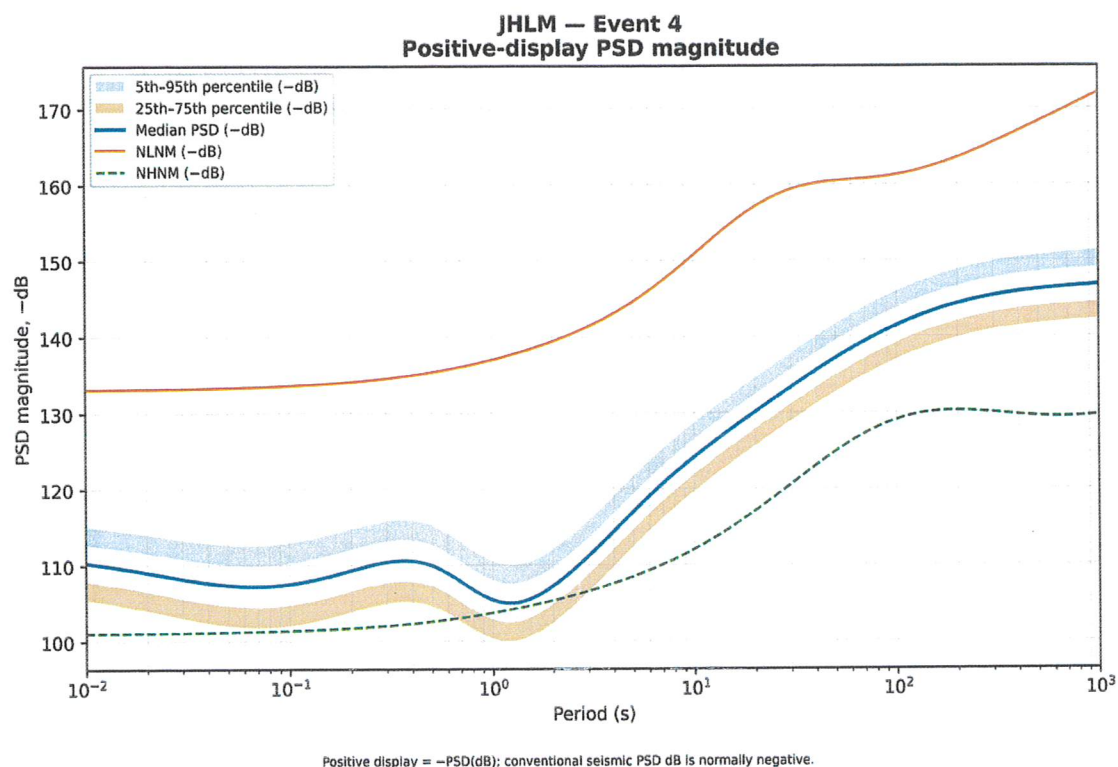


Figure 4. 5 Jhelum (JHLM), Event 4, power spectral density.

This is the second strongest Jhelum record, peaking at 105.0 -dB at 1.22 s (0.82 Hz), 6.0 dB above the station average in power. The peak is broad, exceeding the 1 s level by 0.4 dB and the 0.1 s level by 2.5 dB. Event 4 also produced one of the larger Jhelum travel-time residuals at 27.92 s. High recorded power at this station did not correspond to a well-picked arrival, which argues against the assumption that stronger records automatically yield better phase picks.

Event 5

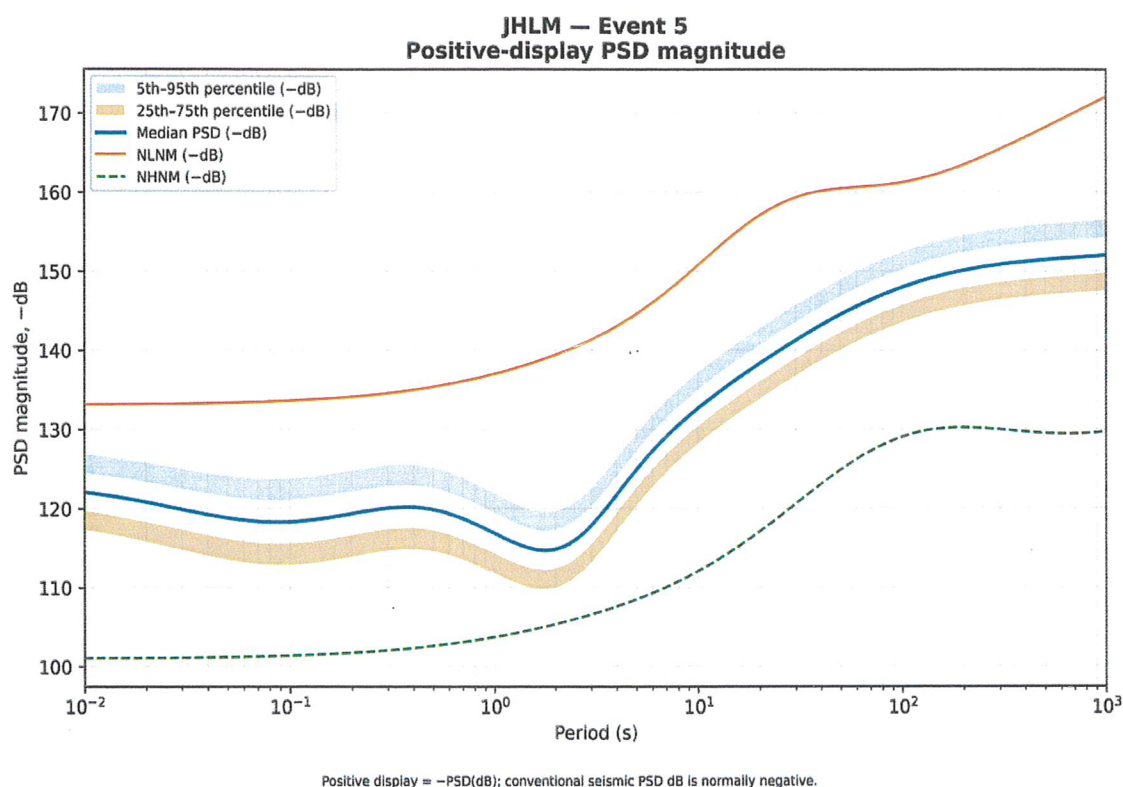


Figure 4. 6 Jhelum (JHLM), Event 5, power spectral density.

Maximum power falls at 1.81 s (0.55 Hz), towards the long-period end of the intermediate band. The peak level of 114.7 -dB is 3.7 dB below the station average in power. This is one of the weaker Jhelum records, despite an epicentral distance of only 230 km. The peak is nonetheless well defined, standing 2.2 dB above the 1 s level and 3.6 dB above the 0.1 s level. A nearby but weakly recorded event of this kind usually points to a small source magnitude rather than a propagation effect.

Event 6

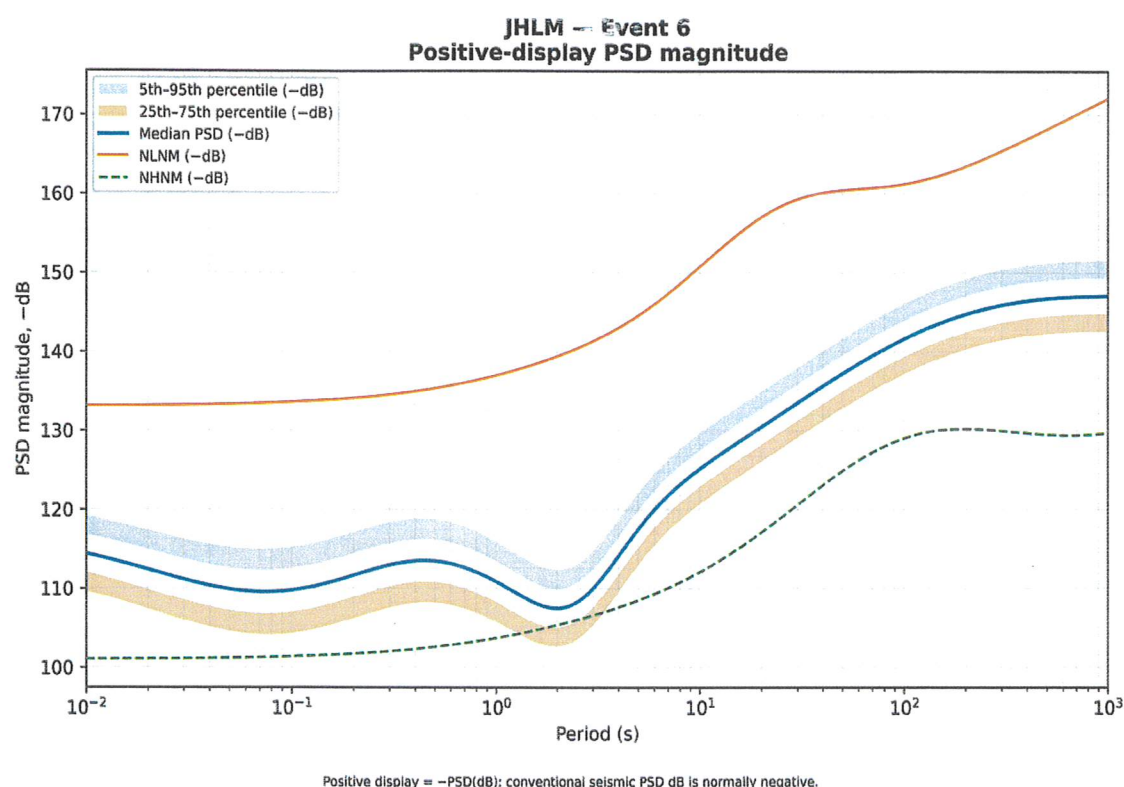


Figure 4. 7 Jhelum (JHLM), Event 6, power spectral density.

This record has the most sharply defined peak in the Jhelum set, standing 3.4 dB above the 1 s level. The maximum occurs at 1.98 s (0.50 Hz), the longest peak period recorded at Jhelum and at the boundary of the intermediate band, and at 107.5 -dB the record is 3.5 dB stronger than the station average. A well-developed narrow maximum near 2 s is the signature usually associated with resonance in a thick, low-velocity sedimentary column. This should be checked against the site description given for Jhelum in Chapter 3.

Event 6

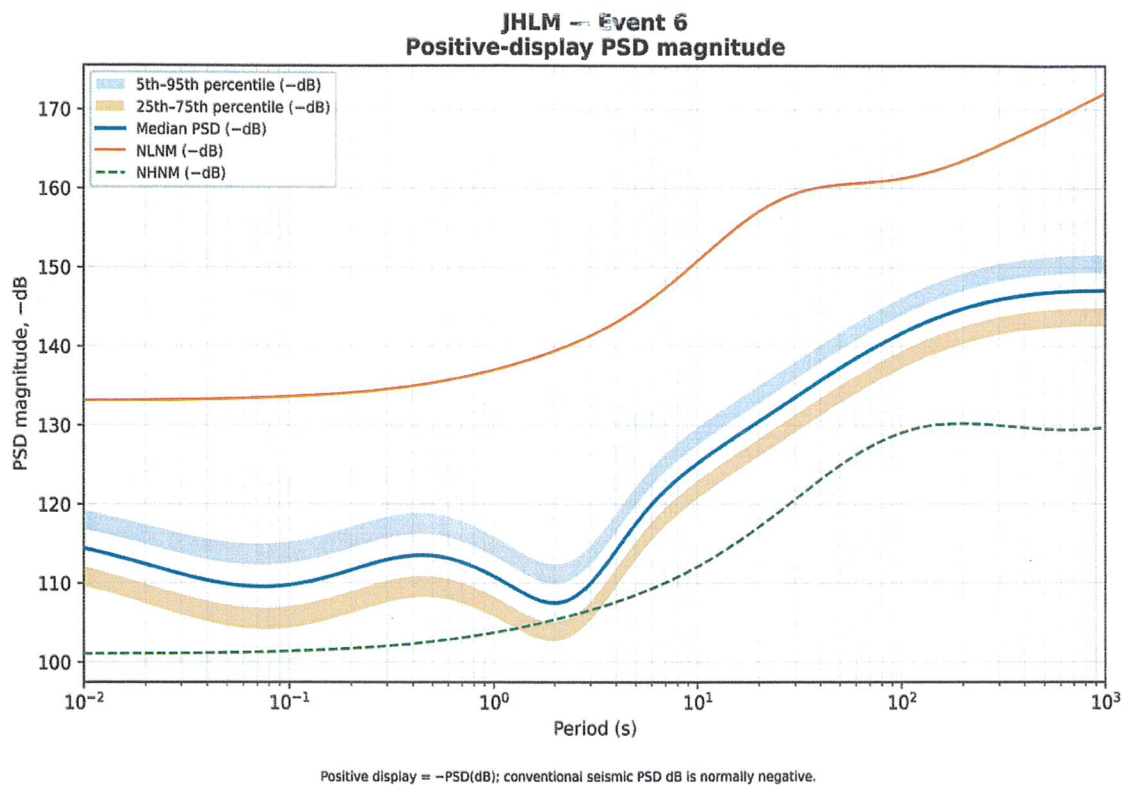


Figure 4. 7 Jhelum (JHLM), Event 6, power spectral density.

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Event 7

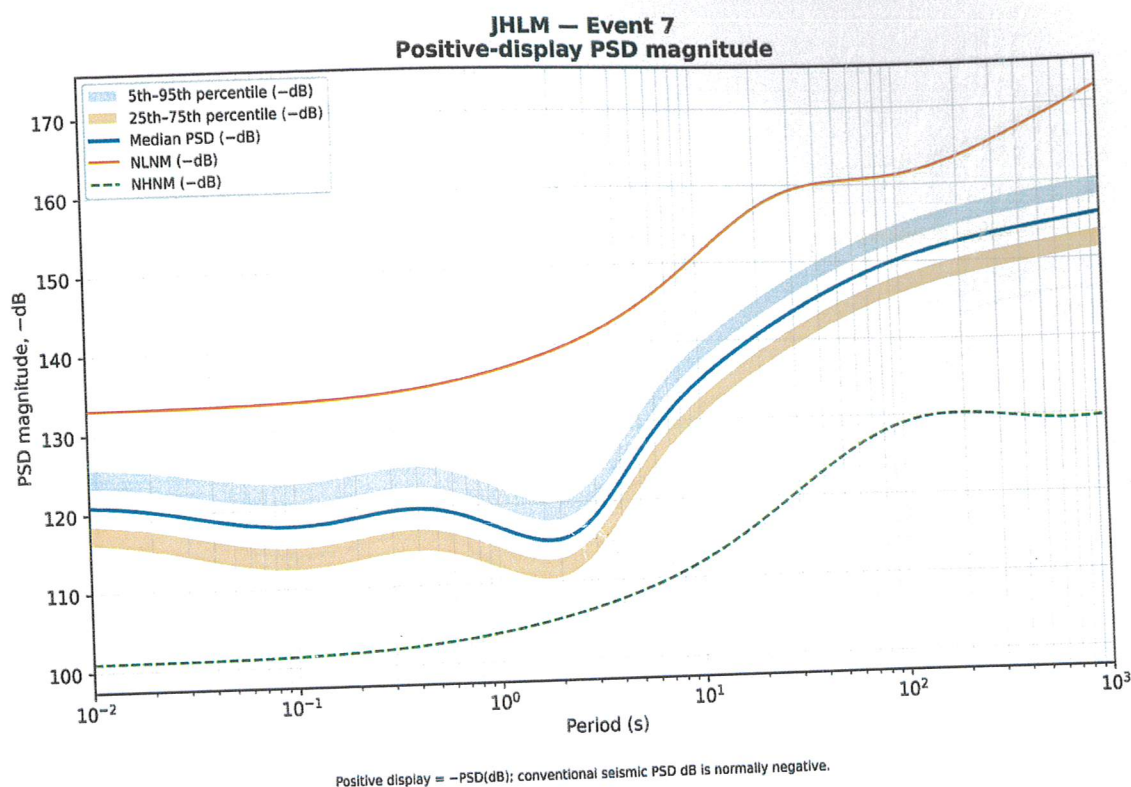


Figure 4. 8 Jhelum (JHLM), Event 7, power spectral density.

Peak power is at 1.81 s (0.55 Hz), identical to Event 5, but the level of 115.2 -dB makes this the second weakest Jhelum record. The two events lie at very different distances, 230 km for Event 5 and 1046 km for Event 7. The same peak period recurring across that gap is the clearest single indication in the Jhelum set that the site controls the peak period, not the source or the path. The peak stands 1.9 dB above the 1 s level, so it remains identifiable despite the low overall power.

Event 8

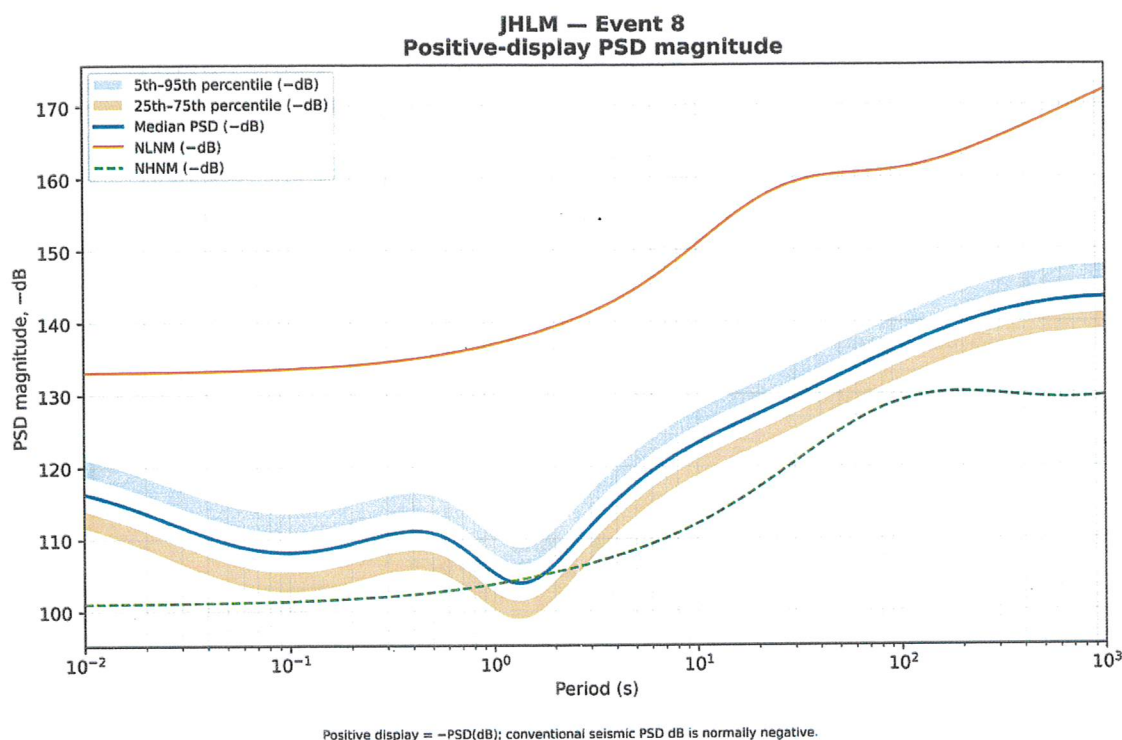


Figure 4.9 Jhelum (JHLM). Event 8, power spectral density.

This is the strongest Jhelum record, peaking at 103.9 $-dB$ at 1.33 s (0.75 Hz), 7.1 dB above the station average in power. It comes from the most distant event in the catalogue, at 1291 km, which indicates a large source whose radiated energy more than compensates for geometrical spreading and attenuation. Event 8 also produced the largest Jhelum travel-time residual at 41.14 s. That reinforces the pattern seen for Event 4, recorded power and pick quality are not related in a simple way at this station.

4.6.3 Lahore (LHR)

Lahore has a mean peak level of 108.8 $-dB$ and contains both the strongest record in the study, Event 2 at 99.9 $-dB$, and two records for which no reliable peak period can be read. Six of the eight events peak between 0.97 and 1.74 s. The remaining two return a value at the short-period band edge and are discussed as unresolved cases below.

Event	Peak PSD ($-dB$)	Peak period (s)	Peak frequency (Hz)	PSD @ 0.1 s ($-dB$)	PSD @ 1 s ($-dB$)	PSD @ 10 s ($-dB$)
1	110.2	0.97	1.03	113.8	110.3	132.6

2	99.9	1.02	0.98	104.1	99.9	124.3
3	113.3	1.59	0.63	117.7	115.5	135.0
4	113.2	1.59	0.63	113.7	115.3	131.4
5	109.7	1.74	0.58	113.5	112.1	127.0
6	109.3	0.10	10.36	109.3	109.7	126.1
7	104.0	1.39	0.72	109.6	105.8	128.4
8	110.9	0.09	11.33	111.0	111.4	128.5

Table 4. 6 Power spectral density parameters for Lahore (LHR) across the eight events. Values are $-PSD$ in dB, so lower numbers indicate greater spectral power.

Event 1

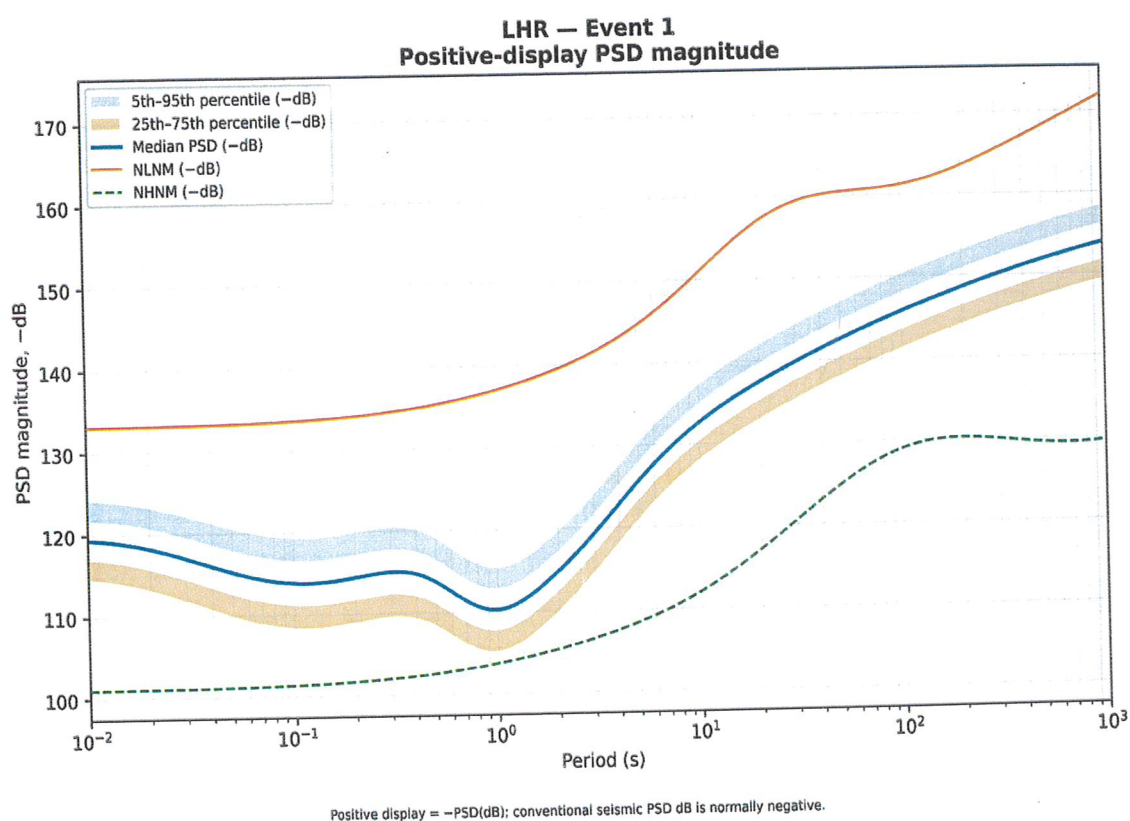


Figure 4. 10 Lahore (LHR), Event 1, power spectral density.

Maximum power occurs at 0.97 s (1.03 Hz), at the boundary between the intermediate and high-frequency bands. The level of 110.2 $-dB$ is 1.4 dB below the Lahore average in power. The peak exceeds the 1 s value by only 0.1 dB, so the spectrum is flat across the 1 s region and the picked period carries little precision. The fall of 22.4 dB from the peak to 10

s is the second largest at Lahore and describes a spectrum concentrated in the short- and intermediate-period range with very little long-period content.

Event 2

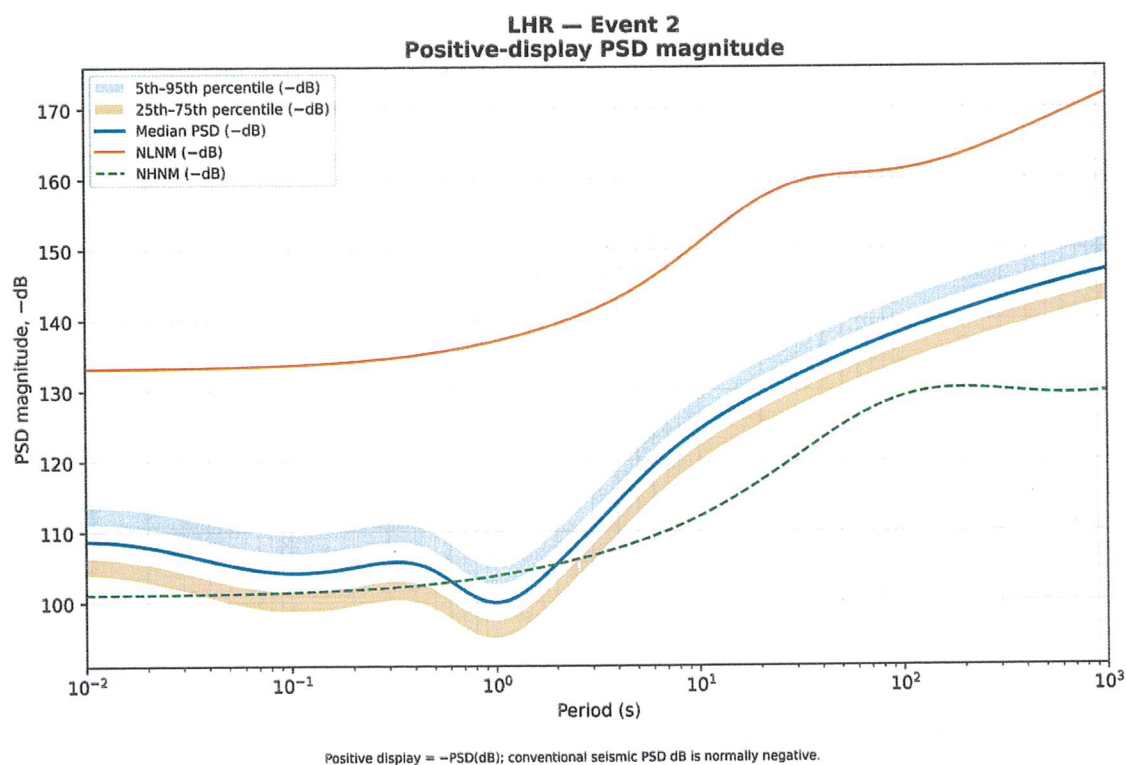


Figure 4. 11 Lahore (LHR). Event 2, power spectral density.

This is the strongest single record in the entire dataset, reaching 99.9 -dB at 1.02 s (0.98 Hz), and the only record anywhere in the study to fall below 100 -dB. It sits 8.9 dB above the Lahore average in power. Event 2 also produced the smallest Lahore travel-time residual at 4.74 s, the clearest case in the chapter of a strong record coinciding with an accurate arrival-time pick. The peak level equals the 1 s level exactly, so the maximum is broad rather than sharp, and the 24.4 dB fall to 10 s is the largest at this station.

Event 3

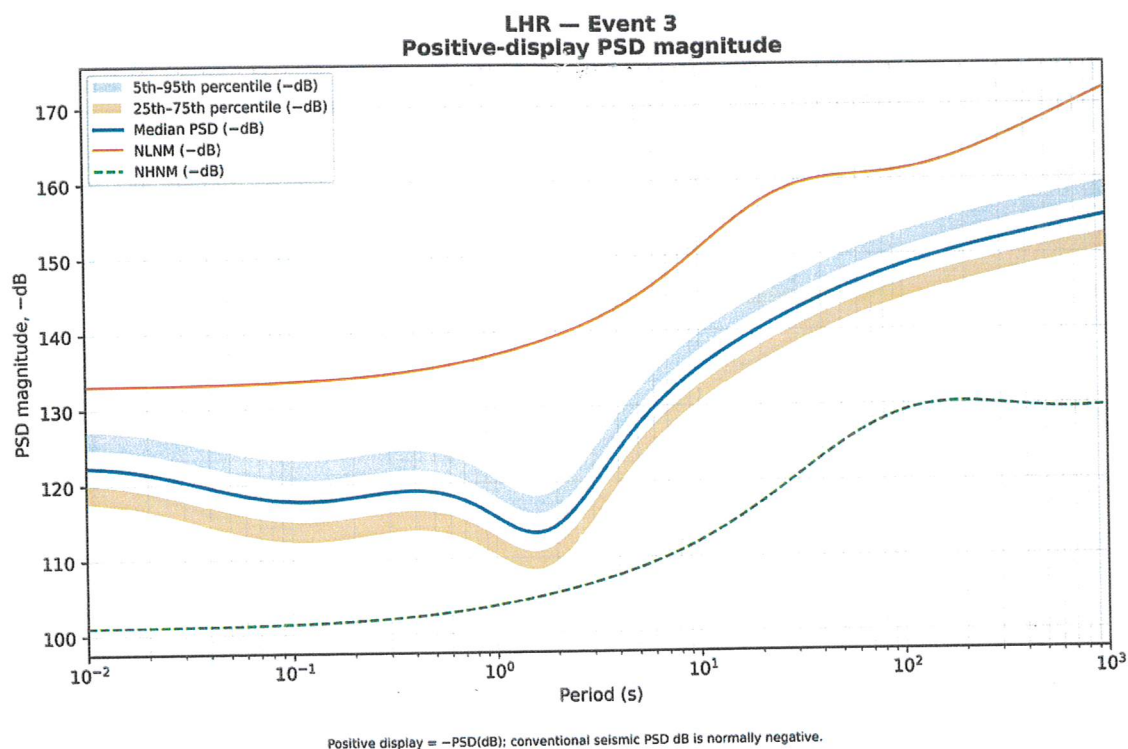


Figure 4. 12 Lahore (LHR), Event 3, power spectral density.

At 113.3 -dB this is the weakest of the eight Lahore records, 4.5 dB below the station average in power, with the peak at 1.59 s (0.63 Hz). Despite the low level the peak is well defined, standing 2.2 dB above the 1 s value and 4.4 dB above the 0.1 s value. Event 3 also gave a high Lahore residual of 30.13 s. Weakly recorded and poorly picked, then, at this station.

Event 4

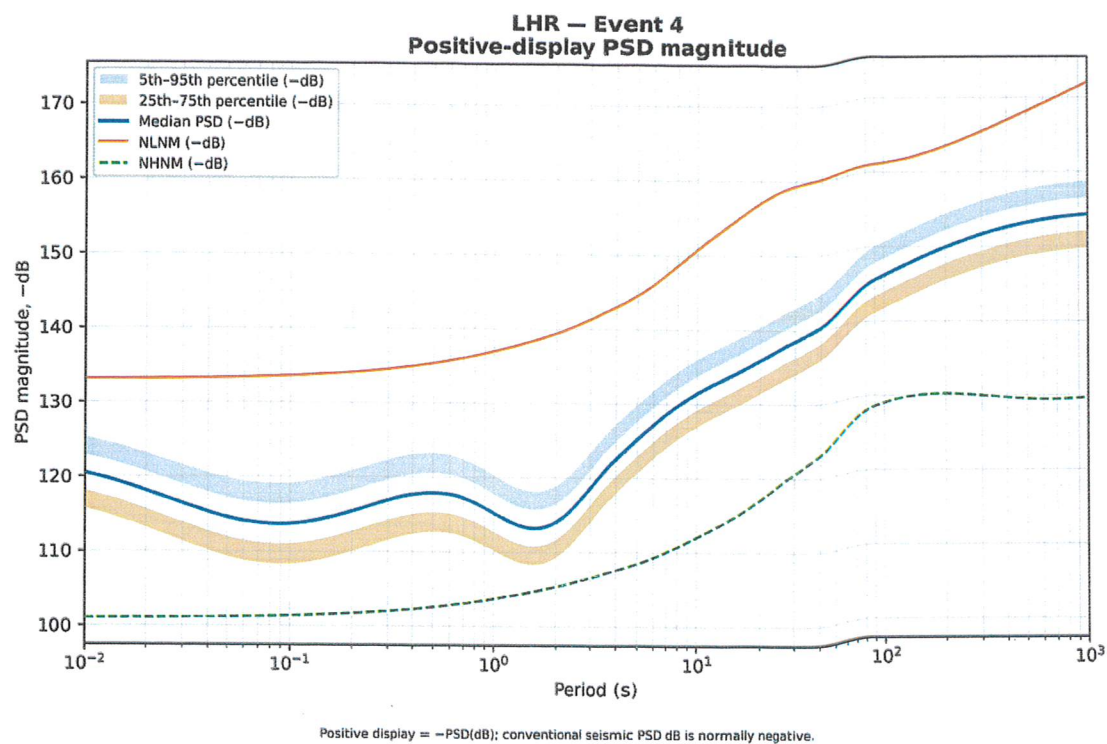


Figure 4. 13 Lahore (LHR), Event 4, power spectral density.

The maximum is at 1.59 s (0.63 Hz), the same period as Event 3, and the level of 113.2 -dB is within 0.1 dB of it. The two events lie at comparable epicentral distances of 620 km and 688 km, which accounts for the near-identical spectra. What distinguishes this record is its short-period content. The 0.1 s level is only 0.5 dB below the peak, against 4.4 dB for Event 3, so this spectrum is much flatter at high frequency.

Event 5

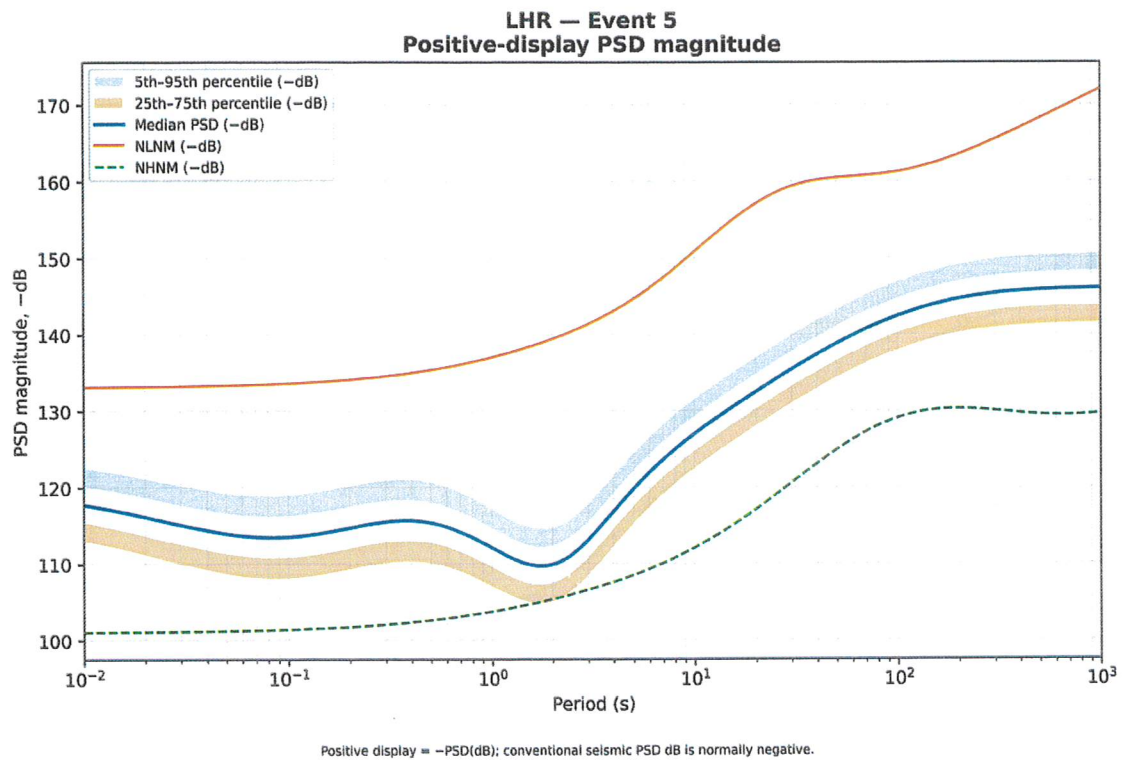


Figure 4. 14 Lahore (LHR), Event 5, power spectral density.

In relative terms this record has the most prominent peak at the station, standing 2.4 dB above the 1 s level and 3.8 dB above the 0.1 s level. Maximum power occurs at 1.74 s (0.58 Hz) at 109.7 -dB, close to the Lahore average. The 17.3 dB fall to 10 s is the second smallest at Lahore, so the spectrum retains comparatively more long-period energy than the other records here.

Event 6

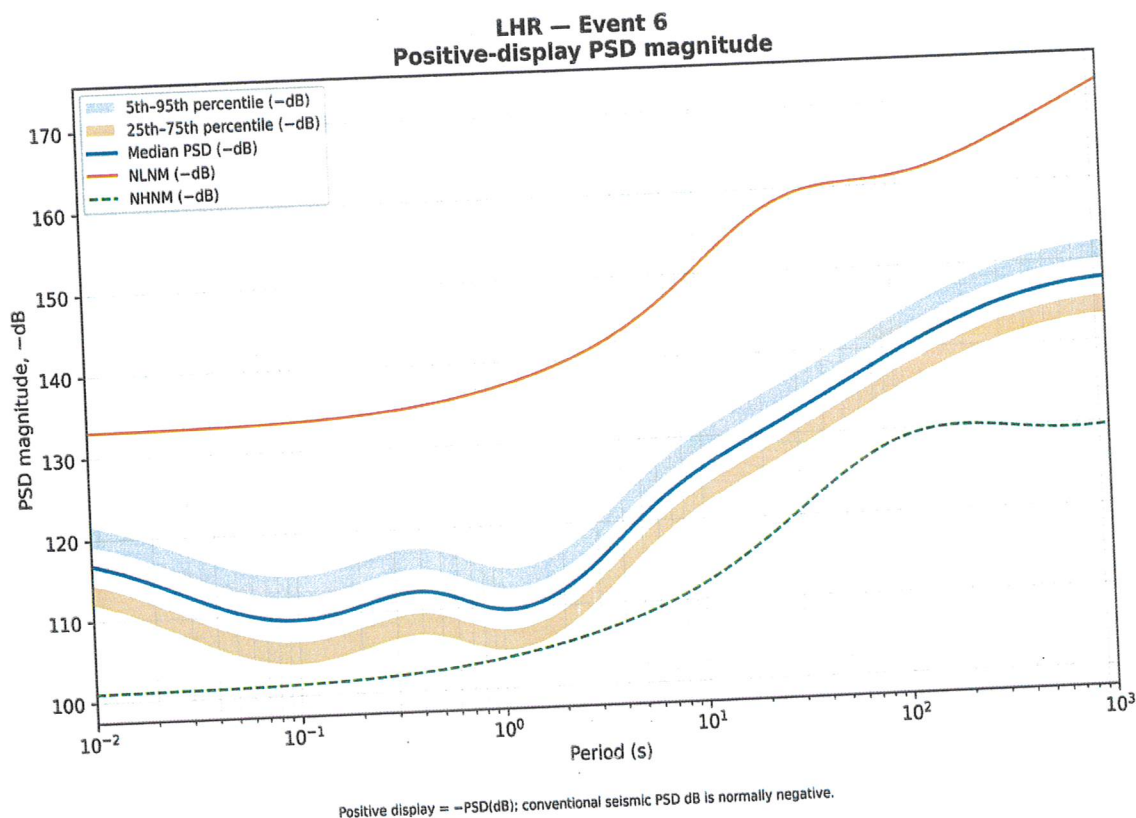


Figure 4. 15 Lahore (LHR). Event 6, power spectral density.

The automated peak search returns 0.10 s (10.36 Hz) at 109.3 -dB, placing the maximum in the high-frequency band instead of near 1.5 s as in the other Lahore records. This value needs qualification. The peak level equals the 0.1 s reference level and is only 0.4 dB stronger than the 1 s level, so the spectrum is essentially flat from 0.1 to 1 s with no dominant feature. The picked period sits at the short-period edge of the analysis band, which means the algorithm has selected the endpoint of a nearly flat curve rather than a genuine resonance. This record is best described as having no resolved spectral peak.

Event 7

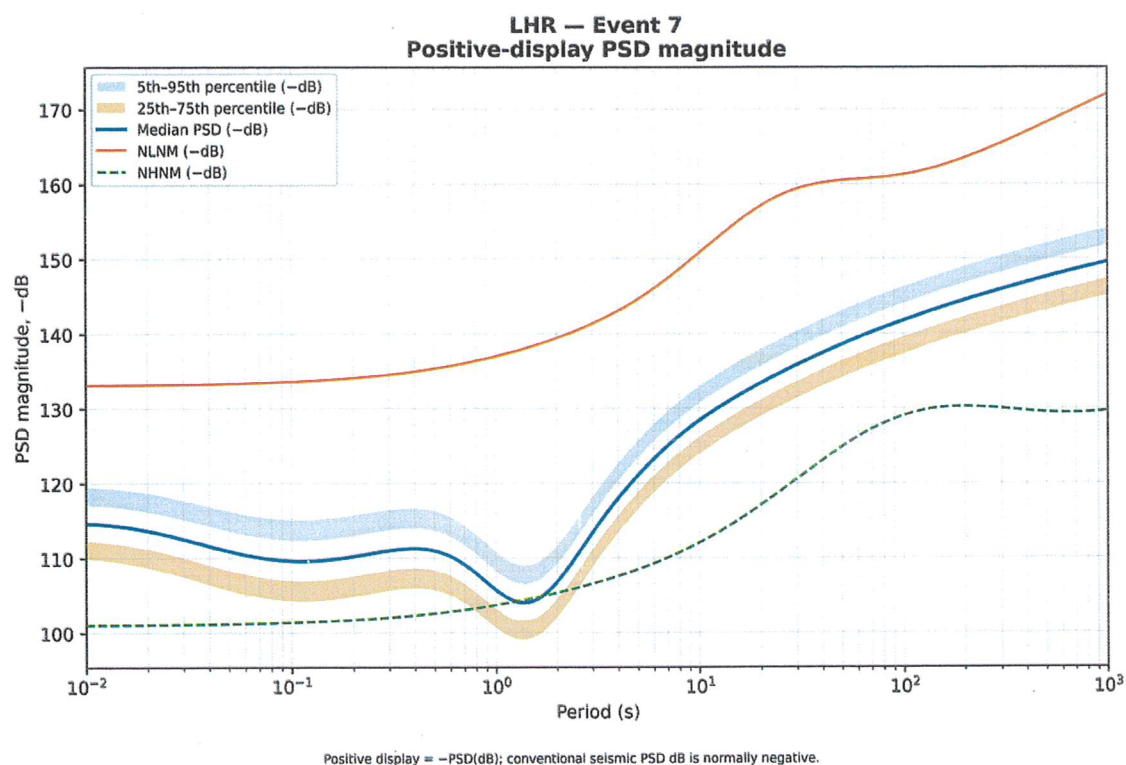


Figure 4. 16 Lahore (LHR), Event 7, power spectral density.

Peak power is at 1.39 s (0.72 Hz) and reaches 104.0 -dB, the second strongest Lahore record and 4.8 dB above the station average. The peak is 5.6 dB stronger than the 0.1 s level, the largest short-period contrast at Lahore, so high-frequency energy is strongly suppressed relative to the maximum. That is what would be expected for a source 1024 km away, where anelastic attenuation removes high-frequency content along the path.

Event 8

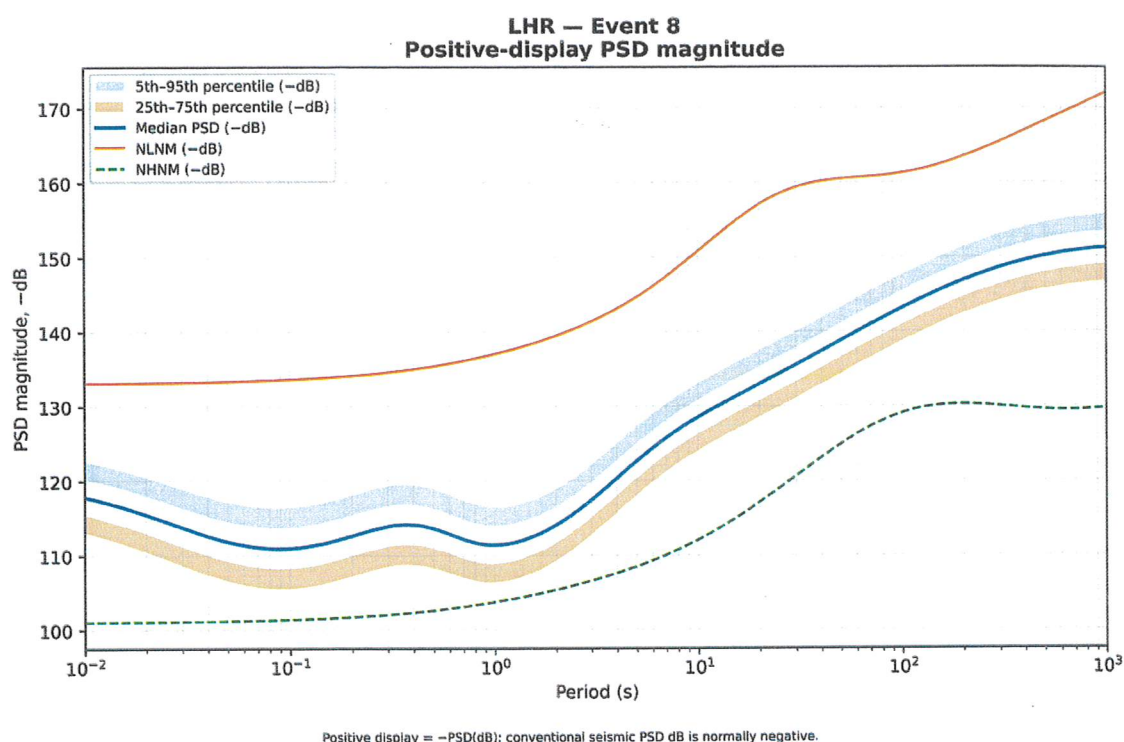


Figure 4. 17 Lahore (LHR), Event 8, power spectral density.

As with Event 6, the reported maximum at 0.09 s (11.33 Hz) sits at the short-period edge of the analysis band and is only 0.1 dB stronger than the 0.1 s level and 0.5 dB stronger than the 1 s level. The spectrum is flat rather than peaked, and the picked period should not be read as a site frequency. That matters because Event 8 produced the largest travel-time residual in the whole dataset at this station. 58.15 s. A featureless spectrum offers no independent evidence of a clear arriving phase that would support a confident pick.

4.6.4 Islamabad (ISB)

Islamabad has a mean peak level of 108.8 -dB, matching Lahore, but with a slightly narrower spread of 4.3 dB. Seven of eight records peak between 0.93 and 1.98 s. The eighth, Event 4, returns a short-period value and is treated below as a bimodal spectrum rather than a single peak.

Event	Peak PSD (-dB)	Peak period (s)	Peak frequency (Hz)	PSD @ 0.1 s (-dB)	PSD @ 1 s (-dB)	PSD @ 10 s (-dB)
1	115.0	1.33	0.75	117.3	115.8	131.7

2	106.6	0.97	1.03	108.8	106.6	126.5
3	108.6	0.93	1.07	114.8	108.7	129.9
4	107.3	0.08	12.38	107.5	111.2	127.8
5	106.1	1.74	0.58	106.8	107.5	124.5
6	110.0	1.33	0.75	112.7	111.3	129.9
7	114.3	1.98	0.50	116.7	117.7	131.4
8	102.3	1.33	0.75	108.9	103.7	125.8

Table 4. 7 Power spectral density parameters for Islamabad (ISB) across the eight events. Values are $-PSD$ in dB, so lower numbers indicate greater spectral power.

Event 1

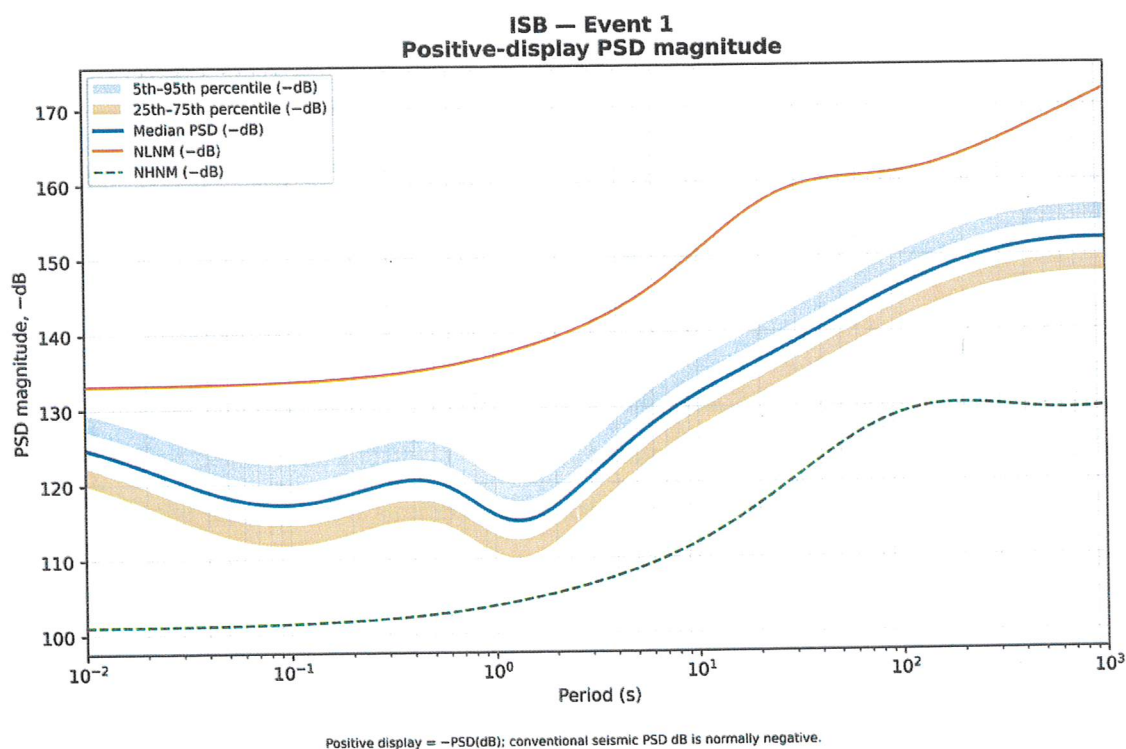


Figure 4. 18 Islamabad (ISB), Event 1, power spectral density.

Maximum power falls at 1.33 s (0.75 Hz) at 115.0 $-dB$, the weakest of the eight Islamabad records and 6.2 dB below the station average in power. This is also the closest event in the entire study, at 114.8 km, and the weakest record coming from the closest event strongly suggests a small magnitude for Event 1. Islamabad nonetheless produced its second-lowest travel-time residual for this event at 4.47 s. A low-power record was still picked accurately here.

Event 2

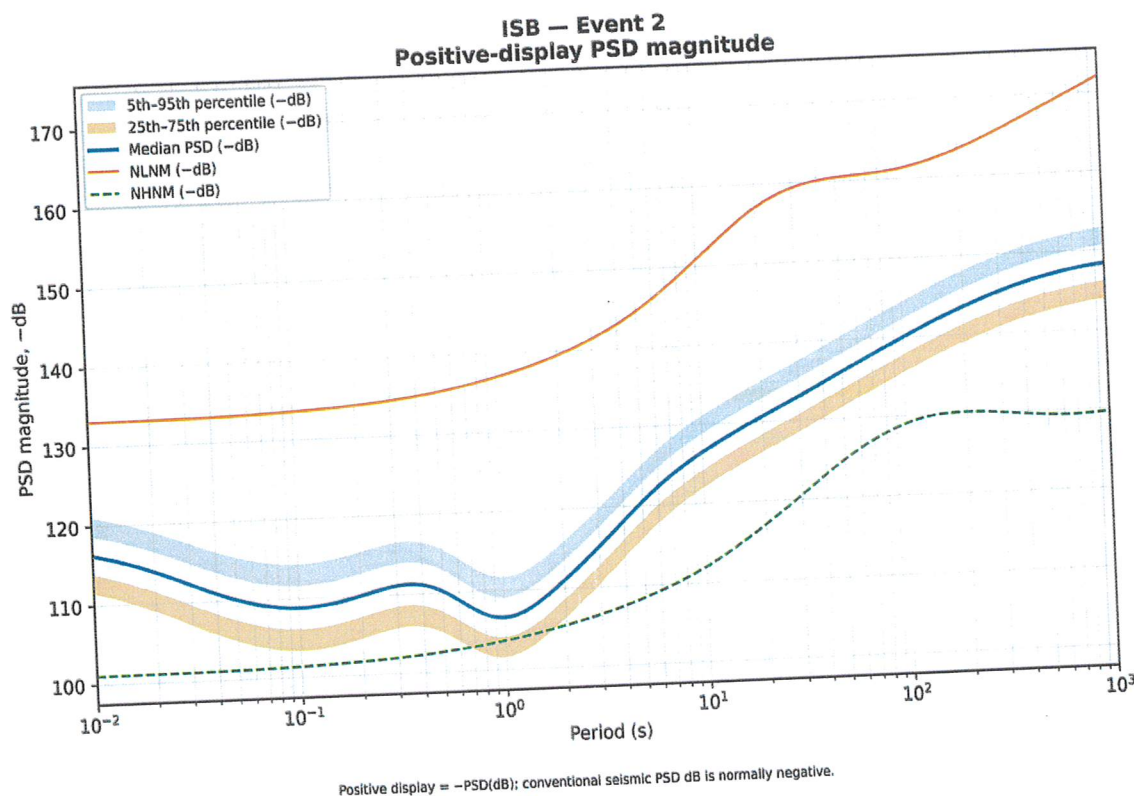


Figure 4. 19 Islamabad (ISB), Event 2, power spectral density.

The maximum is at 0.97 s (1.03 Hz) at 106.6 -dB, 2.2 dB above the station average in power. The peak level and the 1 s level are identical to the reported precision, so the spectrum is flat through the 1 s region. Islamabad recorded a comparatively large residual of 23.13 s for this event, in contrast to the well-picked nearby Event 1. The difficulty lies with the arrival itself rather than with signal strength.

Event 3

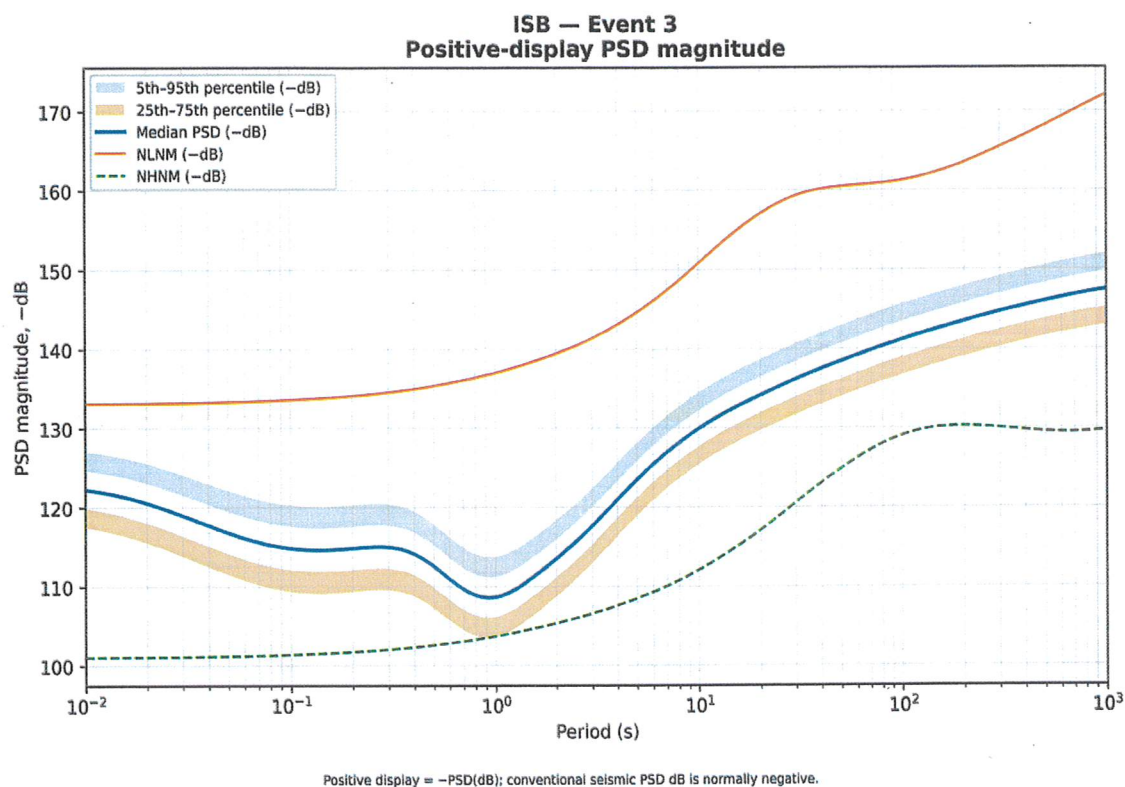


Figure 4. 20 Islamabad (ISB), Event 3, power spectral density.

Peak power is at 0.93 s (1.07 Hz), the shortest well-resolved peak period at Islamabad, and the level of 108.6 -dB is close to the station average. The peak is 6.2 dB stronger than the 0.1 s level, the largest short-period contrast at this station. High-frequency energy is pronouncedly suppressed. A 688 km propagation path accounts for that pattern without any site explanation.

Event 4

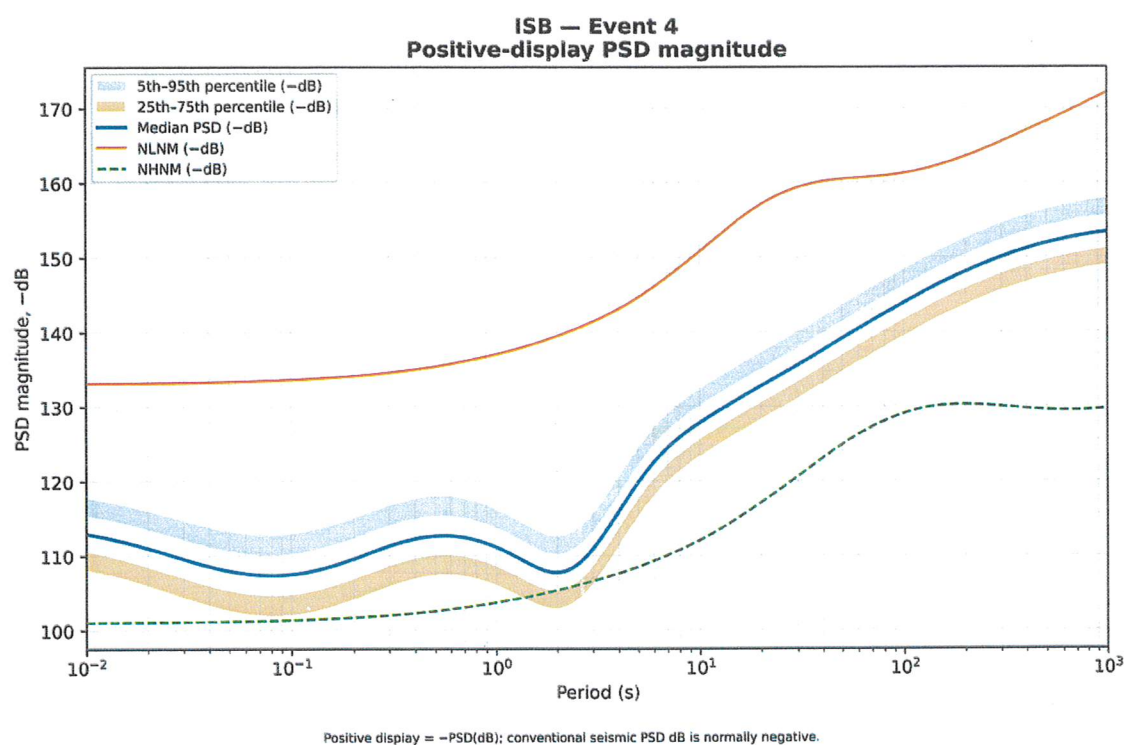


Figure 4. 21: Islamabad (ISB). Event 4, power spectral density.

The reported maximum at 0.08 s (12.38 Hz) requires qualification. The curve shows two power maxima of almost equal strength, one near 0.08 s and a second near 2 s with the short-period lobe deeper by only a fraction of a decibel. The automated search returned the short-period value, but the 2 s feature is the same one seen in every other Islamabad record and is the physically meaningful site response. This record should be reported as bimodal, with a secondary maximum near 2 s. Event 4 also produced the largest Islamabad travel-time residual at 32.10 s, and substantial energy near 12 Hz alongside the long-period lobe fits a record carrying strong high-frequency noise that would complicate a P-phase pick.

Event 5

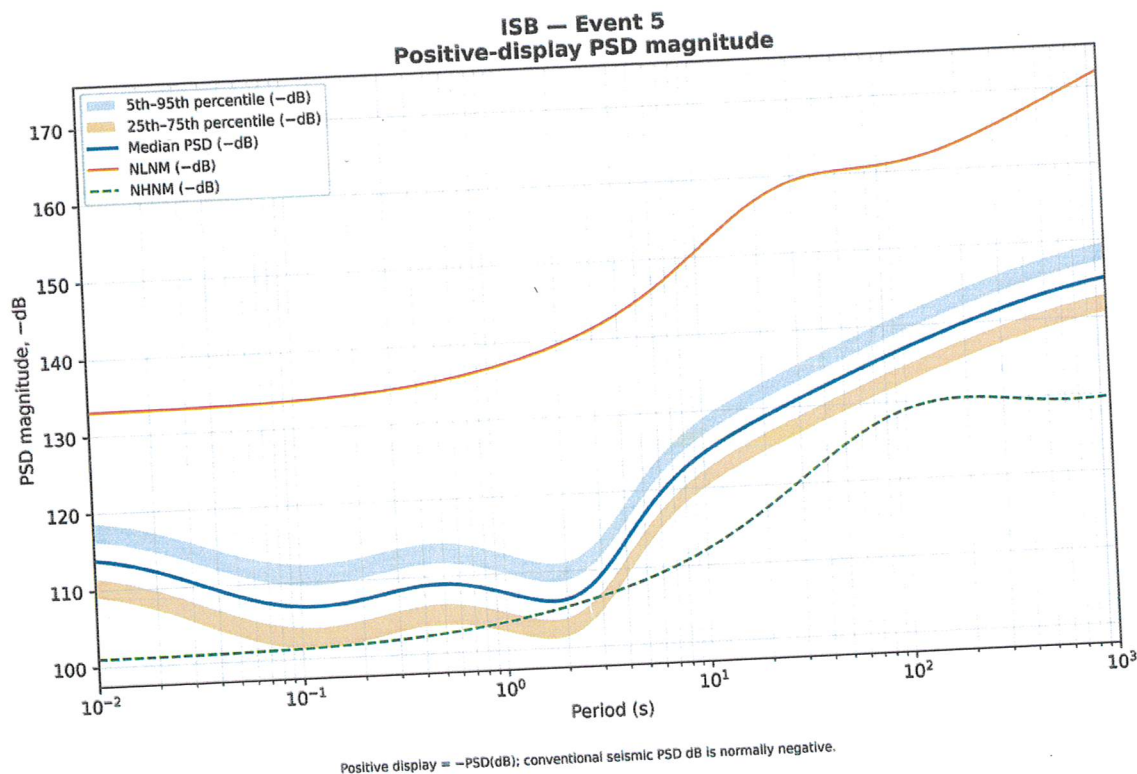


Figure 4. 22 Islamabad (ISB). Event 5, power spectral density.

Maximum power occurs at 1.74 s (0.58 Hz) at 106.1 -dB. the second strongest Islamabad record. The spectrum is unusually flat at short period: the 0.1 s level is only 0.7 dB below the peak, so appreciable energy persists to 10 Hz. That is expected for an event 136 km away, where high frequencies have not been substantially attenuated. Islamabad produced its second smallest residual for this event at 2.61 s, consistent with a strong, broadband, nearby record.

Event 6

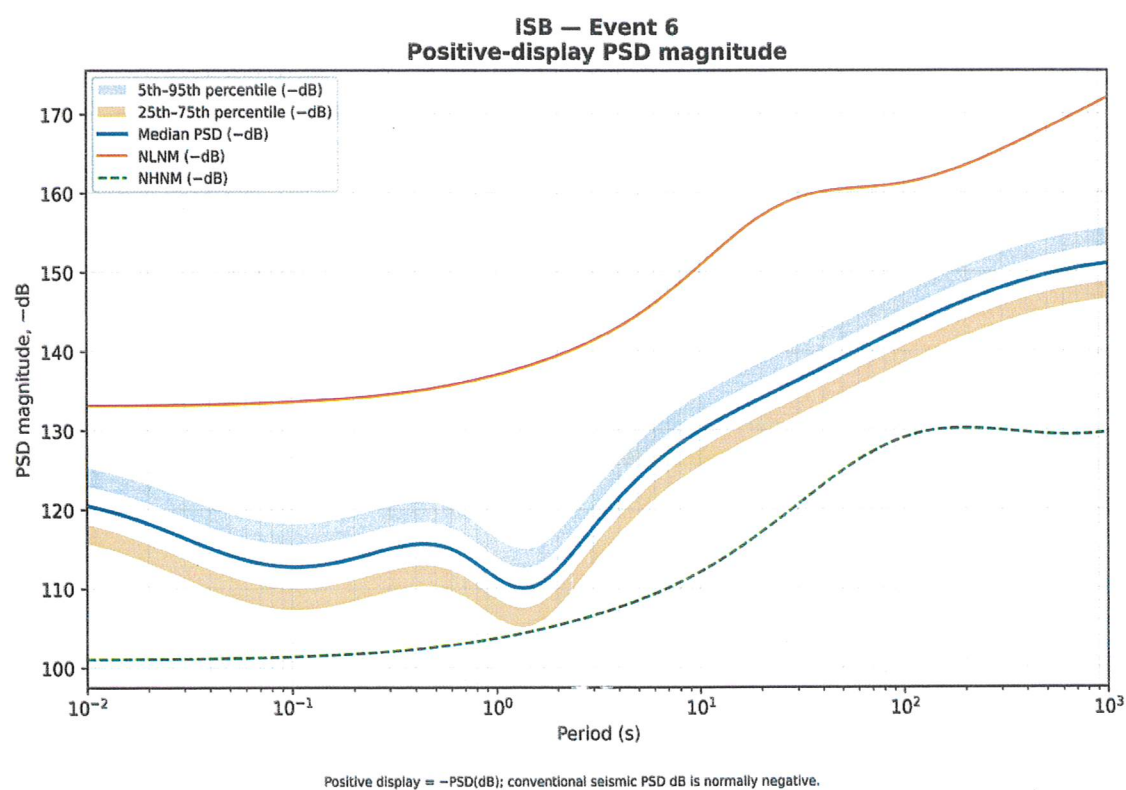


Figure 4. 23 Islamabad (ISB), Event 6, power spectral density.

The maximum is at 1.33 s (0.75 Hz) at 110.0 -dB, slightly below the Islamabad average in power. The peak period matches Events 1 and 8 exactly, and those three events span distances from 115 km to 1314 km. Recurrence of 1.33 s across that range is the main evidence at Islamabad that this period reflects the site rather than the source.

Event 7

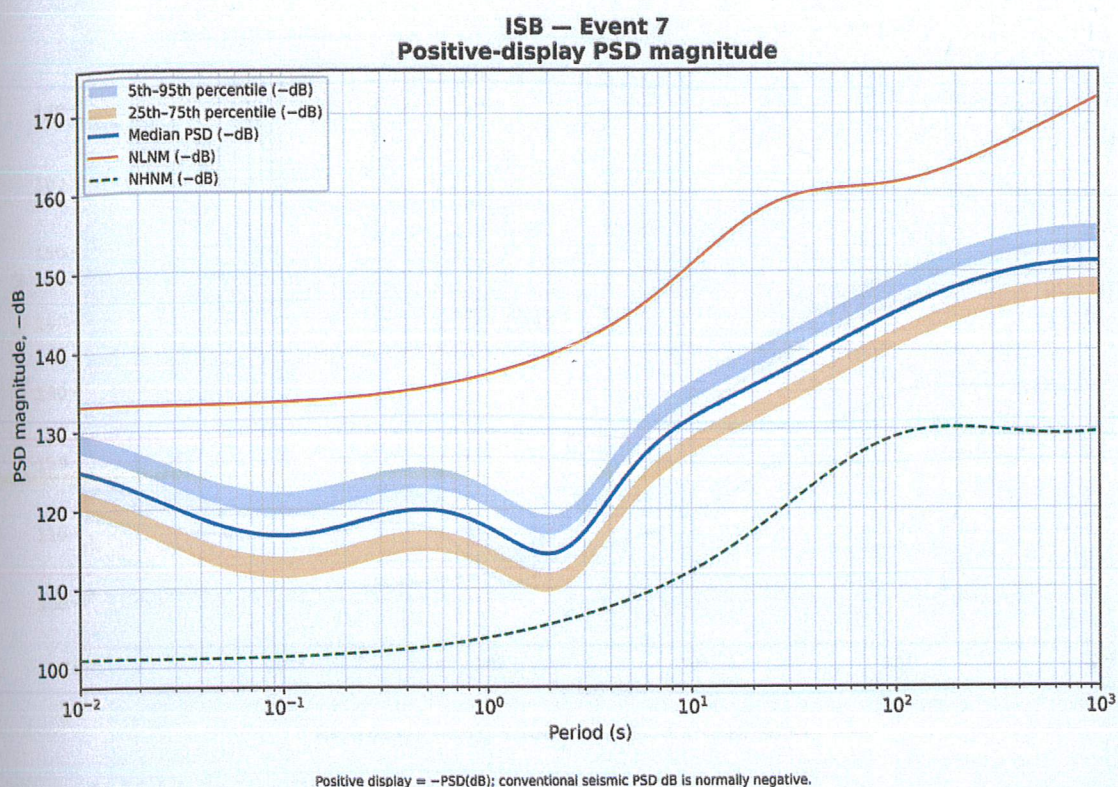


Figure 4. 24 Islamabad (ISB), Event 7, power spectral density.

Peak power falls at 1.98 s (0.50 Hz), the longest peak period at Islamabad, at a level of 114.3 -dB that is 5.5 dB below the station average. Despite the low power the peak is the most prominent at this station, standing 3.4 dB above the 1 s level. Islamabad recorded its smallest residual of the whole study for this event at 2.14 s. A clean, well-defined spectral peak can evidently accompany an accurate pick even when absolute power is low.

Event 8

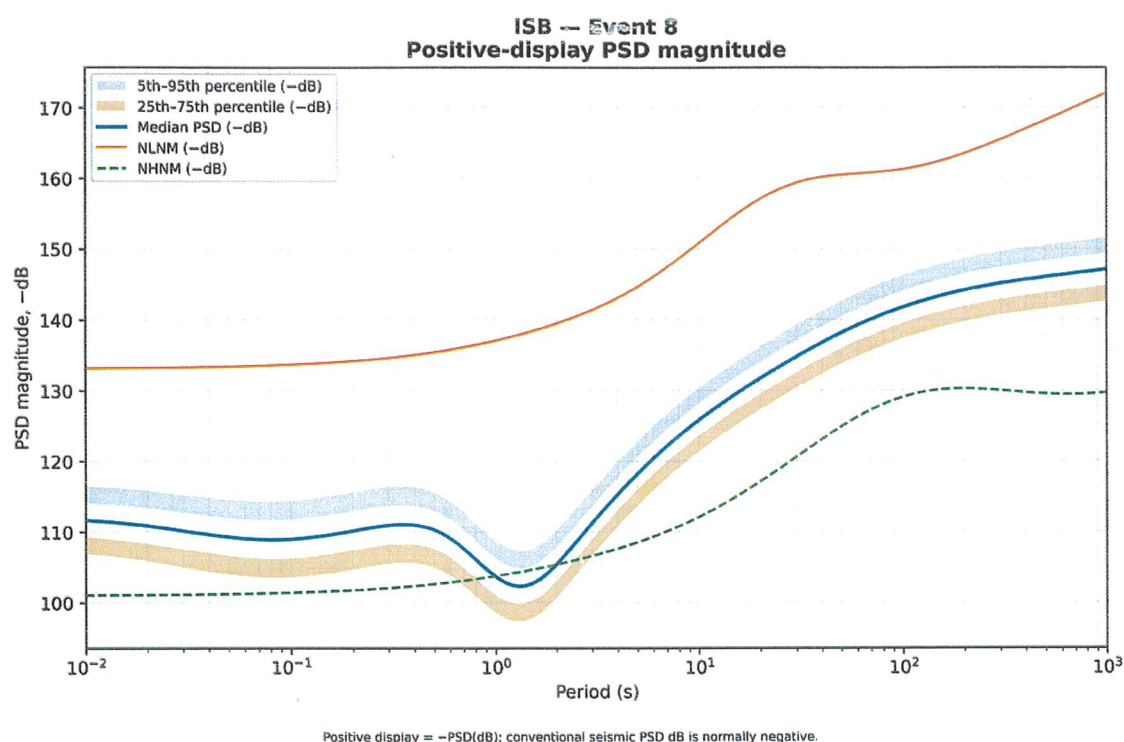


Figure 4.25 Islamabad (ISB), Event 8, power spectral density.

This is the strongest Islamabad record, reaching 102.3 $-\text{dB}$ at 1.33 s (0.75 Hz), 6.5 dB above the station average and second strongest in the entire study. It comes from the most distant event at 1314 km, which again points to a large source magnitude. The 6.6 dB contrast between the peak and the 0.1 s level is the largest at this station and reflects the loss of high-frequency energy over a long path. The 23.5 dB fall to 10 s is also the largest at Islamabad.

4.6.5 Peshawar (PSH)

Peshawar records the highest average power of the four stations at 107.2 $-\text{dB}$ and by far the narrowest spread at 2.2 dB, less than half that of Jhelum. Its spectra are the most reproducible in the study. Peshawar also carries the largest travel-time residuals. Seven of eight records peak between 1.06 and 1.90 s.

Event	Peak PSD ($-\text{dB}$)	Peak period (s)	Peak frequency (Hz)	PSD @ 0.1 s ($-\text{dB}$)	PSD @ 1 s ($-\text{dB}$)	PSD @ 10 s ($-\text{dB}$)
1	104.1	1.59	0.63	106.6	106.8	125.7
2	108.0	0.10	9.91	108.0	108.9	128.4

3	104.9	1.81	0.55	108.5	106.7	124.0
4	109.0	1.06	0.94	115.3	109.1	131.3
5	106.9	1.45	0.69	111.3	108.3	126.2
6	106.9	1.33	0.75	107.5	107.6	125.6
7	111.1	1.33	0.75	112.3	112.0	128.3
8	106.8	1.90	0.53	112.2	111.6	125.4

Table 4. 8 Power spectral density parameters for Peshawar (PSH) across the eight events. Values are $-PSD$ in dB, so lower numbers indicate greater spectral power.

Event 1

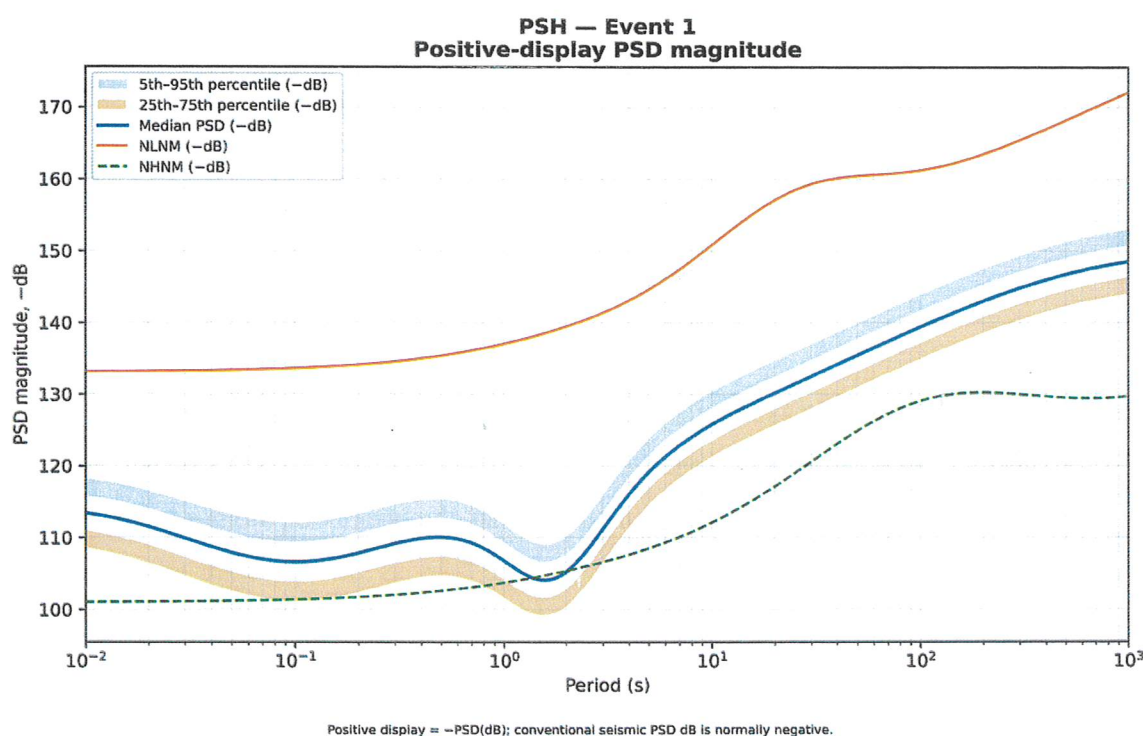


Figure 4. 26 Peshawar (PSH), Event 1, power spectral density.

This is the strongest Peshawar record, peaking at 104.1 $-dB$ at 1.59 s (0.63 Hz), 3.1 dB above the station average. The peak is also the second most prominent at this station, standing 2.7 dB above the 1 s level and 2.5 dB above the 0.1 s level, so the maximum is clearly resolved rather than a flat interval. At 186 km this is the second closest event to Peshawar. Short distance and high power together are straightforward to interpret.

Event 2

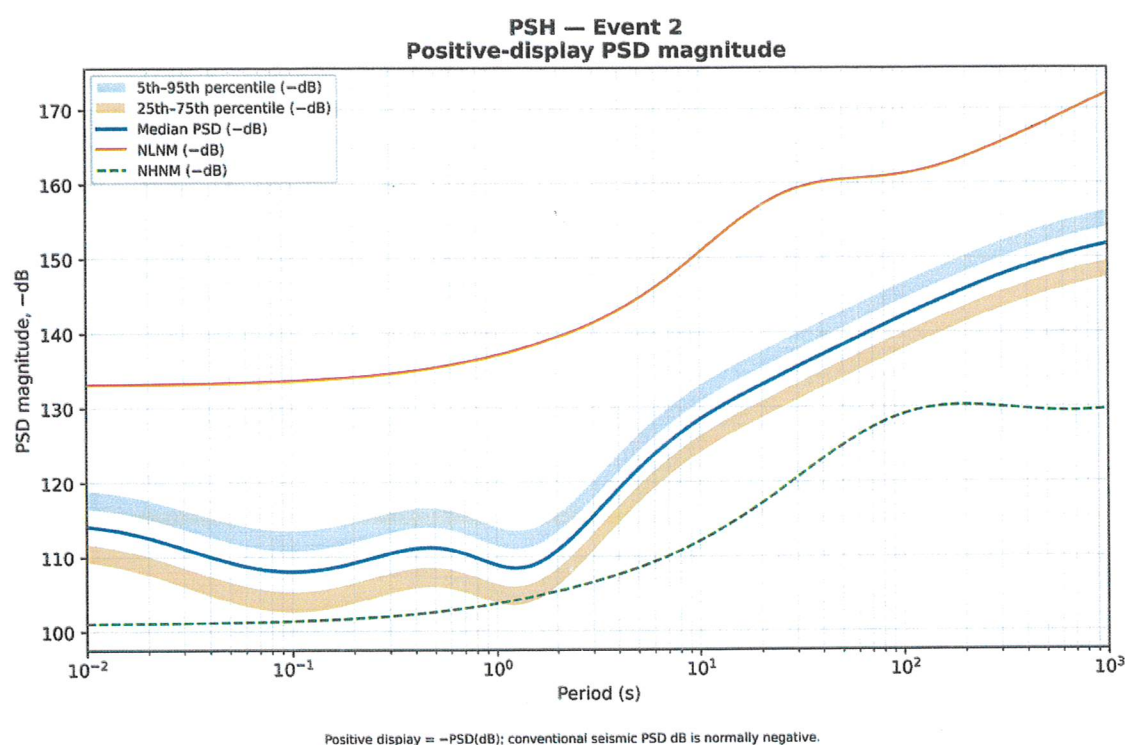


Figure 4. 27 Peshawar (PSH), Event 2, power spectral density.

The reported maximum at 0.10 s (9.91 Hz) coincides exactly with the 0.1 s reference level and exceeds the 1 s level by only 0.9 dB. As in the two Lahore cases, the peak search has returned the short-period end of a nearly flat curve rather than a resolved resonance, and no reliable site frequency can be read from this record. Peshawar produced a high residual of 27.50 s for Event 2, and a featureless spectrum gives no independent support for the reliability of that pick.

Event 3

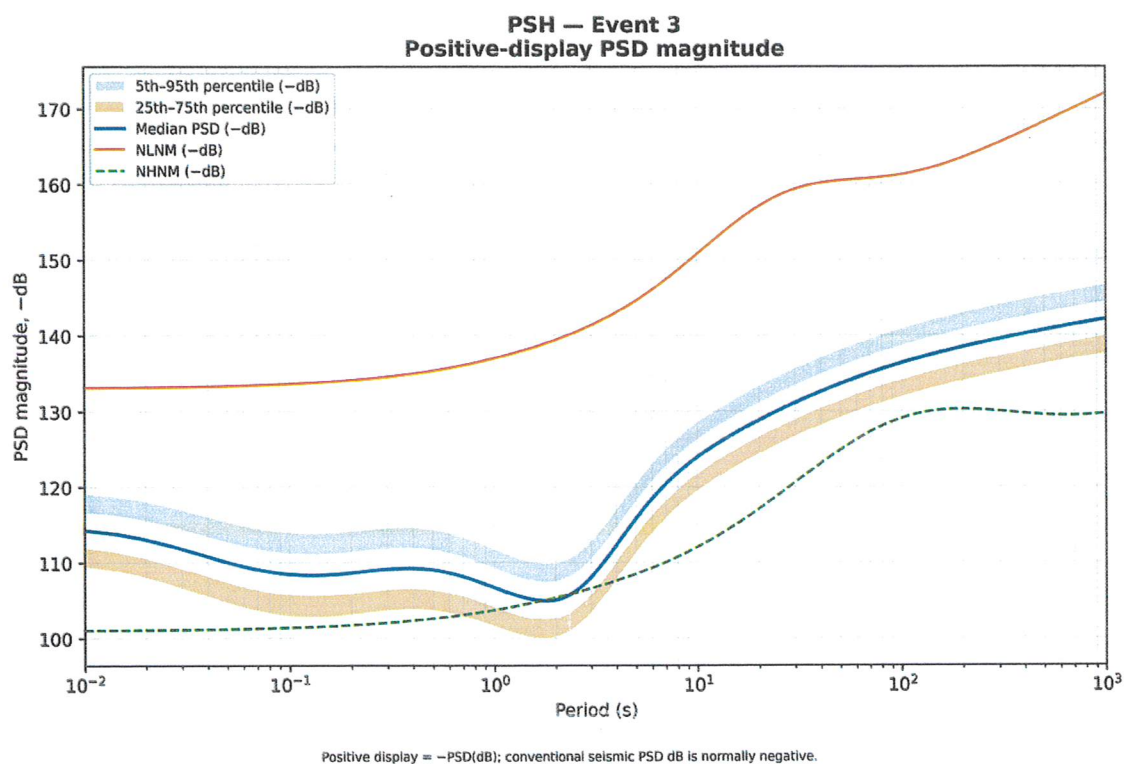


Figure 4. 28 Peshawar (PSH), Event 3, power spectral density.

Maximum power falls at 1.81 s (0.55 Hz) at 104.9 -dB, the second strongest Peshawar record. The peak stands 1.8 dB above the 1 s level and 3.6 dB above the 0.1 s level. Event 3 produced the largest Peshawar residual at 38.68 s, so this station again shows a strong record accompanied by a poor pick. The pattern recurs often enough at Peshawar that weak signal can be ruled out as the explanation for its residual performance.

Event 4

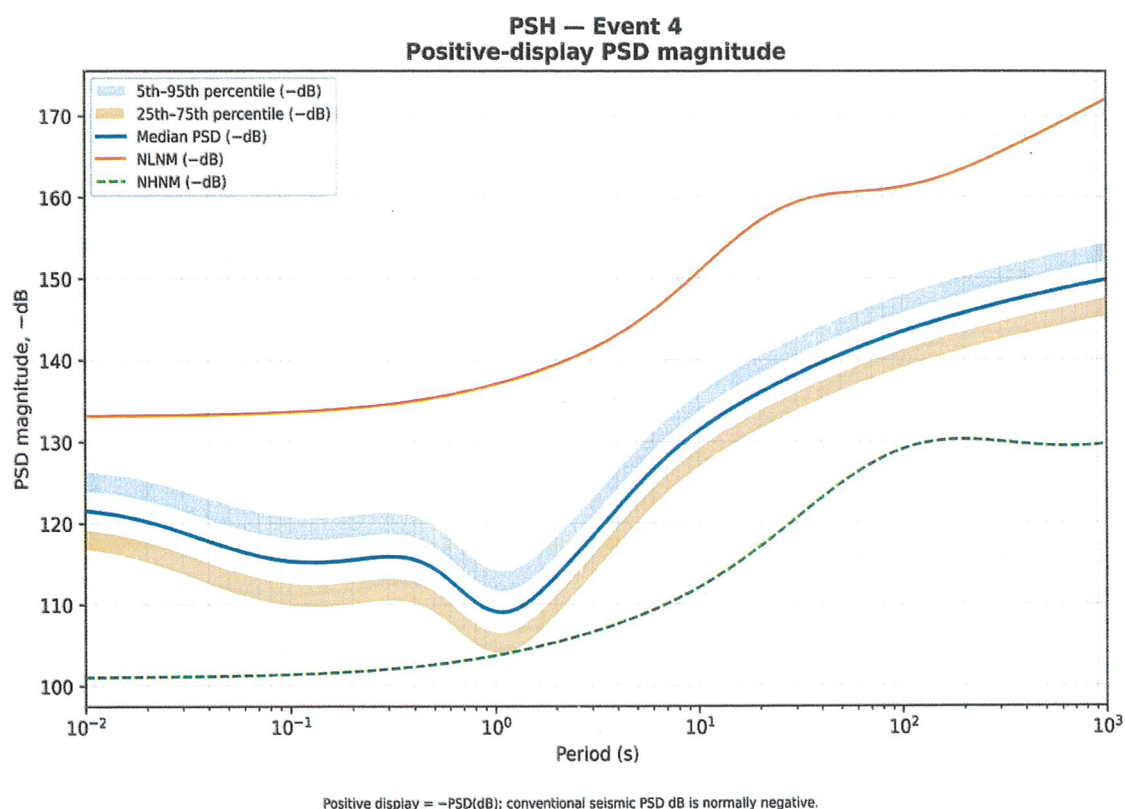


Figure 4. 29 Peshawar (PSH), Event 4, power spectral density.

Peak power is at 1.06 s (0.94 Hz) at 109.0 -dB, the second weakest Peshawar record. The peak is only 0.1 dB above the 1 s level, so the maximum is broad and the picked period is imprecise. The 6.3 dB contrast with the 0.1 s level is the largest at this station and is greater than a path of 274 km alone would produce. That raises the possibility of an instrument response or site effect suppressing high frequencies.

Event 5

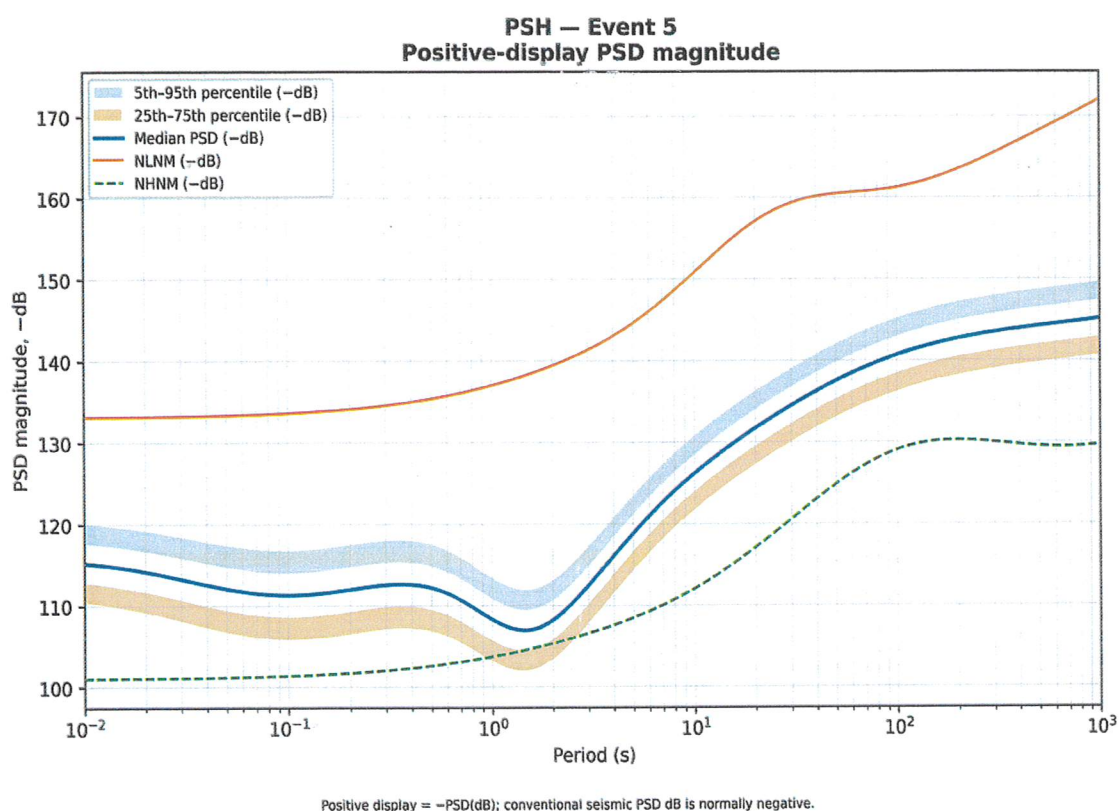


Figure 4. 30 Peshawar (PSH), Event 5, power spectral density.

The maximum occurs at 1.45 s (0.69 Hz) at 106.9 -dB, essentially at the Peshawar average. At 158 km this is the closest event to the station, yet the record is only average in power, which points to a modest source magnitude. The peak stands 1.4 dB above the 1 s level and 4.4 dB above the 0.1 s level.

Event 6

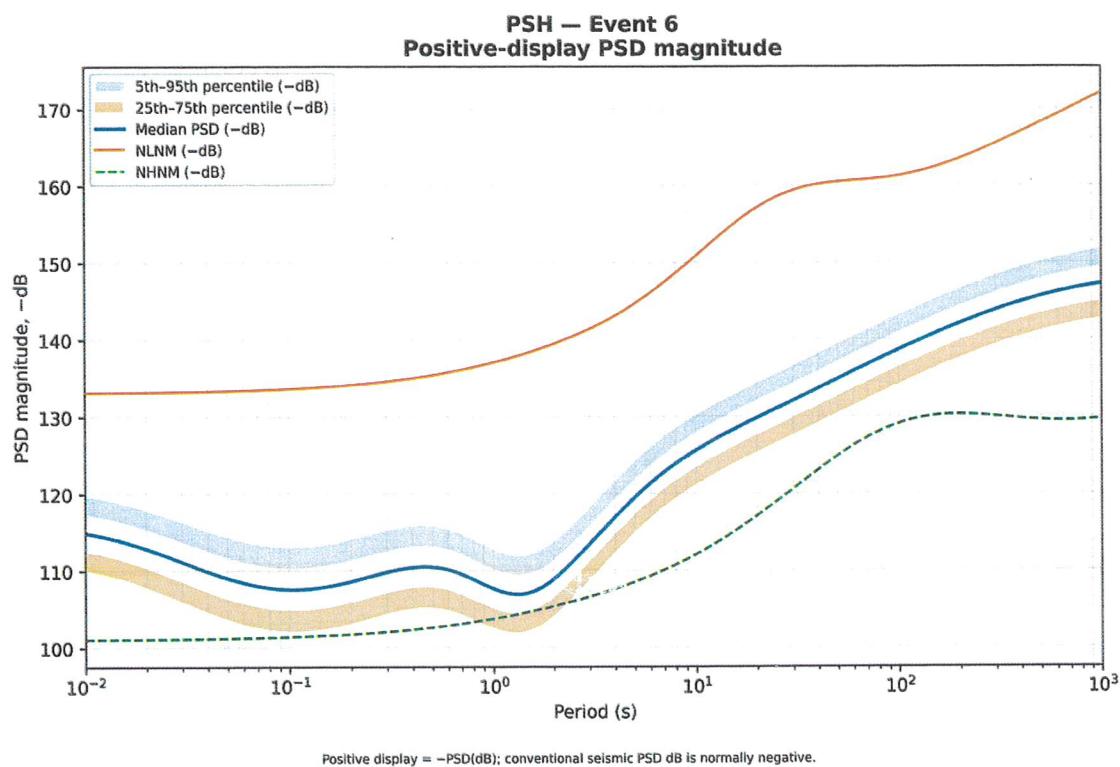


Figure 4. 31 Peshawar (PSH), Event 6, power spectral density.

Peak power is 106.9 -dB at 1.33 s (0.75 Hz), identical in level to Event 5. The spectrum is the flattest of the well-resolved Peshawar records, with the peak only 0.7 dB above the 1 s level and 0.6 dB above the 0.1 s level, so energy is spread almost evenly from 0.1 to 2 s. Peshawar recorded its smallest residual for this event at 13.27 s, the station's best performance in the study.

Event 7

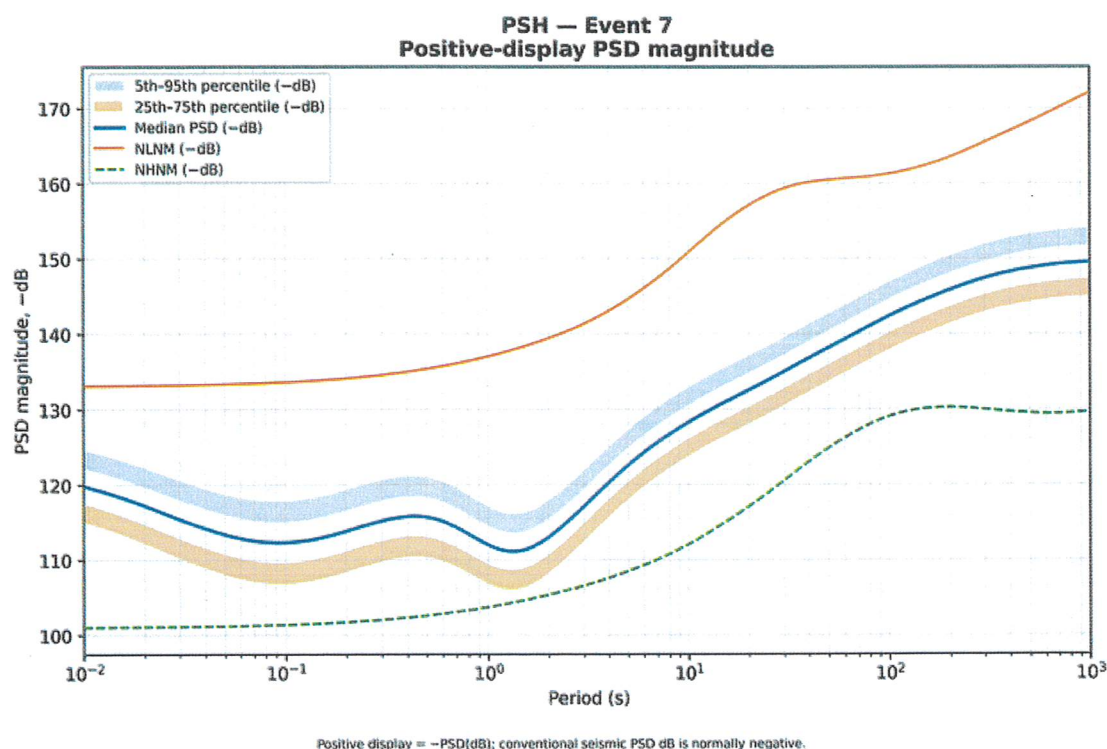


Figure 4. 32 Peshawar (PSH), Event 7, power spectral density.

This is the weakest Peshawar record, at 111.1 -dB and 1.33 s (0.75 Hz), 3.9 dB below the station average. The peak period matches Event 6 exactly although the epicentral distances differ by more than a factor of three, 301 km against 966 km. Again the site appears to control the peak period. The 17.2 dB fall to 10 s is the smallest at Peshawar.

Event 8

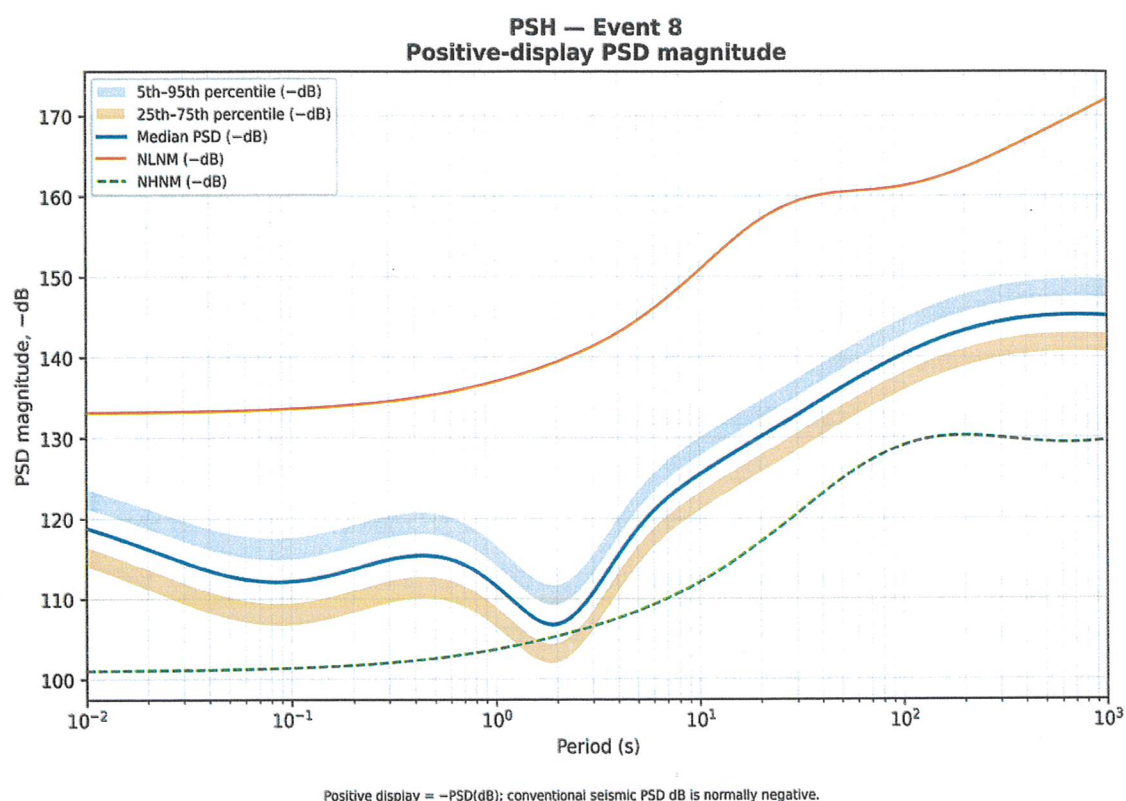


Figure 4. 33 Peshawar (PSH), Event 8, power spectral density.

This record has the most prominent peak in the entire study, standing 4.8 dB above the 1 s level and 5.4 dB above the 0.1 s level. Maximum power falls at 1.90 s (0.53 Hz), the longest peak period at Peshawar, at a level of 106.8 $-dB$ close to the station average. A sharply defined maximum near 2 s, from a source 1265 km away where attenuation has stripped the high frequencies, is the clearest example in the dataset of a distant event isolating a long-period site response.

4.7 Cross-station synthesis

Table 4.9 brings the residual and spectral results together so the two analyses can be read against each other.

Station	Mean residual (s)	RMS residual (s)	r vs distance	Mean peak ($-dB$)	SD of peak (dB)	Mean peak period (s)
Islamabad	13.79	17.22	+0.134	108.8	4.3	1.37
Jhelum	20.79	23.18	+0.768	111.0	5.2	1.55

Lahore	21.04 .	26.63	+0.814	108.8	4.6	1.38
Peshawar	27.53	29.67	+0.675	107.2	2.2	1.50

Table 4. 9 Combined residual and spectral summary for the four stations. Mean peak period excludes the four unresolved short-period cases identified in Section 4.6.1.

The table contains an apparent contradiction. Peshawar has the highest average recorded power at 107.2 -dB and the most reproducible spectra of any station, with a peak-level standard deviation of 2.2 dB against 4.3 to 5.2 dB elsewhere. It also carries the largest residuals by a clear margin. Islamabad is the reverse. its spectra are unremarkable and its average power is 1.6 dB below Peshawar. yet its residuals are the smallest in the study. Signal strength as measured by PSD does not explain residual performance. and the poor performance of Peshawar cannot be attributed to weak records.

That conclusion narrows the field of plausible explanations. If Peshawar records strong. Consistent. well-behaved spectra but produces residuals that are large at every distance. and grow steadily with distance. the error is unlikely to lie in the recording itself. The more plausible candidates are a timing offset at the station. an error in the recorded station coordinates or elevation. or a systematic difference in how arrivals at that station were picked. Each would produce exactly the pattern observed. a fixed offset present even for the nearest event. with path-accumulated error added on top. Checking the station metadata and the clock record is the obvious next step. and a cheaper test than reprocessing the waveforms.

The spectral results are more uniform across the network than the residual results. All four stations peak in the same 1 to 2 s band, all four show the same 17 to 19 dB fall between the peak and 10 s, and all four sit between the Peterson noise models in the same relative position. The differences between the stations are matters of degree. Jhelum is the quietest and most variable, Peshawar the most energetic and most consistent, with Islamabad and Lahore between them at almost identical mean levels. A network whose stations differ by a factor of two in residual performance but only by 3.8 dB in mean spectral level has a problem in processing and metadata, not in siting.

One caveat limits how far the spectral comparison can be pushed. The PSD values were computed from event records, which contain both signal and background noise. Without a separate calculation over pre-event noise windows the two cannot be separated, so the levels reported here describe total recorded power rather than site noise as such. A noise-only PSD, computed over quiet intervals, would allow the sites to be classified against

the Peterson models properly. It would also give the signal-to-noise ratio for each pick, which is the quantity most directly relevant to the residual analysis.

4.8 Limitations

The results above are subject to a number of limitations, gathered here rather than repeated through the chapter.

The sample is small. Eight events give six degrees of freedom for correlation and no realistic prospect of separating four station means whose error bars overlap, as panel (a) of Figure 4.1 shows. The rankings in Section 4.3 describe this dataset. They are not established properties of the stations, and Jhelum and Lahore in particular are too close to be ordered meaningfully.

The definition of the residual is unresolved. As set out in Section 4.2.1, the reported values are too large and uniformly too positive to be travel-time residuals in the standard sense. Until the calculation is documented in Chapter 3 and signed values are reported, the absolute magnitudes should not be interpreted physically, although the comparison between stations remains valid.

The Jhelum distances are reconstructed rather than measured. The trilateration check in Section 4.1 shows agreement to within 4 km, but that test cannot detect an error common to all three input distances. The values should be confirmed against the PMD event catalogue.

The spectral analysis mixes signal and noise. The PSD was computed from event records, so the levels reported describe total recorded power. Separate noise-window PSDs would be needed to characterise the sites against the Peterson models and to compute signal-to-noise ratios for the picks.

The instrument response is not documented. The consistent 17 to 19 dB roll-off between the peak and 10 s at all four stations is more likely instrumental than physical. The sensor type at each station, and whether the response was removed before computing the PSD, must be stated before the long-period values are used.

The automated peak search is unreliable at the band edge. Four of the thirty-two records return a peak period of 0.08 to 0.10 s that reflects the endpoint of a flat curve rather than a resolved maximum. These have been identified individually in Section 4.6 and excluded from the peak-period statistics. A peak-detection routine with a prominence threshold would avoid the problem entirely.

4.9 Summary of findings

Islamabad performs best on every residual metric, with a mean of 13.79 s and an RMS of 17.22 s, and shows no dependence of residual on epicentral distance. Peshawar performs worst, with a mean of 27.53 s and an RMS of 29.67 s, and records the largest residual for six of the eight events. Its residuals are consistently rather than occasionally large, and its minimum value exceeds the Islamabad mean. Lahore and Jhelum lie between the two and are indistinguishable from each other on this sample, though Lahore reaches its total through a single extreme value while Jhelum accumulates it evenly.

Distance dependence separates the stations more sharply than the residual magnitudes do. Islamabad shows none ($r = +0.134$). Lahore and Jhelum show strong Pearson correlations that weaken substantially under rank correlation and are therefore outlier-driven. Peshawar shows a moderate but genuinely monotonic increase with distance.

The spectral results are consistent across the network. Twenty-eight of the thirty-two records peak between 0.93 s and 1.98 s, a band that recurs independently of epicentral distance and therefore reflects shallow structure beneath each site. All four stations lie between the Peterson noise models and closer to the high-noise bound at short and intermediate periods.

The two analyses together indicate that signal strength does not control station performance. Peshawar records the strongest and most reproducible spectra while producing the largest residuals, and Islamabad the reverse. The explanation for the Peshawar offset is more likely to lie in station timing, metadata or picking procedure than in the recordings, and those should be checked before the waveforms are reprocessed.

CONCLUSIONS AND DISCUSSION

5.1 Conclusions

1. Common catalogue and P-wave picks: A single dataset of eight local-to-regional earthquakes (M 4.0 to 5.2, 2017) was compiled and P-wave arrivals picked manually at Islamabad, Lahore, Peshawar and Jhelum, giving thirty-two event–station determinations over epicentral distances of 114.8 km to 1313.8 km, so that all four stations are compared on identical records and identical geometry.
2. Absolute time differences against a 1D reference model: With the catalogue hypocentre and origin time held fixed and no relocation performed, the computed values are absolute differences between observed and predicted arrivals rather than inverted hypocentral residuals; they consequently absorb catalogue origin-time error along with station-side error, which explains their size (2.14 s to 58.15 s) and uniformly positive sign, and they are valid for comparing stations but not as absolute measures of location accuracy.
3. Statistical comparison and ranking: Islamabad performs best (mean 13.79 s, RMS 17.22 s) and Peshawar worst (27.53 s and 29.67 s), with Jhelum and Lahore tied between them; Lahore fails occasionally through a single extreme event while Peshawar fails uniformly, and because the station error bars overlap this ranking describes the present dataset rather than a demonstrated property of the stations.
4. Relation to event characteristics: Islamabad shows no distance dependence ($r = +0.134$), Lahore and Jhelum show strong Pearson correlations that collapse under rank correlation and are therefore outlier-driven, and Peshawar shows a moderate but genuinely monotonic increase with distance superimposed on an offset already present at the shortest distance; depth and magnitude correlations were weak and inconsistent, and with $n = 8$ all these relationships remain exploratory.
5. Spectral and noise characterisation: All four stations lie between the Peterson noise models and nearer the high-noise bound, with twenty-eight of thirty-two records peaking between 0.93 s and 1.98 s independently of epicentral distance, indicating a site-controlled response in shallow structure; read against the timing results, Peshawar records the strongest and most reproducible spectra while carrying the largest time differences, and Islamabad the reverse, so signal strength does not control timing performance.
6. Station-specific recommendations: Peshawar's clock record, coordinates and elevation should be checked before any waveform is reprocessed, Lahore's far-regional events re-

picked individually, Event 4 re-picked manually at Islamabad and Peshawar, and the Jhelum distances confirmed against the PMD catalogue, with noise-window spectra, documented instrument responses and a catalogue of at least thirty events needed network-wide to make these rankings testable.

5.2 Discussion

Islamabad is the best-performing of the four stations on the present dataset. It returned the lowest mean, median, root-mean-square and total residuals, and its residuals showed no measurable dependence on epicentral distance. Its spectra were unremarkable, with an average peak level of 108.8 -dB and a mean peak period of 1.27 s. Taken together, these indicate a station whose residuals are consistent with ordinary phase-picking uncertainty, with no evidence of a systematic problem.

Peshawar is the worst-performing station, and its deficiency is systematic rather than occasional. Its mean and median residuals were close to each other, at 27.52 s and 28.42 s, so outliers did not distort its performance. Its residuals were uniformly large. Because Peshawar simultaneously produced the strongest and most reproducible spectra in the study, weak signal can be excluded as the cause. The observed pattern, a fixed offset present even at the shortest epicentral distance combined with a steady increase with distance, is most consistent with an error in station timing, coordinates or elevation, or with a systematic difference in picking practice at that station.

Lahore is intermediate in accuracy but the least consistent of the four. It had the largest standard deviation, at 17.46 s, and the widest range, from 4.74 s to 58.15 s. Its strong correlation between residual and epicentral distance is driven principally by the most distant event rather than by a steady trend. Lahore is better described as a station that fails occasionally on far-regional events than one with a uniform distance-dependent bias, and improvement there requires the problematic events to be identified individually.

Jhelum performed second-best on residual metrics and was the quietest of the four stations spectrally, with an average peak level of 111.0 -dB. Its residuals accumulated evenly rather than through outliers, and all eight of its records produced a well-resolved spectral maximum between 1.11 s and 1.98 s, the most consistent set in the study. Jhelum is suitable for routine broadband monitoring, though its residual performance is not distinguishable from that of Lahore on a sample of this size.

The peak period observed at each station is a property of the site. Its recurrence across events spanning more than a factor of ten in epicentral distance, and across a range of depths

and azimuths, rules out a source or path origin. The band concerned, roughly 1 to 2 s, is also of engineering interest: it corresponds to the fundamental period of typical mid-rise structures.

A consistent fall in power of 17 to 19 dB between the spectral peak and 10 s was present at all four stations. Its uniformity across four separate sites points to an instrumental or processing origin rather than to ground motion. The long-period values should not be treated as site characteristics until the sensor type and the handling of the instrument response are documented.

Combining travel-time residual analysis with power spectral density characterisation is more informative than either analysis alone. Neither would have shown that the worst-performing station in the network is also the one recording the strongest and most stable signals. That inversion is what directs attention towards metadata and timing instead of siting or instrumentation, and it is the practical value of applying the two methods to the same records.

RECOMMENDATION

The most useful extension is also the simplest. Enlarging the event catalogue to at least thirty earthquakes would allow the station rankings to be tested statistically instead of only described. would give the correlation analysis enough power to distinguish a genuine distance dependence from an outlier effect. and would resolve whether Jhelum and Lahore differ at all. Nothing in this study requires new field deployment. The limitation is the number of events, not the instrumentation.

Spectra computed over pre-event quiet windows would separate background noise from earthquake signal. The spectra reported here were computed from event records. and therefore describe total recorded power rather than ambient noise alone. A noise-only calculation would allow the four sites to be classified against the Peterson models properly. and would yield the signal-to-noise ratio for each arrival. which is the quantity most directly relevant to explaining the residual differences between stations.

Extending the spectral analysis to continuous waveform archives. would show how the noise environment at each station varies through the day and through the year. Cultural noise is higher during working hours and microseism levels vary seasonally, so a single year of event windows cannot describe either. Long-term spectra would also reveal changes in instrument behaviour that a short study cannot detect.

Joint hypocentre relocation with station corrections would test the interpretation offered here directly. If the Peshawar offset is genuinely a station term, estimating station corrections should absorb it and improve location accuracy across the network. If it does not, the cause lies elsewhere. Combining this with a three-dimensional velocity model would also separate path effects from station effects more rigorously than correlation against epicentral distance can.

Finally, the approach can be applied to the remaining stations of the national network. The workflow requires only earthquake records the stations already produce. The finding that spectral strength and timing accuracy can point in opposite directions suggests that a network-wide assessment would identify problems neither analysis would find on its own.

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