18TH WORLD CONFERENCE ON EARTHQUAKE ENGINEERING
WCEE2024
MILAN

MILAN, ITALY
30TH JUNE - 5TH JULY 2024
www.wcee2024.it

A JOURNEY TO THE CENTER OF THE USGS NATIONAL STRONG-MOTION PROJECT PROCESSING AND BEYOND

L. Schleicher[1], J. Steidl[1,2], E. Thompson[3], A. Yong[4], J. Brody[1], L. Blair[1], S.K. Ahdi[3,5], M. Hearne[3], B. Aagaard[3], S.E. Hough[4], H. Shao[1], G. Huddleston[1], K. Heilpern[1], K. Marano[3], G. Ferragut[3], B. Worden[3], D. Wald[3], J. De Cristofaro[1,6], A. McClain[1], B. Dunham[1], D. Nget[1], J. Aragon[1], J. Gomez[1], V. Amador[1], V. Carrasco Rodriquez[1], E. Luna, E. [1], D. Cembalski[1], D. Childs[1], J. Smith[1], D. Croker[1] & L. Gee[1]

[1] U.S. Geological Survey, Earthquake Science Center, Moffett Field, California, USA, lschleicher@usgs.gov

[2] University of California Santa Barbara, Earth Research Institute, Santa Barbara, California, USA

[3] U.S. Geological Survey, Geologic Hazards Science Center, Golden, Colorado, USA

[4] U.S. Geological Survey, Earthquake Science Center, Pasadena, California, USA

[5] AECOM, Los Angeles, California, USA

[6] U.S. Geological Survey, Earthquake Hazards Program, Vancouver, Washington, USA

Abstract: *The United States Geological Survey (USGS) National Strong-Motion Project (NSMP) has the primary United States (U.S.) government responsibility to acquire, process, and disseminate to the earthquake engineering community significant strong-motion earthquake ground motion records measured at surficial free-field stations, structures (buildings, dams, and bridges), and geotechnical arrays. As a result of the deployment of modern seismic instrumentation and growth of tools such as web-services, earthquake data from U.S. and international seismic networks are more accessible than ever. The NSMP mission is to provide raw and processed strong-motion waveforms with peak ground acceleration values greater than 0.1% g for M3.0 earthquakes and larger in California and M4.0 and larger within the conterminous U.S., Hawaii, Puerto Rico, and Alaska. NSMP also aims to include special datasets of interest to the earthquake engineering and observational seismology communities, such as event sequences in areas of induced seismicity and significant global events. All NSMP datasets are processed and posted at the Center for Engineering Strong-Motion Data (CESMD) at strongmotioncenter.org. Here we outline (1) the NSMP's current workflow to acquire, process, and distribute data at CESMD; (2) new endeavours and collaborations focusing on comparison and integration of waveform processing software, development of techniques for metadata quality checks before and after earthquakes, and construction of a dynamic site characterization repository; and (3) topics for possible future collaboration across the global strong-motion community.*

1. Introduction

Although the instrumental era in seismology dates back to the late 19th century (e.g., Byerley and Dewey, 1969), strong ground motions were not recorded on-scale until so-called strong-motion (SM) instruments were introduced in the early 1930s (Neumann, 1935). Until the early 1930s, ground motions from damaging earthquakes could only be estimated. The terms strong-motion and weak motion have become somewhat blurred with the advent of modern multi-channel data acquisition systems where stations can now have both strong and weak motion sensors. Today the broadband "weak-motion" sensor can record on-scale data at larger distances from the same event that produced significant strong-motion at closer distances that would have clipped the weak motion sensor. However, the distinction between weak- and strong-motion is still important to reflect data recorded by specialized instruments that stay on scale at large shaking intensities (accelerometers), and that are often processed differently from standard seismic network data. The United States Geological Survey (USGS) National Strong-Motion Project (NSMP) continues to focus on collection and processing of records at shaking levels and frequencies of engineering interest. These strong-motion records provide critically important ground-truth observations that advance the ability to estimate seismic hazards in different regions, providing the basis for development of modern building codes and design of earthquake-resilient structures and infrastructure. In this report we provide an overview of the current NSMP workflow, data processing, and endeavours to collect strong-motion data for important earthquakes around the world.

2. NSMP Dataflow

To expand the availability of strong-motion datasets to the community, the USGS NSMP replaced their manual processing workflow with an automated system in 2018 (Jones et al., 2017; Steidl et al., 2022). This automated workflow, combined with the growth and modernization of seismic networks in both the US and abroad and the expansion of tools such as webservices, have spurred a significant increase in data availability at the Center for Engineering Strong-Motion Data (CESMD) (Hagos et al., 2024; Shao et al., 2024). The primary components of the NSMP's current workflow are shown in Figure 1 and described below:

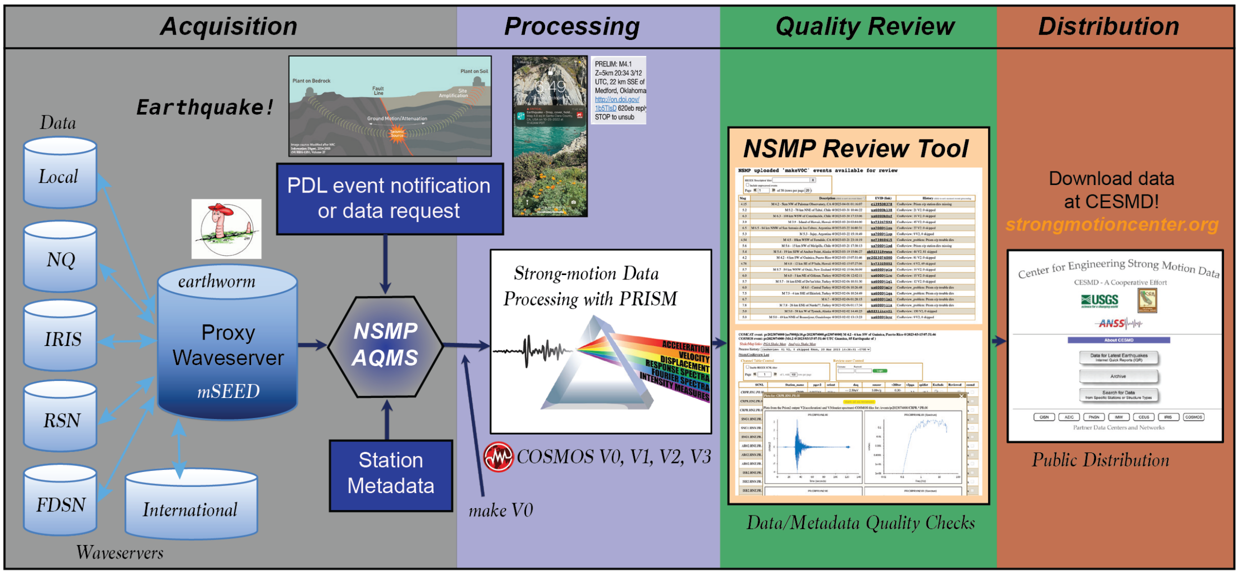

Figure 1. The USGS/NSMP system automatically collects USGS Advanced National Seismic System (ANSS) strong-motion data from multiple sources and processes it to produce COSMOS data products for distribution at the CESMD.

2.1. Acquisition

The NSMP receives event notifications distributed by the Product Distribution Layer (PDL) (Fee, 2019) of the ANSS (USGS, 2017) and then, based on a magnitude-based distance threshold, we acquire available waveform data and metadata from US and global networks operating strong-motion instruments. Earthquake records from various wave servers are pooled into a central waveserver. Data are output in mini Standard for the Exchange of Earthquake Data (mSEED) format and metadata are incorporated into database that is then referenced to generate Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) V0 (Volume zero) format, a self-contained product that includes earthquake information, seismic instrumentation metadata, and raw acceleration time histories in digital counts (COSMOS Strong-Motion Programs Board, 2001).

2.2. Processing

The NSMP currently processes waveform records in COSMOS V0 format using a software package called PRISM (Processing and Review Interface for Strong-Motion Data; Jones et al., 2017). PRISM takes the COSMOS V0 format and automatically produces acceleration time histories in physical units (COSMOS V1 format), processed acceleration, velocity, and displacement time histories (COSMOS V2 format), and acceleration, velocity, and displacement response spectra at standard damping values (COSMOS V3 format). The PRISM software was designed with both a GUI interface for the desktop user, and a command line processing engine for programmatic use when dealing with large amounts of data (https://code.usgs.gov/prism, accessed 2023) (Jones et al., 2017).

2.3. Review

The NSMP has developed a web-based tool for rapid review of the PRISM products to facilitate data quality control. The event review tool was implemented in late 2019 and we anticipate that in the future the review step will only be triggered for previously blocked stations, and that stations on the unblocked list will automatically make it to public distribution without requiring review (Steidl et al., 2022).

2.4. Distribution

All NSMP products, raw and processed strong-motion datasets in COSMOS format, are distributed to the public at the CESMD (strongmotioncenter.org; Hagos et al., 2024). Data sources may be acknowledged via citations for individual networks that can be obtained using the International Federation of Digital Seismograph Networks (FDSN) reference tool (http://www.fdsn.org/networks/citation/) and guidance is provided in the "highlights" button on event pages such as the following for the 2023 Turkiye earthquake sequence: https://www.strongmotioncenter.org/NCESMD/data/us6000jllz/highlights_us6000jllz.pdf.

3. Recent NSMP Data Center Endeavors

To illustrate an overview of dataflow within the NSMP, as well as recent data center development projects, here we outline data from the field deployment stage to the NSMP data center, using examples at various types of instrumented locations that showcase free-field ground reference stations and structural arrays.

3.1. Data Acquisition Source Expan sion

The USGS Earthquake Monitoring Project (EMP) oversees two networks that are part of the ANSS – the NSMP (FDSN network code "NP", https://doi.org/10.7914/SN/NP) and the Northern California Seismic Network (NCSN), (FDSN network code "NC," https://doi.org/10.7914/SN/NC). These networks are two of many networks within the United States (U.S.) that comprise the ANSS, which includes a national backbone network, the National Earthquake Information Center (NEIC), the NSMP, and more than 15 regional seismic networks operated by the USGS and its partners. The NSMP operates and maintains strong-motion instruments at more than 660 free-field, and more than 3200 channels of data from about 180 structural arrays, which include buildings, dams, geotechnical, and bridge arrays. Some information regarding the overall NSMP mission and context within the USGS is detailed in the NSMP strategic plan (Aagaard et al., 2017); and details on how to access raw and processed data collected at these sites and others at CESMD is described in our companion WCEE paper (Hagos et al., 2024).

Why collect earthquake strong-motion data beyond the U.S.?

As part of its mission, the NSMP has a long history of acquiring and processing strong-motion data from "significant global earthquakes" around the world for inclusion at CESMD, both in a raw and processed form for easy access and use by the engineering community. Before late 2018 (when the automated workflow was deployed), the data were processed manually. As knowledge of probabilistic seismic hazard analysis (PSHA) has advanced to include ground motions from events of various magnitudes and tectonic environments, alongside the ability to automate workflow, the value and importance that earthquakes from all over the world offer is recognized. For example, the NGA-Subduction model (Bozorgnia et al., 2020) aimed to improve ground motion modelling in the Pacific Northwest but is based in part on a collection of waveforms from subduction zones around the world (i.e., Japan and Chile). Similarly, a PSHA may resolve the "controlling earthquake" for which earthquake engineers will need a global repository of earthquake time series to ensure possible ground motions at a specific site are bounded by the design spectra (i.e., Baker, 2011).

Some examples of relatively recent "significant global earthquakes" at CESMD (due to their large magnitude, impact to human lives and the human-built environment, and station record availability) include the 2010 M8.8 Chile; 2010 M7.1 and 2011 M6.2 Christchurch, New Zealand; 2010 M7 Haiti; 2011 M9.0 Tohoku, Japan; 2015 M7.8 Gorkha, Nepal; 2020 M7.4 Mexico; 2021 M7.3 Gisborne, New Zealand; 2021 M7.2 Petit Trou de Nippes, Haiti; and 2023 M7.8 Kahramanmaras, Turkiye, earthquakes. As open-source data and metadata become increasingly available, the opportunity to incorporate data at lower magnitude thresholds and from a variety of tectonic environments has significantly improved.

The NSMP aims to 1) backfill missing significant global earthquakes at CESMD where possible (Shao et al., 2024) for both interplate and intraplate tectonic environments and 2) proactively configure the NSMP Advanced Quake Monitoring System (AQMS) to read and process data from data centers around the globe. The development of the ground motion processing software by Hearne et al. (2019) known as “gmprocess” has also significantly advanced the ability to work with an increasing number of global datasets due to its integration of several webservices around the world. Figure 2 shows the stations from a variety of U.S. and international networks, for which the NSMP AQMS is currently configured for real-time processing. International networks have been added in an ad hoc fashion to process significant events of interest and NSMP is currently working to proactively identify the appropriate webservices and metadata for data acquisition to be “ready” to acquire, process, review, and distribute data for the next significant global earthquake. To this end, NSMP is also currently working towards integrating webservices for networks in Italy, New Zealand, Taiwan, Canada, Israel, and Colombia.

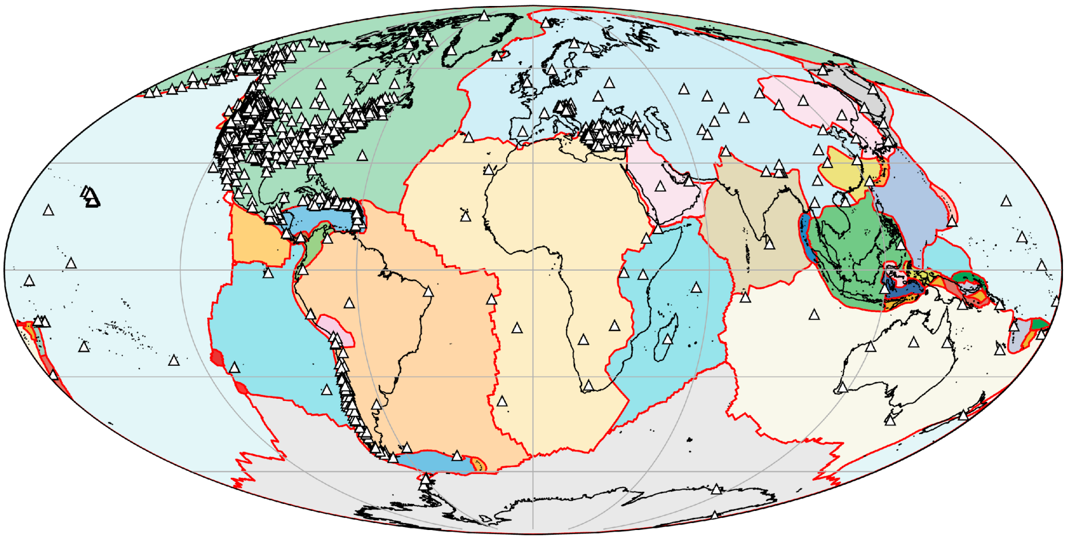

Figure 2. Tectonic plates (colored polygons; Bird, 2003; Ahelenius, 2014) ocean and landmass distribution, and currently active accelerometer sites (triangles) for networks currently incorporated into the NSMP AQMS automatic processing workflow (Projection: Mollweide)

The NSMP AQMS acquires waveform data and metadata from many networks across the U.S. from the EarthScope Consortium’s (SAGE, FDSN network codes = AZ, AE, AG, AK, AO, AY, CN, CO, CU+, CW, CY , DE, DR, EP, ET, FA, G, GI, GM, GS, HV, IC+, IE, II, IU+, IW+, JM, KY, LB, LD,LO, MB, N4+, NE+, NM, NN, NP, NQ, NV, NW, OK, OO, OQ, PB, PE, PO, PT, PY, RA, RB, RE, SB, SN, TA, TX, UO, US+, and UU) (formerly the Incorporated Research Institution for Seismology). A subset of the SAGE networks traverse the U.S. and extends globally (FDSN networks = CU, IC, IU, IW, N4, NE, and US). In California, the system queries the Northern California Earthquake Data Center (NCEDC, FDSN network codes = BG, BK, BP, NC, NP, PG, WR, and CE) and Southern California Earthquake Data Center (SCEDC, FDSN network code = CI) and it also queries local webservices hosted from some U.S. institutions (i.e., TX and PR). Additional information regarding each of these networks can be found at fdsn.org (accessed 2024).

To process significant global earthquakes in near real-time, NSMP has also begun exploring integrating international networks into its workflow to process earthquakes of interest to the engineering community. This is being implemented for earthquakes occurring in Chile from SAGE webservices distributed by the Chilean Seismic Network (CSN) (FDSN networks codes = CX, C1, C) (Leyton et al., 2024) and earthquakes proximal to Europe from the European Integrated Data Archive (EIDA) webservices (Strollo et al., 2021; Luzi et al., 2020; Cambaz et al., 2021; and Lanzano et al., 2021), starting with event sequences in Italy, and also from the Disaster and Emergency Management Authority (AFAD) Turkish Accelerometric Database and Analysis System (TADAS) in response to the February 2023 Mw Turkiye earthquake sequence (FDSN network codes – KO, TU, HL, HI, HA, HP and HC).

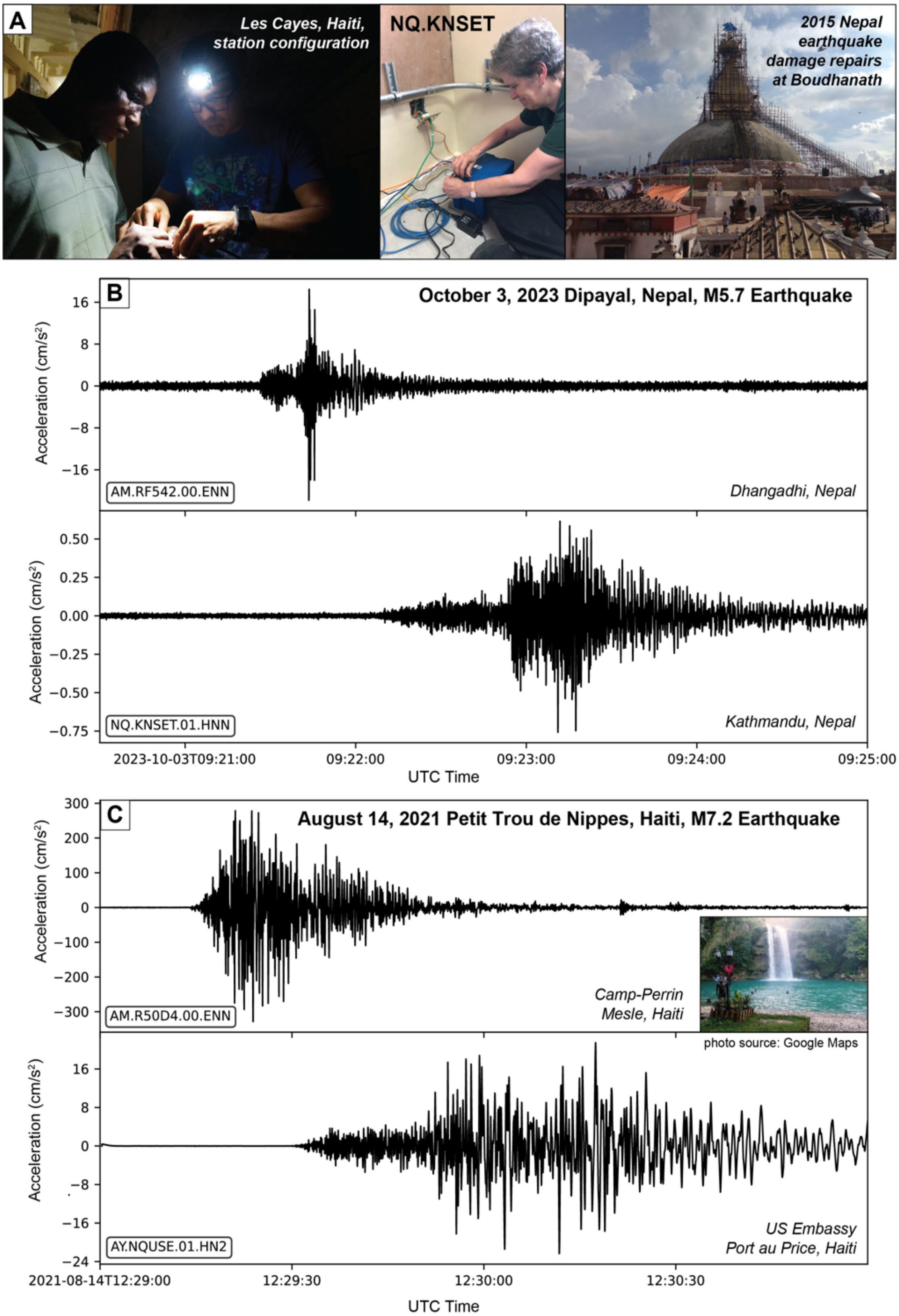

Figure 3. A) Field technicians servicing stations in Haiti (left) and Nepal (center) and a view of ongoing damage repairs in 2016 to Boudhanath following the 2015 Nepal Gorkha, earthquake (right); B and C) Waveform timeseries for two stations that recorded the 2023 Dipayal, Nepal, and 2021 Petit Trou de Nippes, Haiti damaging earthquakes. Data were acquired from RaspberryShake webservices (Christensen, 2024) and the NSMP Netquakes Winston Wave Server (Aagaard et al., 2017) and are in acceleration with units of cm/s^2 with instrument response correction, linear detrending, and a 0.3-40 Hz band pass filter applied.

Although the USGS continues to deploy seismic stations on a global scale for earthquake detection, additional collaboration and support may improve NSMP instrumentation and data collection outside the U.S. Figure 3 shows recent earthquakes recorded by the NSMP seismic stations temporarily deployed in Nepal (Dixit et al., 2015; McNamara et al., 2017) and by Raspberry Shake instruments supported by the United States Agency for International Development (USAID) deployed in Haiti (Douilly et al., 2023). The NSMP has begun to explore the potential value of incorporating Raspberry Shake ("AM" net code stations) with appropriate flagging and uncertainty (Christensen, 2024; Anthony et al., 2018) and further collaboration with global counterparts to configure additional data centers along with the appropriate citation and dataflow attribution into the NSMP workflow may improve data collection.

3.2. Metadata Quality Checks

In addition to manual quality checking of waveforms and metadata using the NSMP event review page (Steidl et al., 2022, Figures 2 and 3), the NSMP is working on developing scripts that can identify potential metadata issues before earthquakes occur. These same checks can also be deployed to flag problems during post-earthquake data response mode. The NSMP is also proactively using records of global large-magnitude (M7+) teleseisms recorded by multi-channel arrays to quality check building arrays in advance of potential strong-motion damaging regional and local earthquakes. NSMP envisions integrating these checks automatically into the workflow to identify and correct any issues and data more rapidly. The NSMP is also aiming to integrate various instrument state of health information into its processing workflow to increase transparency on data recovery following significant earthquakes (e.g., Massa et al., 2021) and to incorporate metadata checks from international counterparts into its workflow to flag anomalous stations within the system in advance of data distribution.

Flagging Metadata Inconsistencies Before and After Earthquakes

Pre-earthquake checks include flagging stations where the full-scale voltage range of the sensor exceeds the datalogger range and identifying cases where the overall station response sensitivity does not match the combined individual sensitivity values provided by the metadata source for the sensor and datalogger. Post-earthquake checks include methods for flagging potentially anomalous peak ground acceleration values by sorting stations by distance from the epicenter and comparison to estimates from regional ground motion models (Table 1). In addition, the NSMP has begun to develop scripts to programmatically flag metadata inconsistencies in a map view in addition to a list of stations with metadata issues. An example of flags related to the assumed bit-weight of the digitizer (Flag ID number 2 in Table 1) are shown for a recent earthquake in Washington in Figure 4.

Table 1. Metadata check goals to flag inconsistencies via script before and after earthquakes

Flag ID	Metadata Check	After Earthquake	Before Earthquake
1	Does the datalogger clip the sensor range?	Yes	Yes
2	Does the one-sided full-scale input of the data make sense assuming 24 bit?	Yes	Yes
3	Does the total combined instrument sensitivity match the individual sensor and datalogger sensitivity used by PRISM (and between data centers)?	Yes	Yes
4	Data Recovery/Completeness – did we get all the data?	Yes	No
5	Does the calculated peak ground acceleration (PGA) match other processing workflows (ShakeMap, gmprocess)?	Yes	No
6	Does site response explain anomalous PGAs?	Yes	No/Maybe

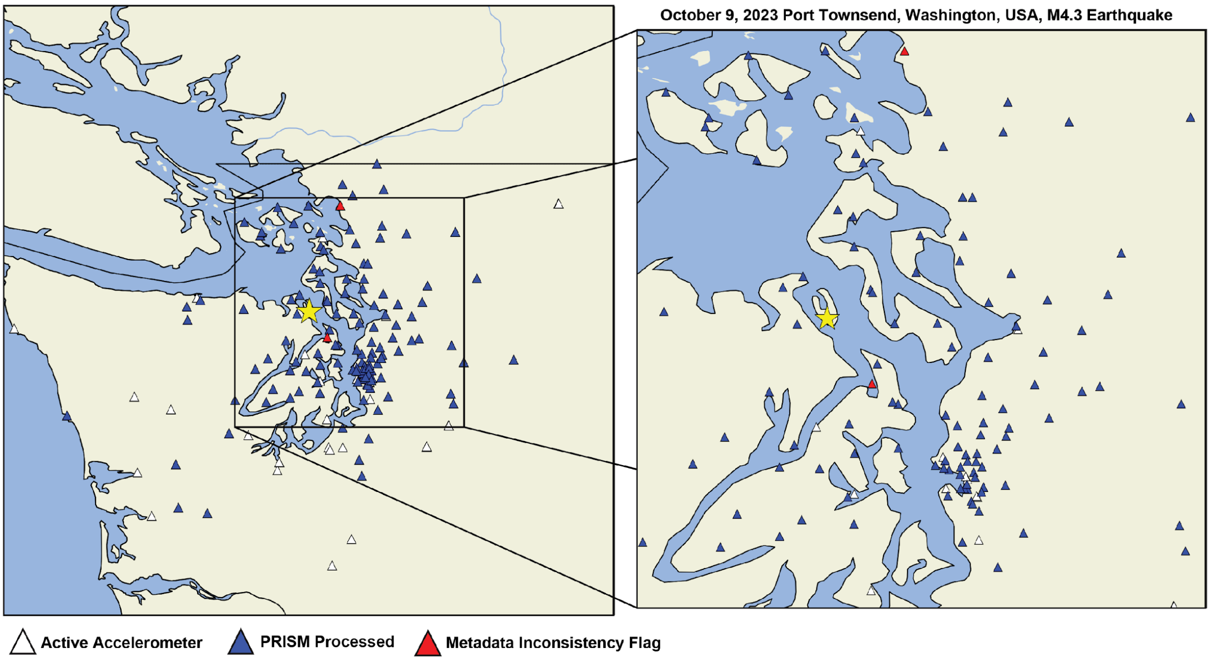

Figure 4. An example of map view output resulting from scripted metadata checks in Table 1 for the October 9, 2023 Port Townsend, WA, M4.3 earthquake (epicenter is the yellow star).

We have found including spatial information alongside the metadata flags aides in discovering and either correcting metadata inconsistencies or alternatively identifying stations requiring field response to address instrumentation issues (e.g. replacement of a failed sensor). The NSMP has begun to incorporate these scripts into automatic production of webmaps within ArcGIS Online Platform to facilitate field campaigns for maintenance and data recovery (Figure 5) to address data gaps following major quakes. The NSMP is also using this platform to track long-standing metadata issues requiring correction in underlying metadata repositories and for comparisons of peak ground acceleration values calculated by ShakeMap (Worden et al., 2019) and gmprocess (Hearne et al., 2021).

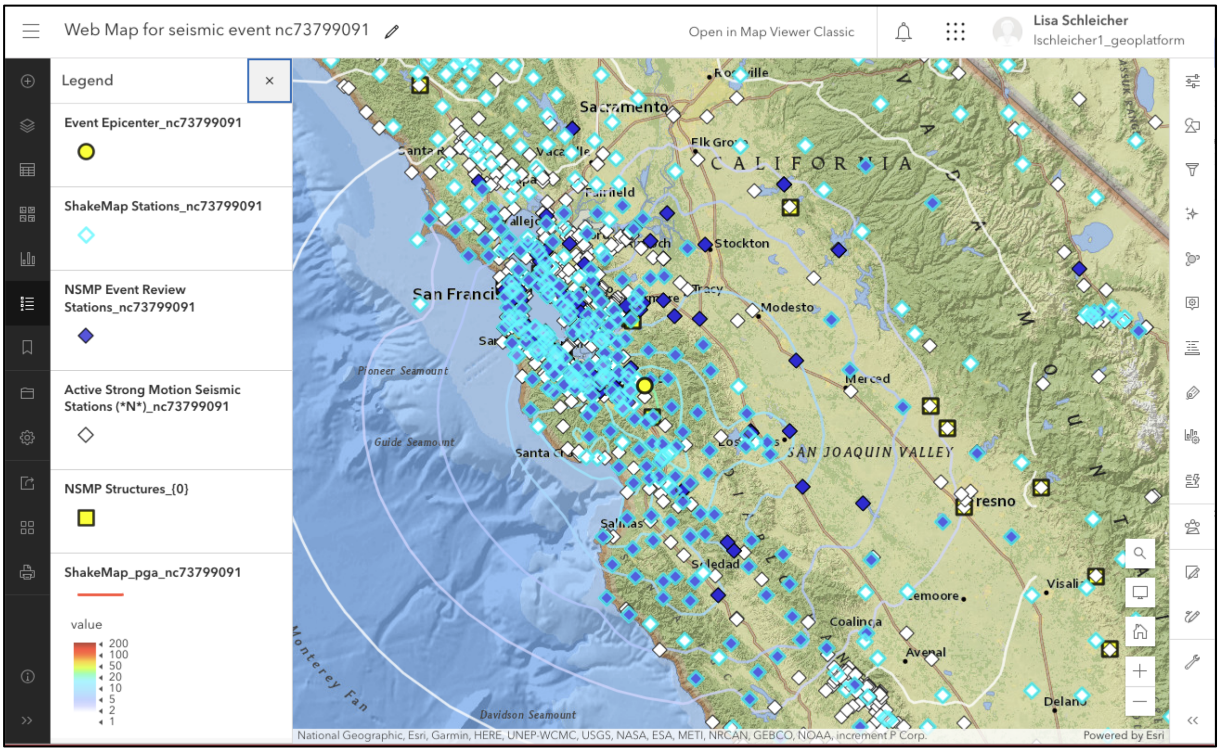

Figure 5. Example script generated webmap for the 2022 Alum, Rock, California earthquake

Systematic Quality Control of Multi-channel Building Structural Arrays using Teleseisms

Recordings of large earthquakes from structures (e.g., buildings, dams, bridges) are critical for understanding performance during strong shaking. These data help with structural-health assessments following potentially damaging events and can also inform the design of future earthquake-resistant structures. The NSMP currently operates approximately 190 structural arrays with over 3200 channels in the U.S., which includes 90 buildings, 76 dams, 16 bridges or overpasses, 19 geotechnical or boreholes, and five miscellaneous arrays (see: https://earthquake.usgs.gov/monitoring/nsmp/) (Aagaard et al., 2017).

To improve the rapid and accurate dissemination of strong-motion waveform data, the NSMP is currently implementing a systematic review of the metadata and schematics associated with its structural instrumentation using teleseisms and regional earthquake recordings. The approach uses filtered long-period data from various large magnitude earthquakes around the world to enable the analyst to quickly discover where data channels within the structures deviate from the expected metadata database and identify potential sensor malfunctions. This approach works especially well with multi-channel stacked arrays, such as building arrays, for which the long period energy recorded by modern dataloggers can reveal potential issues in advance of a major strong-motion earthquake. Some examples of buildings with NSMP-monitored multi-channel arrays in the San Francisco Bay area are shown in Figure 6. The NSMP has also found this approach to be useful for field planning to identify failing sensors and for performing quality checks following major upgrades to instrumentation (Figure 7).

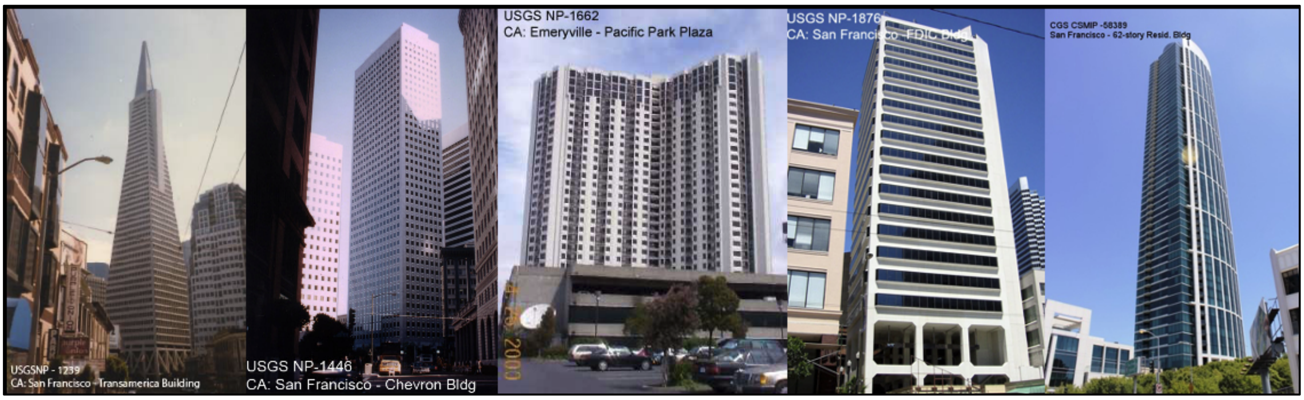

Figure 6. San Francisco Bay Area Multi-Channel Building Arrays monitored by NSMP and CSMIP

Figure 7. 2022 upgrade to digitizer at Berkeley City Hall, California

The NSMP began collecting teleseisms at structures in 2020 and has now collected data at all NSMP building arrays with IP telemetry paths and modern instrumentation. The NSMP successfully identified errors using events such as: the 4 March 2021, Mw 7.3 earthquake near Gisborne, New Zealand; the 8 July 2021, Mw 6.0 Antelope Valley earthquake; and the 28 November 2021, Mw 7.5 earthquake near Barranca, Peru, and continues to build on the database of teleseism events for quality-checking structures. Most recently, the 6 February 2023, Mw7.8 Turkiye and 9 September 2023, Mw 6.8 Morocco earthquakes were added to the repository. This approach is particularly useful for highlighting cases where sensors may be oriented in the structure differently than described by metadata and seismic array schematics, so that corrections can be made in advance of the next local triggering strong-motion event. The NSMP has begun tracking structures having good data for future automatic transfer to CESMD and to others that need corrections to metadata before distribution.

3.3. Waveform Processing Benchmarking

Waveform data at CESMD are currently processed by either the California Geological Survey's (CGS) California Strong-Motion Instrumentation Program (CSMIP) or the USGS NSMP. Generally, the processing workflow is aligned by network (but not always) according to the following FDSN network codes: CSMIP: CE, BK. CI, NC, and WR; NSMP: NP, and all other regional and global networks. CGS processing is based on the CSMIP Strong-motion Automated Recovery and Analysis (SARA) software (Shakal et al., 2018). In 2018, the NSMP adopted the PRISM software package for data processing (Jones et al, 2017). CESMD waveform datasets are primarily provided in either COSMOS (COSMOS Strong-Motion Programs Board, 2001) or in CGS format (Shakal and Huang, 1985). In parallel, the USGS Geologic Hazard Science Center (GHSC) has developed gmprocess in part to support ShakeMap operations (Hearne et al., 2019).

The NSMP recently developed new code that is integrated into the latest version of gmprocess that allows "PRISM-like" processing when a unique processing configuration file is applied that allows multi-channel array processing (i.e., building structural array), a constant filtering approach, and PRISM's corner frequency method. Our ongoing work involves "benchmarking" comparisons of PRISM, SARA, and gmprocess (i.e., Kalkan and Stephens, 2017) that is geared towards the overall vision to compare and possibly integrate the various waveform processing workflows (Aagaard et al., 2022). The NSMP is also developing a COSMOS V0 writer within gmprocess leveraging ObsPy (Beyreuther et al., 2010) station metadata readers to facilitate processing significant global earthquakes recorded by networks of various metadata schemas.

Preliminary comparison of processed waveforms between PRISM, SARA, and gmprocess indicate that similar results can be achieved with each processing software and differences are statistically insignificant (Figure 8). The NSMP envisions streamlining the processing workflows to improve user access to the waveforms behind ShakeMap for rapid response applications as well as providing traditional quality vetted products for engineering applications at CESMD, such as the rapid raw strong-motion (RRSM) and engineering strong-motion (ESM) repositories of the Observatories and Research Facilities for European Seismology (ORFEUS) coordinated strong-motion seismology services (Lanzano et al., 2021; Aagaard et al., 2022).

3.4. Dynamic Site Characterization Repository

The NSMP is currently working on a strategy to integrate a recent compilation of geologic characteristics and estimates of seismic velocity at the US ANSS strong-motion accelerometer sites archived by the CESMD (Huddleston et al., 2021). The extensive number of parameters in the compilation presents an interesting challenge in how to best represent the complexity of the information alongside the waveform repository at CESMD. Additional information regarding the schema being developed for implementation at CESMD is detailed in Hagos et al. (2024). The NSMP is also also working to incorporate this information into the pre- and post-earthquake station data checks to identify sites with anomalous ground motion effects influenced mainly by local site characteristics. The most recent effort includes adding the maximum recorded peak ground acceleration and number of records at each station to facilitate planning and prioritizing new field measurements, and integrating the information into a "living" dashboard where users can contribute new measurements to the database.

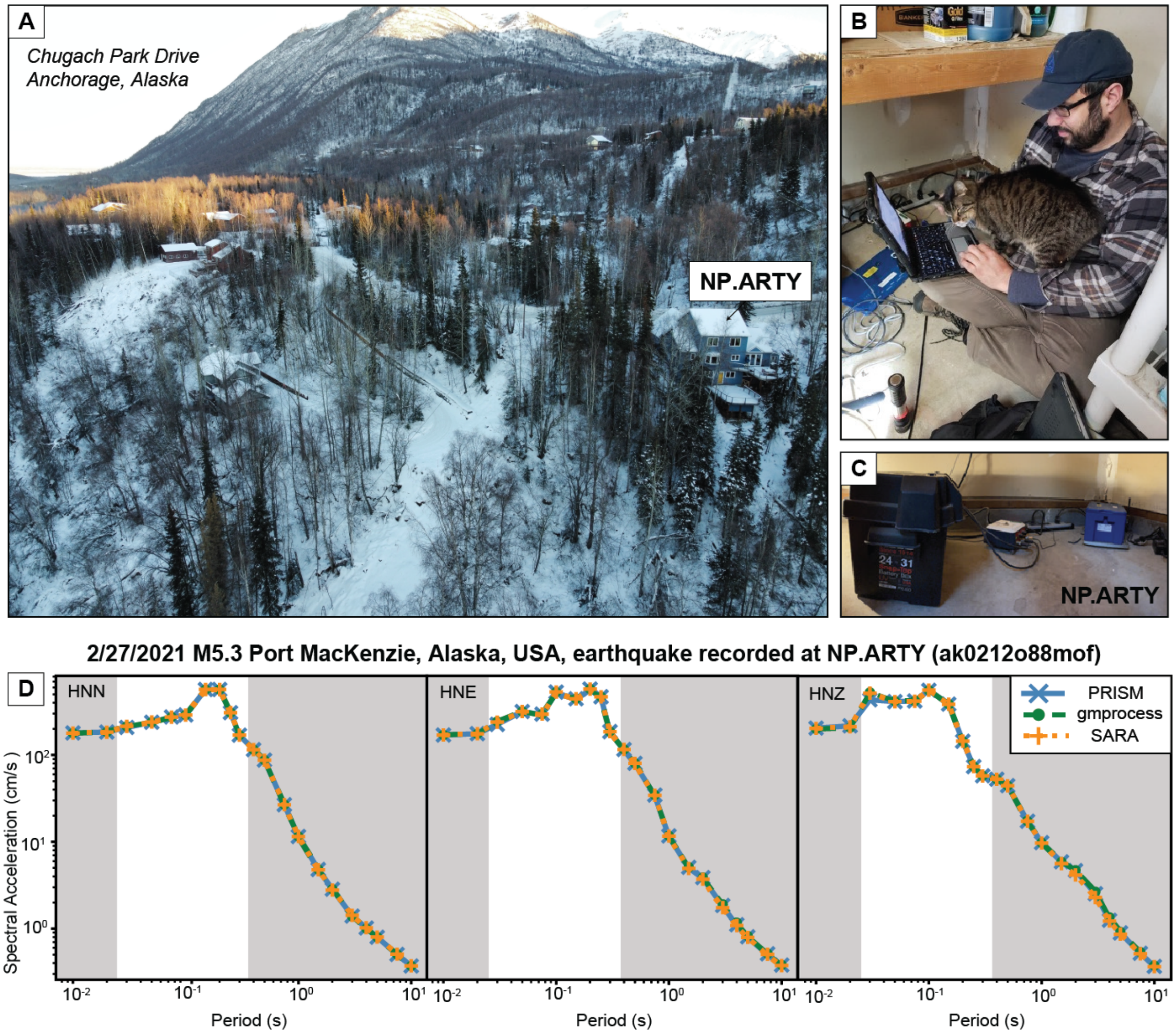

Figure 8. A) Site NP.ARTY in the Chugach Mountains, Alaska, USA; B) NSMP field technician works on station ARTY with assistance from a local resident; C) instrumentation configuration (GeoSIG GMS-IA18 NetQuakes); crack in wall from 2018 Anchorage M7.1 earthquake is visible; and D) spectral accelerations of the 2021 M5.3 Point MacKenzie, Alaska, earthquake processed via PRISM (Jones et al., 2017), gmprocess (Hearne et al., 2019), and SARA (Shakal et al., 2018).

4. Global Strong-motion Community Collaboration

We conclude by reiterating the significant benefit of global collaboration among strong-motion data centers and participation in new initiatives to advance strong-motion data acquisition, processing, and distribution. Topics of interest may include declaration of webservices available from strong-motion data centers at the International Federation of Digital Seismograph Networks (FDSN) and development of international standards for strong-motion data processing methods and products. In the end, these efforts may streamline and facilitate access to data about significant global earthquakes for members of the earthquake engineering community around the world.

5. Acknowledgements

We thank CSMIP staff, especially Hamid Haddadi, Lijam Hagos, Mahesh Dhar, Heather Crume, and Adam Gardner for the USGS NSMP and CGS partnership that allows NSMP data to be accessible at CESMD by the earthquake engineering community and for collaboration on the various topics discussed in this paper. We would also like to thank Paul Hegarty who developed the code behind the NSMP review page. We also thank the peer-reviewers for their valuable inputs and constructive feedback that improved this manuscript.

Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

6. References

Aagaard, B., Celebi, M., Gee, L., Graves, R., Jaiswal, K., Kalkan, E., Knudsen, K., Lico, N., Smith, J., Steidl, J., Stephens, S. (2017). U.S. Geological Survey National Strong-Motion Project Strategic Plan, 2017-22, USGS Open-File Report, 2017-1156.

Aagaard, B., Wald, D.J., Thompson, E.M., Hearne, M., and Schleicher, L.S. (2022). Improving the Development Pipelines for USGS Earthquake Hazards Program Real-Time and Scenario Products, *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT.

AFAD-TADAS, R.T. Ministry of Interior, Disaster of Emergency Management Presidency, Department of Earthquake, Turkish Accelerometric Database and Analysis Software, https://tadas.afad.gov.tr/.

Anthony, R.E., Ringler, A.T., Wilson, D.C., Wolin, E. (2019), Do Low-Cost Seismographs Perform Well Enough for Your Network? An Overview of Laboratory Tests and Field Observations of the OSOP Raspberry Shake 4D, *Seismological Research Letters*, 90(1):219-228, doi:10.1785/0220180251.

Ahelenius, H. (2014). World tectonic plates and boundaries, https://github.com/fraxen/tectonicplates.

Baker, J. (2011). Conditional Mean Spectrum: Tool for ground motion selection, Journal of Structural Engineering, 137(3):322-331, doi:10.1061/(ASCE)ST.1943-541X.000021.

Bird, P. (2003). An update digital model of plate boundaries, 4(3), doi:10.1029/2001GC000252.

Beyreuther, M., Barsch, R., Krischer, L., Megies, T., Behr, Y., and Wassermann, J. (2010). ObsPy: A Python Toolbox for Seismology, Seismological Research Letters, 81(3):530-533, doi:10.1785/gssrl.81.3.530.

Bozorgnia Y., Stewart J.P., Abrahamson N.A., Ahdi S.K., Ancheta T.D., Archuleta R.J., Atkinson G.M., Boore D.M., Boroschek R, Campbell K.W., Chiou B.S.-J., Contreras V., Darragh R.B., Gregor N., Gulerce Z., Idriss I.M., Ji C., Kamai R., Kishida T., Kuehn N., Kwak D.Y., Kwok A.O., Lin P.S., Magistrale H., Mazzoni S., Muin S., Midorikawa S., Parker G.A., Si H., Silva W.J., Walling M., Wooddell K.E., Youngs R.R. (2020). PEER Report No. 2020/02.

Cambaz M.D., Özer M., Güneş Y, Ergün, T., Öğütcü, Z., Altuncu-Poyraz, S., Köseoğlu, A., Turhan, F., Yilmazer, M., Kekovali, K., Necmioğlu, O., Kalafat, D., Çakti, E., and Özener, H. (2021). Evolution of the Kandilli Observatory and Earthquake Research Institute (KOERI) Seismic Network and the Data Center Facilities as a Primary Node of EIDA, *Seismological Res Letters*, doi:10.1785/0220200367.

Cauzzi, C., Bieńkowski, J., Crawford, W., Custódio, S., D'Amico, S., Evangelidis, C., Haberland, C., Haslinger, F., Kiratzi, A., Kolínský, P., Lanzano, G., Roumelioti, Z., Sigloch, L., Sleeman, R., and Strollo, A. (2024). ORFEUS Data Services, Products and Actions to Coordinate Access to Seismic Waveform Data in the Euro-Mediterranean Region, EGU-23-9051, doi:10.5194/egusphere-egu23-9051.

Christensen, B. (2024). Raspberry Shake: the largest real-time streaming seismic network in the universe, *Proceedings of the 18th World Conference on Earthquake Engineering*, Milan, Italy.

COSMOS Strong-Motion Programs Board (2001). COSMOS Strong-Motion Data Format, v. 1.20, https://www.strongmotioncenter.org/NCESMD/reports/cosmos_format_1_20.pdf

Dewey, J., and Byerly, P. (1969). The early history of seismometry (to 1900), Bulletin of the Seismological Society of America, 59(1): 183-227, doi:10.1785/BSSA0590010183.

Dixit, A.M., Ringler, A.T., Sumy, D.F., Cochran, E.S., Hough, S.E., Martin, S.S., Gibbons, S., Luetgert, J.H., Galetzka, J., Shrestha, S.N., Rajaure, S., and McNamara, D.E. (2015). Strong-Motion Observations of the M 7.8 Gorkha, Nepal, Earthquake Sequence and Development of the N-SHAKE Strong-Motion Network, Seismological Research Letters, 86(6):1533-1539, doi:10.1785/0220150146.

Douilly, R., Paul, S., Monfret, T., Deschamps, A., Ambrois, D., Symithe, S.J., St Fleur, S., Rupture segmentation of the 14 August 2023 Mw 7.2 Nippes, Haiti, earthquake using aftershock relocation from a local seismic deployment, *Bulletin of the Seismological Society of America*, 113(1):58-72, doi:10.1785/0120220128.

Fee, J. (2019). USGS Product Distirbution Layer, https://code.usgs.gov/ghsc/hazdev/pdl.

Hagos, L., Haddadi, H., Schleicher, L., Steidl, J., Thompson, E.M., Crume, H., Dhar, M., and Leue, N. (2024). New Developments at the Center for Engineering Strong-Motion Data (CESMD), *Proceedings of the 18th World Conference on Earthquake Engineering*, Milan, Italy.

Hearne, M., E. M. Thompson, H. Schovanec, J. Rekoske, B. T. Aagaard, and C. B. Worden (2019). U.S. Geological Survey automated ground motion processing software, USGS Software Release, doi:10.5066/P9ANQXN3.

Huddleston, G.J., Schleicher, L., Knudsen, K., Gee, L., Steidl, J. (2021). Compilation of Geologic and Seismic Velocity Characteristics at Advanced National Science System Strong-Motion Accelerometer Sites, U.S. Geological Survey Data Release, doi:10.5066/P9YKIUW2.

Jones, J., Kalkan, E., Stephens, C. (2017). Processing and Review Interface for Strong-Motion Data (PRISM)-Methodology and Automated Processing, *U.S. Geological Survey Open-File Report*, 2017–1008, 81 p.

Kalkan, E., Stephens, C. (2017), Systematic comparisons between PRISM version 1.0.0, BAP, and CSMIP ground motion processing, *U.S. Geological Survey Open-File Report*, 2017-1020.

Lanzano, G., Luzi, L., Cauzzi, C., Beinkowski, J., Bindi, D., Clinton, J., Cocco, M., D'Amico, M., Douglas, J., Faenza, L., Felicetta, C., Gallovic, F., Fiardini, Ktenidou, O., Lauciani, Mankou, M., Marmureanu, A., Maufoy, E., Michelini, A., Özener, H., Puglia, R., Rupakhety, R., Russo, E., Shahvar, M., Sleeman, R., Theodoulidis, N. (2021). Accessing European Strong-Motion Data: An Update on ORFEUS Coordinated Services, Seismological Research Letters, 92(3): 1642-1658 doi:10.1785/0220200398.

Leyton, F., Garcia, B., and Montalva, G. (2024). The Strong-Motion Database of the Chilean Seismological Centre, *Proceedings of the 18th World Conference on Earthquake Engineering*, Milan, Italy.

Luzi L., Lanzano G., Felicetta C., D'Amico M. C., Russo E., Sgobba S., Pacor, F., & ORFEUS Working Group 5 (2020). Engineering Strong-Motion Database (ESM) (Version 2.0), https://esmdb.eu/. Istituto Nazionale di Geofisica e Vulcanologia (INGV), doi:10.13127/ESM.2.

Massa, M., Scafidi, D., Mascandola, C., and Lorenzetti, A. (2021). Introducing ISMDq-A Web Portal for Real-Time Quality Monitoring of Italian Strong-Motion Data, Seismological Research Letters, 93(1): 241-256, doi: 10.1785/0220210178.

McNamara, D.E., Yeck, W.L., Barnhart, W.D., Schulte-Pelkum, V., Bergman, E., Adhikari, L.B., Dizit, A., Hough, S., Benz, H.M., and Earle, P.S. (2017). Source modeling of the 2015 Mw 7.8 Nepal (Gorkha) earthquake sequence: Implications for geodynamics and earthquake hazards, Tectonophysics, 21-30, doi:10.1016/j.tecto.2016.08.004.

Neumann, F. (1935). Some New Data on Longe Period Waves in Epicentral Areas, Seismological Research Letters, 7(1-2): 13, doi:10.1785/gssrl.7.1-2.13.

Shakal, A., Haddadi, H., Reitz, T., (2018), Developments in the CSMIP Strong-motion Automated Recovery and Analysis (SARA) System, *Eleventh U.S. National Conference on Earthquake Engineering Integrating Science, Engineering & Policy*, Los Angeles, California.

Shakal T., Huang, H.J., (1985). Standard Tape Format for CSMIP Strong-Motion Data Tapes, California Department of Conservation Division of Mines and Geology Office of Strong-Motion Studies Report OSMS 85-03, https://www.strongmotioncenter.org/NCESMD/reports/DMGformat85.pdf.

Shao, H., Brody, J., Schleicher, L., Marano, K., Steidl, J., Thompson, E., Hearne, M. (2024). International Data Gaps at the Center for Engineering Strong-Motion Data, *Proceedings of the 18th World Conference on Earthquake Engineering*, Milan, Italy.

Steidl, J, Hegarty, P, Schleicher, L, Brody, J, Gee, L. (2022). Modernization of Data Processing and Review at the U.S. Geological Survey's National Strong-Motion Project (NSMP), *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT.

Strollo A, Cambaz D, Clinton J, et al (2021), EIDA: The European Integrated Data Archive and Service Infrastructure within ORFEUS. Seismological Research Letters, doi:10.1785/0220200413.

USGS, Earthquake Hazards Program (2017), Advanced National Seismic Systems (ANSS) Comprehensive Catalog of Earthquake Events and Products: Various, doi: 10.5066/F7MS3QZH.

Worden, C. B., Hearne, M., and Thompson, E. M. (2018). ShakeMap v4 Software, *USGS Software Release*. doi:10.5066/P97FHE0I.