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Strong-Motion Data Processing and Product Generation System for Earthquake Early Warning Network

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Abstract

For processing timeliness, standardizing formats, and reflecting the variety of massive strong motion observation data of the National Seismic Network Center, we developed a strong motion data processing system applicable to different types of strong motion observation stations, which enables rapid data collection, processing, and archiving. It provides a human–machine interaction data processing interface to preprocess the acceleration record of seismic waveforms and analyzes the acceleration event waveform data by calculating ground motion, including peak ground acceleration, peak ground velocity, peak ground displacement, instrumental intensity, duration, Fourier spectrum, response spectrum, and triple spectrum. The system exports metadata and seismic record waveforms to archive and store the data. The system enables platform unity, function integration, and data completeness, playing an effective role in data processing and management for emergency and damage assessment, and scientific research on earthquakes.

Keywords: strong motion observation data; preprocess; event waveform; ground motion parameters; data archiving

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Academic Editor: Christos Douligeris

Received: 8 October 2025
Revised: 30 October 2025
Accepted: 5 November 2025
Published: 14 November 2025

Citation: Liu, Y.; Zou, L.; Zhang, Q.; Li, X. Strong-Motion Data Processing and Product Generation System for Earthquake Early Warning Network. *Appl. Syst. Innov.* **2025**, *8*, 172. https://doi.org/10.3390/asi8060172

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1. Introduction

The development of the strong motion observation network in China has progressed through several stages. During the Tenth Five-Year Plan period, 1154 fixed stations, 310 sub-stations, and 12 monitoring networks in 21 key earthquake monitoring and defense zones were established, forming the foundation of the nationwide digital strong motion observation network [1]. In the subsequent Eleventh Five-Year Plan, an additional 236 monitoring stations, including 160 real-time monitoring stations, were constructed under diverse field projects. Provincial governments, municipalities, autonomous regions, and local authorities shave expanded infrastructure for monitoring of strong motions, primarily by constructing triggered strong motion stations. This led to a significant increase in network scale, with over 2300 stations deployed [2]. The additional stations contribute to a critical shift from primarily archival analog instruments to digital, real-time strong motion stations, which are essential for enabling modern applications such as earthquake early warning (EEW) systems and rapid damage assessment. The resulting deployment of over 2300 stations has significantly improved the spatial resolution of seismic recording for the better capture of near-field ground motions crucial for seismic hazard analysis and structural engineering design [3].

Recently, the National Seismic Intensity Rapid Reporting and Early Warning Project has rapidly expanded strong motion stations and enabled reference, basic, and general monitoring stations to employ strong motion observation capabilities. The project's objective is to alert people before destructive waves arrive, 2–10 s before shaking through early warning, and map earthquake intensity after it occurs within 1–2 min after the quake in rapid reporting [4]. More than 1000 basic stations were upgraded to belong to the national digital network. Presently, China operates 288 early warning stations for strong motions (Figure 1), comprising 2042 reference stations, 3356 basic stations, and 12,890 simple stations. The reference stations serve as high-precision benchmarks for seismic data calibration and validation, equipped with advanced instruments, including broadband seismometers, accelerometers, and global navigation satellite system receivers. The reference stations are strategically placed in geologically stable areas to ensure consistent data quality to provide baseline data for seismic intensity calculations, support scientific research and model refinement, and help calibrate data from other station types. The basic stations are the backbone of the early warning networks, equipped with strong-motion sensors and standard seismometers. The basic stations are densely distributed in seismically active regions to detect and report seismic events in real time for rapid intensity mapping and early warning alerts, and cost and performance balancing for wide-area coverage. The simple stations are deployed to expand coverage to remote or less accessible areas, with compact, cost-effective sensors with limited capabilities. The simple stations are often installed in rural or mountainous regions with limited standalone functionality to provide supplementary data to fill gaps in the network, to enhance the spatial resolution of seismic monitoring.

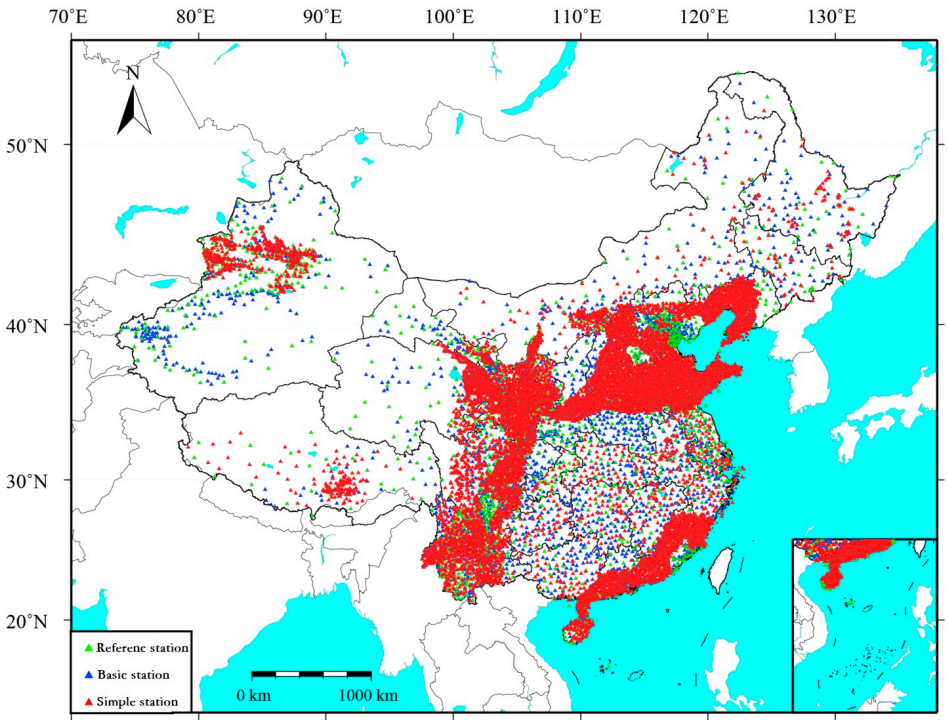


Figure 1. Distribution of observation stations in the National Early Warning Project.

Therefore, the volume of strong motion data collected has considerably increased, accompanied by increasing demands for timeliness, data diversity, and applicability. However, China's strong motion network has lacked a unified national technical platform that integrates data acquisition and automated processing. This has resulted in limited informatization, outcome yield efficiency, and incomplete derivative information [5]. Therefore, an efficient and applicable data processing platform is required for efficient operation.

Several international and regional strong-motion datasets have been developed to support seismic hazard analysis and engineering applications. For example, the European Strong Motion Database (ESM) and its enhanced version ESMpro [5] provide standardized metadata and waveform records for thousands of seismic events across Europe. Similarly, the NGA-West2 database offers a comprehensive collection of ground motion recordings from active tectonic regions worldwide [6]. In China, the Institute of Engineering Mechanics, the China Earthquake Administration (CEA), maintains the CEADX database, which includes strong motion records from major earthquakes such as the 2008 Wenchuan event [7]. These datasets share similar goals with the system proposed in this study—namely, improving data accessibility, standardization, and analytical utility for earthquake engineering and rapid response [3].

At present, only a few provincial research institutions have developed or adopted network management software created by third parties for semi-automated data collection and processing [8]. In addition, the strong motion data monitoring network presented slow throughput and low operational efficiency because it lacked a unified national technical platform that integrates automated data acquisition and processing. This deficiency resulted in limited informatization, high labor demands, and the production of incomplete derivative information. Consequently, these challenges hindered the network from performing rapid processing, standardized formats, and diverse product generation necessary for timely hazard analysis.

To address these issues, we have developed a strong motion data processing system in this study. This system is compatible with existing monitoring stations, supporting rapid data acquisition, automated processing, and systematic archiving. To develop the system, we examined the existing software and its operational requirements. Then, we designed the system architecture, including business functions, operational workflows, and data support mechanisms. Through a detailed analysis of the core technologies and algorithms, the system's functional modules were established for different applications.

2. System Design

2.1. System Architecture

The strong motion data processing system was developed based on the principle of decoupling, which separates business logic from data and the underlying platform from required functionalities. Using this approach, we constructed a layered technical architecture comprising a server and an interactive front-end interface (Figure 2). According to diverse operational scenarios, the system adopts an open technological ecosystem built on the Java platform, with supplementary components implemented in C and Fortran.

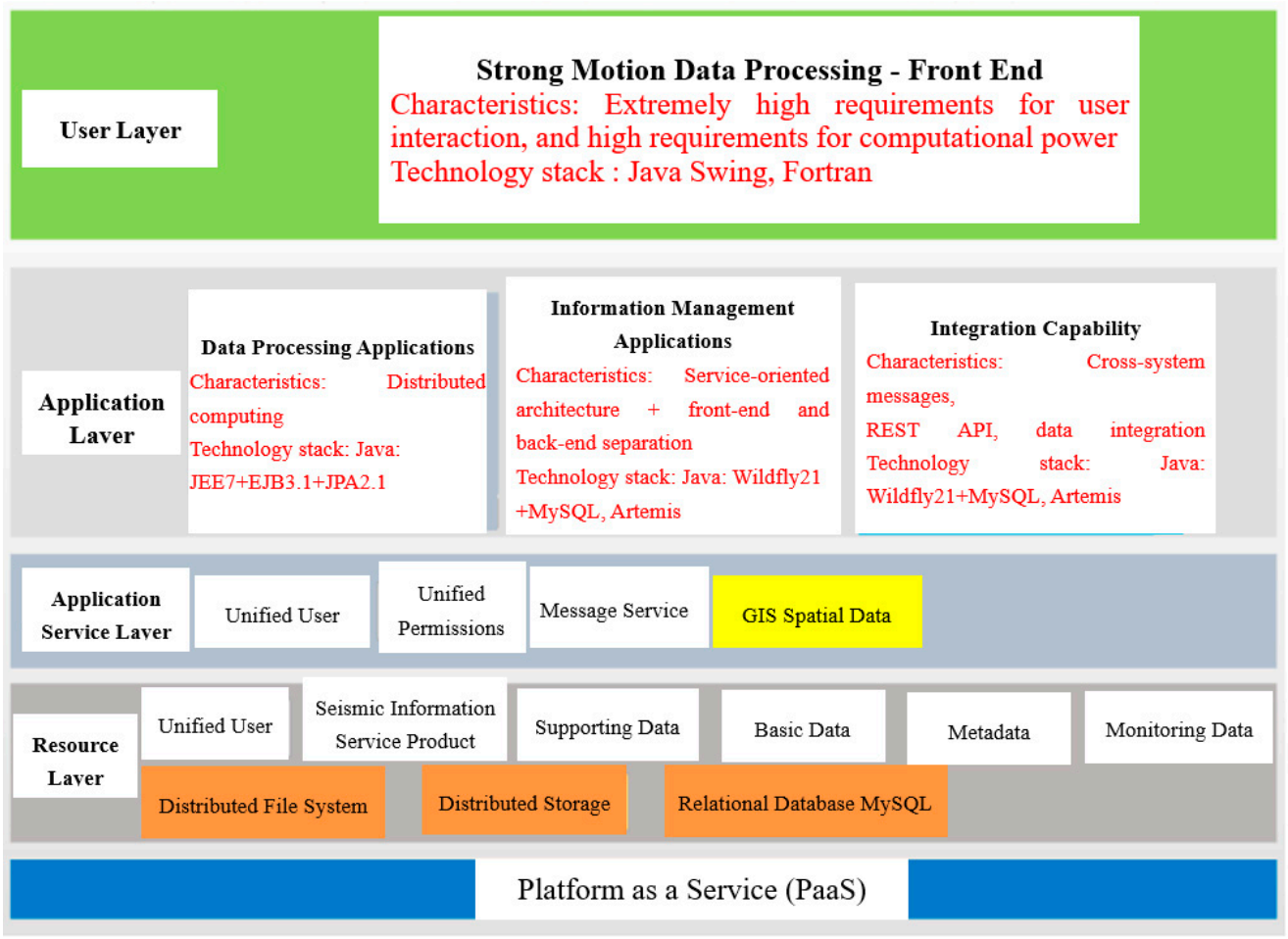


Figure 2. Software architecture of the strong motion data processing system.

2.2. Function

The strong motion data processing system provides a human–computer interaction (HCI) data processing interface to preprocess the acceleration record of seismic waveforms, analyze the acceleration event waveform data, and calculate ground motion parameters including peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), instrumental intensity (IA), duration (the time interval over which significant ground shaking occurs during a seismic event), and spectral value including Fourier, response and triple spectra. IA is a key ground motion parameter calculated by the strong motion data processing system, indicating the severity of ground shaking at a given location, derived mathematically from the recorded ground motion parameters rather than being a subjective observation. IA is computed using PGA and PGV.

The system exports metadata and strong motion seismic record waveforms to an archive and stores them on a server. The system developed includes the acceleration preprocessing module, the velocity and displacement time history conversion module, the ground motion parameter calculation module, the spectral value calculation module, and the data archiving module. The separation of these modules reflects an operational hierarchy. The acceleration preprocessing module and the velocity and displacement time-history conversion module are responsible for signal processing and mathematical integration to produce clean, time-domain waveform records (acceleration, velocity, and displacement). The subsequent ground motion parameter calculation module performs the seismological and engineering analysis by deriving summary metrics from these processed time histories. These resultant ground motion parameters, PGA, PGV, PGD, IA, and dura-

tion, are critical values used directly for rapid earthquake damage assessment, engineering design input, and seismic risk analysis, rather than merely being the processed waveform signals themselves. The functions of the system modules are described in Table 1.

Table 1. Functions of the developed strong motion data processing system modules.

Function	Description
Acceleration record preprocessing	The system imports, loads in real time, and displays acceleration waveform data, preprocesses (demeaning and linear trend removal) on the loaded data, accesses the raw data of event waveforms for processing, and exports strong motion records.
Velocity and displacement time history conversion	The system performs time-domain integration on preprocessed acceleration records, followed by correction procedures (e.g., band-pass filtering) to suppress baseline drift and residual low-frequency noise. This ensures the resulting velocity and displacement time histories are physically accurate and stable.
PGA, PGV, PGD, and IA calculation	The system obtains the PGA, PGV, and PGD values from processed acceleration event waveform records and velocity and displacement time history, and calculates parameters including IA, duration, etc.
Fourier spectrum, response spectrum, and triple spectrum calculation	For the preprocessed acceleration event waveform records, the system calculates the Fourier spectrum using the Fast Fourier Transform (FFT), and the response spectrum and triple spectrum using the exact analytical solution of the Duhamel integral, and then exports spectral parameters and generates metadata.
Data archiving	The system exports strong motion records and metadata for archiving and service.

2.3. Data Processing

The strong motion data processing system operates through a structured sequence of modules, each designed to perform specific analytical tasks. First, the acceleration preprocessing module is critical for initial data cleaning. It handles the linear trend by first performing a demeaning operation to remove the average DC bias from the entire record, setting the mean to zero. Subsequently, it fits a linear function to the signal and subtracts this linear trend to remove any long-period drift that may have been introduced by the instrument or the recording process. This combined process minimizes the baseline drift that would otherwise be severely amplified during later integration steps. Second, the velocity and displacement time-history conversion module integrates and corrects the preprocessed acceleration waveforms to generate the corresponding velocity and displacement time history. Third, the ground motion parameter calculation module computes PGA, PGV, PGD, IA, and duration. Fourth, the spectral value calculation module derives spectral parameters by computing the Fourier, response, and triple spectra. Finally, the data archiving module exports strong motion data and associated metadata for archival and operational purposes. The overall data processing procedure is illustrated in Figure 3.

To assess the reliability and robustness of the system's outputs, statistical treatment methods are incorporated during validation. For each computed ground motion parameter (e.g., PGA, PGV, PGD), the system calculates basic descriptive statistics such as mean, standard deviation, and coefficient of variation across multiple stations. Confidence intervals of 95% are generated using bootstrapping techniques to quantify uncertainty in parameter estimates. We apply residual analysis and outlier detection to identify anomalous readings, since they are consistent across earthquake forecast models [9]. Incorporating these statistical tools enhances the credibility of the system's outputs and supports informed decision-making in emergency response and seismic hazard assessment, emphasizing the importance of statistical tests and confidence metrics in refining seismic likelihood models.

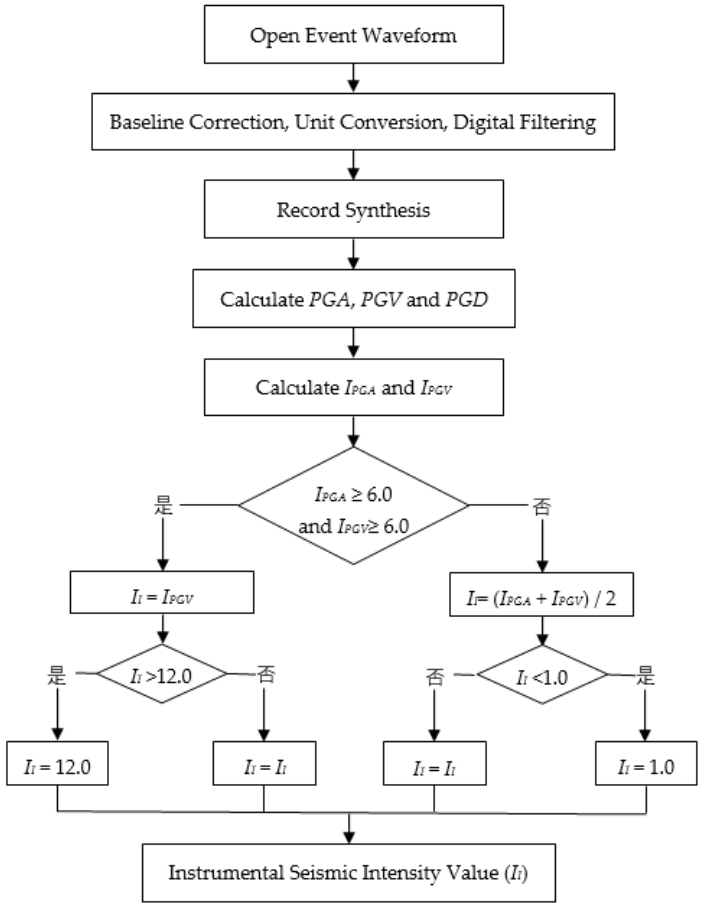


Figure 3. Calculation process of PGA, PGV, PGD, and I_I. "yes (是)" and "no (否)".

2.4. Strong Motion Observation Data

The strong motion database maintained by the National Seismic Network Center comprises two primary types of data: discrete, event-based recordings from triggered observation stations (which begin recording when shaking exceeds a threshold) and continuous stream recordings from real-time acceleration stations. While both types are transmitted in real time, the difference lies in the monitoring strategy: one provides snapshots of seismic events, and the other provides an unbroken record of ground motion.

Triggered strong motion records are collected from stations that respond to seismic events with a magnitude of 4.0 or greater, or a PGA of at least 0.01 gn, and have been systematically archived since 2007. To clarify the triggering process: the physical station is activated locally and instantaneously by the hardware trigger when the measured PGA exceeds 0.01 gn. However, the final decision to process and archive the record in the main database is determined centrally by the National Seismic Network Center based on the final, computed event parameters, including a network-determined magnitude of 4.0 or greater. The magnitude is calculated using a regionalized algorithm that incorporates signal amplitude (PGA/PGV) and hypocentral parameters (epicenter and depth) derived from the full National Seismic Network data. Each record captures a 60 s time window, spanning 30 s before and after the earthquake's origin time, at a rate of 200 sps. The decision to archive a ±30 s window centered on the event's origin time is primarily aimed at capturing the most critical shaking phase (S-wave and strong motion duration) for near-to-intermediate field events, which are of highest interest to earthquake engineers for damage assessment and design. The 30 s interval before the origin time is essential because it captures the background noise for baseline correction and, more importantly, ensures the P-wave and initial Swave arrivals are fully captured, which is crucial for early warning

system research and signal processing. While this window may truncate the coda wave of very distant, large-magnitude events, the National Seismic Network Center prioritizes complete capture of the high-amplitude phase for engineering applications.

The supporting data utilized by the system developed includes waveform data, seismic catalogs, phase data, and station instrument parameters. The datasets serve as essential inputs for subsequent analysis and computation. Waveform data, essential for the system, is categorized into online waveform data, AWS continuous waveform data, archived waveform data, and online seismic event data. The sampling rate is either 100 sps or 200 sps. Catalog data encompasses seismic event parameters, seismic phase data, and hypocentral solutions. To be precise, seismic phase data are the measured arrival times of different seismic waves (P- and S-waves) at each station, which are essential for precisely locating the earthquake hypocenter. The phase readings are categorized as online and offline based on their origin. Online phase data are automatically and immediately picked by the system from the real-time seismic waveform streams and used for rapid, preliminary event location. Offline phase data are the final, manually verified or refined phase readings obtained by seismologists after the event has occurred, which are used to produce the definitive, authoritative seismic catalog.

The system outputs strong motion records, ground motion parameters, and associated metadata. Strong motion records include original and corrected acceleration time histories, integrated velocity and displacement time histories, and spectral data (Fourier, response, and triple spectra). These records are formatted with standardized headers and waveform data, and are presented in the American Standard Code for Information Interchange (ASCII) format. Ground motion parameters include PGA, PGV, PGD, duration, and IA. Metadata comprises seismic event metadata, station metadata, record metadata, and instrument metadata.

3. Technologies and Algorithms

The strong motion data processing system fulfills its functional requirements through the following modules: acceleration preprocessing module, the velocity and displacement time-history conversion module, the ground motion parameter calculation module, the spectral value calculation module, and the data archiving module.

3.1. Acceleration Preprocessing Module

The acceleration preprocessing module consists of three sub-modules for importing raw data at 200 sps, accessing raw data at 100 sps, and data preprocessing. This module provides an HCI analysis interface to browse and display waveforms, demean and remove linear trends on the acceleration event waveform data [7], select waveform and seismic phase data from historical data according to the preset criteria, such as time range, event, and station, and import and load the selected data [10].

To ensure the reliability of the processed data, the module incorporates multiple quality control mechanisms, including baseline correction, demeaning, linear trend removal, and band-pass filtering to suppress low-frequency drift and high-frequency noise. For noisy records, we applied signal-to-noise ratio (SNR) thresholds and waveform clipping to isolate valid seismic signals. Additionally, waveform segments with discontinuities or gaps are flagged and excluded from parameter computation. These procedures align with established practices in strong motion data processing with the guidelines in DB/T 64-2016 and GB/T 17742-2020 [11,12].

3.2. Velocity and Displacement Time History Conversion Module

The velocity and displacement time-history conversion module consists of three submodules for waveform display, velocity time-history generation, and displacement time-history generation. This module visualizes acceleration waveforms derived from preprocessed strong motion data, applies integration and correction procedures, and produces corresponding velocity and displacement time histories. Following station data preprocessing, a bandpass filtering procedure is applied to each component of the acceleration records to obtain filtered acceleration time histories. Filtering is necessary because the integration process is mathematically unstable; even minute, residual low-frequency noise (or baseline drift) in the acceleration record would be severely amplified and accumulated into erroneous, unbounded baseline offsets when integrated into velocity and displacement. The bandpass filter effectively suppresses this low-frequency drift and high-frequency noise, ensuring the time histories remain stable and physically realistic (i.e., velocity and displacement return to near-zero after the shaking ends). The filtered data is then subjected to first-order and second-order time-domain integration to generate velocity and displacement time histories for each component at each station. The filtering parameters (e.g., corner frequencies) are not selected by a human operator or AI for every event; rather, they are pre-determined based on the technical specifications of the strong motion instruments and the established national standards (such as the Chinese seismic design code). This ensures a consistent, standardized processing methodology across all stations in the network. The velocity and displacement time-history conversion module applies band-pass filtering to suppress low-frequency drift and high-frequency noise and then integrates the preprocessed acceleration waveforms to generate the corresponding velocity and displacement time history. This two-part process of filtering (correction) and integration is essential to ensure that the time histories are accurately centered and do not suffer from accumulated baseline errors.

3.3. Ground Motion Parameter Calculation Module

The ground motion parameter calculation module consists of three sub-modules for amplitude calculation, duration calculation, and IA calculation. This module utilizes the acceleration time history, velocity time history, and displacement time history processed by the velocity and displacement time history conversion module to calculate PGA, PGV, and PGD from the synthesis of the three components at each station. The module calculates the IA using PGA and PGV and determines duration parameters. The calculation process is shown in Figure 3. In accordance with DB/T 64-2016 Technical Regulations for Strong Motion Observation [13], it exports the seismic, station, record, and instrument metadata and submits them to the database.

The ground motion parameter calculation module is the vital part of the strong motion data processing system. Amplitude, duration, and IA are calculated as follows.

3.3.1. Amplitude

Amplitude calculation is conducted to determine PGA, PGV, and PGD by synthesizing acceleration, velocity, and displacement from the three orthogonal components recorded at each station. In the calculation, previously processed data obtained from individual channels are used, and the following equation is applied.

$$a(t_i) = \sqrt{a^2(t_i)_{E-W} + a^2(t_i)_{N-S} + a^2(t_i)_{U-D}} \quad (1)$$

where $a(t_i)$ represents the synthetic acceleration value at time point t_i, and $a(t_i)_{E\text{-}W}$, $a(t_i)_{N\text{-}S}$, and $a(t_i)_{U\text{-}D}$ are the filtered east–west, north–south, and vertical acceleration values at time point t_i, respectively. The unit is centimeters per square second (cm/s^2).

Using Equation (1), we obtain the horizontal acceleration magnitude, i.e., the time sequence of synthesized $a(t_i)$ is positive. From this sequence, PGA can be determined. However, the synthesized magnitude sequence, $a(t_i)$ is a non-vector quantity but not used for integration. PGV and PGD values are obtained through a separate, standard procedure: first-order and second-order time-domain integration is applied independently to the individual, filtered, three-component acceleration time histories (North–South, East–West, and Vertical). The final PGV and PGD values are then determined by calculating the respective peak values from the integrated individual component records.

Similarly, the three-component synthetic velocity time history and the three-component synthetic displacement time history are obtained. Based on the synthesized acceleration, velocity, and displacement time histories from the three components at each channel, the component-specific PGA, PGV, and PGD for each channel, as well as the synthesized PGA, PGV, and PGD for each station, are calculated. Equation (2) is used to calculate the PGA of the synthetic ground motion acceleration time history.

$$PGA = max[a(t_i)] \tag{2}$$

Similarly, the PGV and PGD of the synthetic ground motion velocity time history are obtained in (cm/s^2).

3.3.2. Duration Calculation

Following data preprocessing, the duration start time is defined relative to the origin time as the point at which the absolute value of the synthesized waveform first exceeds a specified threshold. The duration end time is identified as the earliest subsequent moment when the waveform amplitude falls below that threshold. The absolute duration corresponding to the threshold is calculated as the time interval between these two points.

3.3.3. IA Calculation

IA is calculated from the calculated PGA and PGV. Specifically, the acceleration- and velocity-based IAs are calculated separately [14,15]. The detailed calculation method is referred to from the national standard GB/T 17742-2020, The Chinese Seismic Intensity Scale [16].

3.4. Spectral Value Parameter

The spectral value calculation module estimates the Fourier, response, and triple spectra based on preprocessed acceleration event waveform records. The Fourier spectrum is computed using the Fast Fourier Transform (FFT), while the response and triple spectra are derived through the analytical solution of the Duhamel integral. The module applies the FFT algorithm to obtain the Fourier spectrum, then calculates the acceleration response spectrum using the Duhamel integral. This response spectrum is subsequently transformed into the triple spectrum. The module then generates standardized header information and spectral data files, which are exported in ASCII format. The calculation process is illustrated in Figure 4.

The spectral value parameter calculation module is another essential component of the strong motion data processing system. It comprises three sub-modules responsible for computing the spectra. The computational principles of each sub-module are described as follows [17].

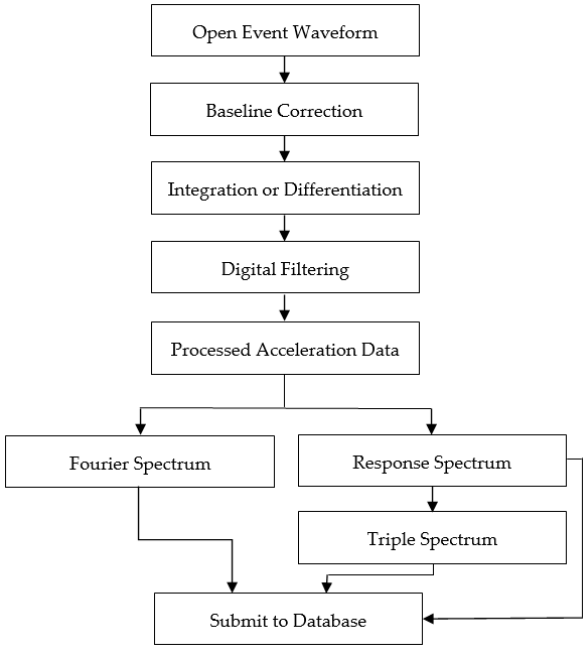


Figure 4. Calculation of the Fourier, response, and triple spectra.

3.4.1. Fourier Spectrum

The Fourier spectrum is computed by applying FFT to the preprocessed acceleration records, resulting in amplitude-frequency representations of the seismic signal.

3.4.2. Response Spectrum

Using preprocessed acceleration records, the system solves the motion equation of a single-degree-of-freedom damped oscillator characterized by a specified natural period T and a damping ratio h. Through the integration, time histories of the system's absolute acceleration response, relative velocity response, and relative displacement response are constructed. For h and T_i, the response spectra of absolute acceleration, relative velocity response, and relative displacement response are obtained by extracting the maximum absolute values from the respective time histories.

3.4.3. Calculation of Triple Spectrum

Based on the response spectrum calculated, the relative velocity response spectrum is computed, and the interrelationships among the relative acceleration, velocity, and displacement response spectra are established to construct the triple spectrum.

3.5. Data Archiving Module

The data archiving module comprises two sub-modules for strong motion record export and metadata export. The strong motion record export sub-module outputs uncorrected acceleration records (UA) and corrected acceleration records (CA), and, following integration, generates velocity (CV) and displacement (CD) time histories. The metadata export sub-module provides seismic metadata, station metadata, record metadata, and instrument metadata.

Seismic metadata includes event parameters, including event name, origin time, geographic coordinates (longitude and latitude), magnitude, and focal depth. Station metadata contains station name, code, location coordinates, and site characteristics. Record metadata encompasses peak values of acceleration, velocity, and displacement, along with record duration and sampling rate. Instrument metadata includes specifications such as instrument model, serial number, key performance indicators, and parameter settings.

All strong motion records and metadata produced by this module are archived in a designated database using standardized formats defined in DB/T 64-2016 Technical Regulations for Strong Motion Observation.

4. System Application

4.1. Platform Construction and Deployment

4.1.1. System Deployment

According to the architectural framework of the National Seismic Intensity Rapid Reporting and Early Warning Project in China, the strong motion data processing system with early warning software is deployed in the National Seismic Network Center, the National Data Backup Center, and Provincial Centers. Each center manages its own databases, data streams, information forwarding middleware, and virtualized storage and computing resources, all integrated within its respective hardware platforms.

The National Seismic Network Center presently operates one physical server and two virtual machines. The physical server is responsible for accessing real-time data streams, while the virtual machines serve as primary and backup clients for data computation and storage.

4.1.2. Implementation of Technical Indicators

Through the platform deployment, the system provides a seismic waveform data processing HCI, which enables data import/export, waveform clipping, format conversion, filtering, calculated parameter output, and data archiving. Enhanced with visualization capabilities, the system integrates observational data from the nationwide high-density seismic network, enabling dynamic and automated processing of strong motion data. The system generates comprehensive data and determines ground motion parameters for early warning. By validating the system performance using real earthquake data from the National Seismic Network Center, the accuracy and operational reliability are confirmed. The system demonstrates its effectiveness in routine data management, emergency response, damage assessment, and scientific research.

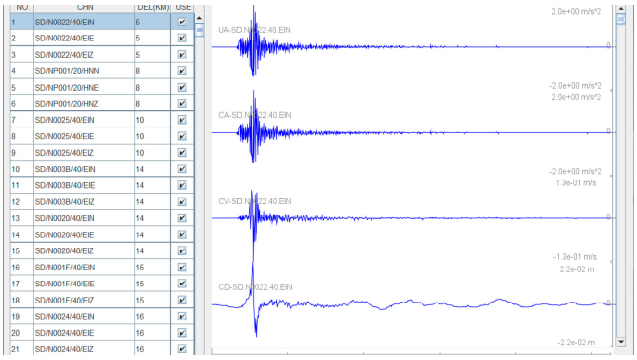
The system retrieves one hour of data from 100 stations at 100 sps in less than three minutes. When data sampled at 200 sps is transferred to the server, the client accesses one hour of data from 100 stations in less than 5 min. The user interface shows a response time of less than 2 s for normal interactions. For computationally intensive tasks, a waiting prompt is displayed immediately upon initiation and remains until processing is complete. Following the minimum system requirements, strong motion records, metadata, and ground motion observation reports from 100 stations can be transferred at 100 sps in less than 30 s. Similarly, velocity and displacement time histories, peak ground motion parameters (PGA, PGV, and PGD), IA, and duration for 100 stations are computed and compiled in less than 30 s.

4.2. Business Application Case

For testing and validating the strong motion data processing system, acceleration records from historical earthquakes of varying magnitudes and geographic regions since 2021 were selected [7]. In addition, recent seismic events, including the M5.5 earthquake on the Shandong Plain (6 August 2023), the M5.5 earthquake in Subei County, Gansu Province (23 October 2023), and the M6.2 earthquake in Jishishan County, Gansu Province (18 December 2023) in China, were used to assess the system's output capabilities. For each event, the system generated corrected acceleration records by integrating velocity and displacement time histories and spectral data. The system computed ground motion parame-

ters, IA, and duration. Furthermore, the system exported seismic metadata and waveform records in standardized formats.

Figure 5 presents the processing outcomes of the M5.5 Shandong Plain earthquake data processing. The system's rapid generation of ground motion parameters serves as vital information for emergency management agencies to make real-time decisions, command operations, and coordinate disaster relief. Its standardized data processing and format compliance also provide data for near-field strong earthquake seismology and earthquake engineering research. Equation (1) is used in waveform processing that leads to the velocity and displacement time histories shown in Figure 5a. Instead, the synthesized acceleration magnitude, $a(t_i)$ is a unipolar scalar used exclusively for calculating PGA and IA for rapid event reporting. Figure 5a shows the final velocity and displacement time histories using the original, three-component, bipolar (positive and negative) acceleration data after being individually filtered. This vector-based integration preserves the directionality and phase information necessary to accurately reconstruct the time sequences for velocity and displacement.



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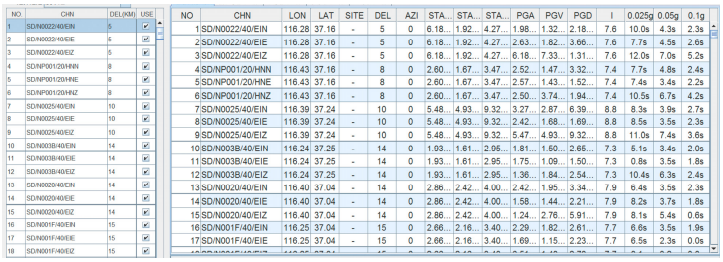

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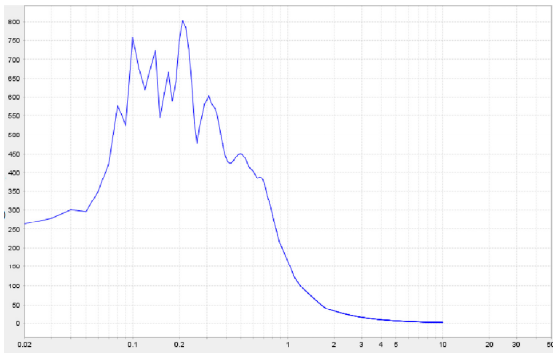

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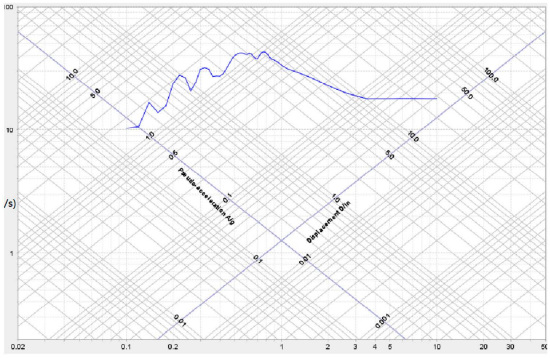
Figure 5. *Cont.*



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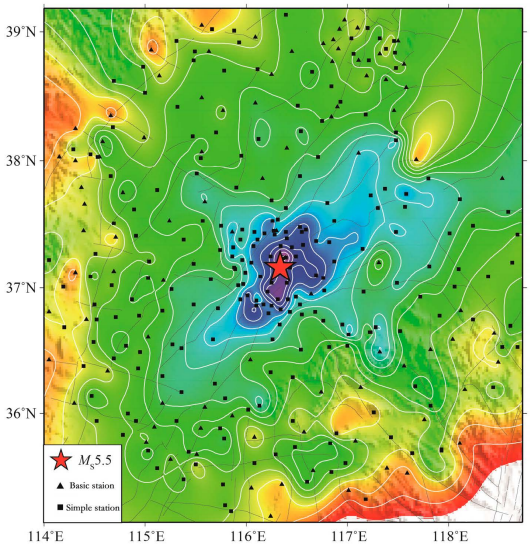

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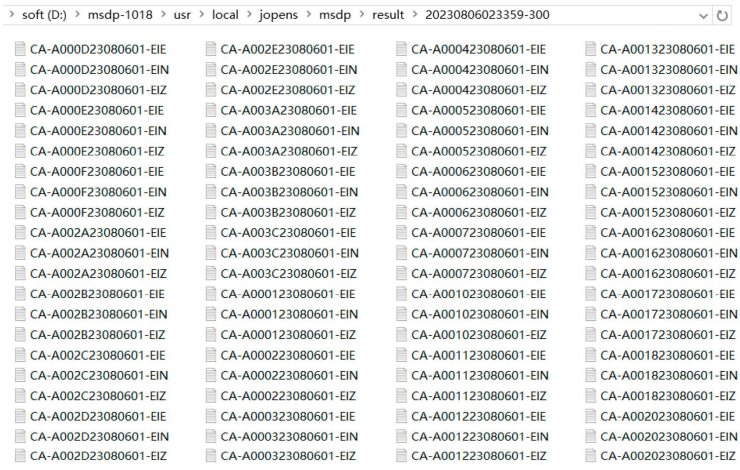

(**f**)

Figure 5. Processing and output of strong motion data of the M5.5 earthquake on the Shandong Plain (6 August 2023). (**a**) Original acceleration, corrected acceleration, integrated velocity, and displacement. (**b**) Ground motion parameters. (**c**) Acceleration response spectrum. (**d**) Tripartite response spectrum. (**e**) IA distribution map. (**f**) Archiving of output results.

5. Characteristics of Strong Motion Data Processing System

The strong motion data processing system developed serves as a unified national technical platform for processing data from various types of acceleration observation stations. It provides multiple equipment interfaces and functionalities, including data acquisition,

visualization, processing, and archiving. The system enhances the capacity for detailed analysis of large-scale datasets collected from the three seismic networks. The system also supports interactive analysis of continuous and event-based waveform data and regularly generates ground motion parameters based on basic seismic parameters. By delivering scientifically robust datasets, the system enables rapid and accurate earthquake damage assessment, emergency response decision-making, and engineering seismology research.

The system presents the following advantages.

- Platform integrity

The system is a standardized national platform compatible with all equipment types deployed in different stations in the early warning system. It enables end-to-end standardization, from data acquisition and aggregation to processing and application, by using intuitive HCIs for metadata management. This ensures seamless integration and consistency throughout the operational workflow.

- Service Integration

The system meets the needs of National and Provincial Seismic Network Centers by providing functions for data import/export, waveform clipping, format conversion, signal filtering, parameter computation, and report generation. By embedding these capabilities into the workflows of the early warning system, the system improves operational efficiency and effectively manages acceleration observation data.

- Data Completeness

The system provides comprehensive metadata for seismic events, stations, records, and instruments. It enables the export of strong motion record data, including uncorrected and corrected acceleration records, integrated velocity and displacement time histories, amplitude parameters (PGA, PGV, PGD, IA, and duration), and spectral data (Fourier, response, and triple spectra). These datasets and outcomes are yielded with scientific rigor and practical utility, meeting the requirements of post-earthquake analysis and supporting damage assessment, emergency coordination, and research in earthquake engineering and seismology.

6. Conclusions

We developed a strong motion data processing system to address the challenges of processing timeliness, standardizing formats, and managing the diversity of the massive strong motion observation data collected from various networks. The system was designed based on the principle of decoupling and a layered architecture using an open technological ecosystem built on the Java platform with supplementary components in C and Fortran. The system incorporates modules of acceleration preprocessing, velocity and displacement time-history conversion, ground motion parameter calculation, spectral value calculation, and data archiving. This system supports rapid data acquisition, automated processing, and systematic archiving, compatible with various monitoring stations. FFT and the Duhamel integral are adopted to analyze preprocessed acceleration event waveforms.

The developed system processes strong motion data from different types of acceleration observation stations and provides an interactive interface to preprocess acceleration records and calculate a comprehensive set of ground motion parameters, including PGA, PGV, PGD, IA, duration, and the Fourier, response, and triple spectra. The system presents platform integrity, function integration (e.g., data import/export, filtering, parameter computation), and data completeness (e.g., exporting corrected time histories and comprehensive metadata), and its performance was validated using real earthquake data, confirming its accuracy and operational reliability.

The system developed enables the establishment of an efficient and applicable platform that standardizes data processing and format across the nationwide high-density seismic network. The enhanced data processing and management capability for emergency response and damage assessment improves operational efficiency and provides robust datasets for engineering and scientific research.

For enhanced quality control of data processing and outcomes, full-process data monitoring, internal quality control, real-time visualization, historical waveform replay, and robust handling of datasets with breakpoints need to be added. The system also needs to support the aggregation of global, high-volume datasets and diverse data formats from fixed and mobile strong motion stations deployed during the Tenth and Eleventh Five-Year Plan periods, requiring prioritized integration with the early warning system's components. Data sharing services for diverse user needs must also be included to provide data in multiple formats (maps, diagrams, models, and raw datasets) and enable graphical preview and export capabilities for parameter tables and analytical reports. Further refinements of the system developed in this study also lead to socioeconomic development, emergency decision-making, earthquake prediction, early warning, and rapid reporting.

Author Contributions: Conceptualization, Y.L.; methodology, Y.L.; software, L.Z.; validation, Q.Z.;investigation, X.L.; data curation, L.Z.; writing—original draft preparation, Y.L.;writing—review and editing, Y.L.; project dministration, Y.L.; funding acquisition, L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by National Natural Science Foundation of China (Grant No. 52478504) and National Key Research and Development Program of China (Grant No. 2024YFC3012805).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Research results and data are confidential according to contractual requirements, except for those that have been disclosed in this article.

Acknowledgments: This research has also been supported by the China Earthquake Networks Center, Yunnan Earthquake Agency, Sichuan Earthquake Agency, Xinjiang Earthquake Agency, Fujian Earthquake Agency, Guangdong Earthquake Agency, and the Institute of Engineering Mechanics, CEA, and experts in the strong motion observation discipline of the China Earthquake Administration. The authors would like to express their sincere gratitude to all of them.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript.

ASCII	American Standard Code for Information Interchange
CA	Corrected Acceleration Records
CD	Displacement Time Histories (Corrected Displacement)
CV	Velocity Time Histories (Corrected Velocity)
EVT	Event Data Format
FFT	Fast Fourier Transform
GBR	General Binary Record
GSR	Ground Shaking Record
I_I	Instrumental Intensity
MRF	Motion Record Format
PaaS	Platform as a Service
PGA	Peak Ground Acceleration
PGD	Peak Ground Displacement

PGV	Peak Ground Velocity
sps	Samples Per Second
UA	Uncorrected Acceleration Records
U-D	Up-Down (Vertical filtered acceleration value component)
XMR	Extended Metadata Record

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