# INTERNATIONAL DATA GAPS AT THE CENTER FOR ENGINEERING STRONG MOTION DATA

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**Abstract**: *The Center for Engineering Strong Motion Data (CESMD) is utilized by seismologists, engineers, and disaster management professionals in the US and has historically achieved and distributed waveforms from across the globe for significant earthquakes. The increased access to the waveforms via Web API (Application Programming Interface) offers a unique opportunity to provide the community complete datasets, sampling a variety of tectonic environments and geologic conditions, increasing the number of available ground motion records for use in ground motion models (GMMs) and improving the accuracy of earthquake engineering evaluations. The objective of this study is to programmatically identify gaps in global event data from the past decade and backfill missing data gaps at CESMD. We first compare the CESMD catalog with the Advanced National Seismic System (ANSS) Comprehensive Earthquake Catalog identifying regions and time periods where strong-motion data is limited or inadequate. To backfill datasets at CESMD for significant events, we pinpoint regions and time intervals that lack information, creating a list of events for which we'd like to obtain data. An important facet of this work is identifying the source of data and metadata across earthquake repositories around the world and integrating these data repositories into our current strong-motion data processing workflow. In parallel with these newly processed datasets, we are developing a script to produce data origination citations to include provenance and attribution information to associate with respective datasets at CESMD. We showcase our methodology for identifying and filling data gaps at CESMD using three case studies (the 2018 Anchorage Alaska earthquake sequence, seismicity associated with the 2018 Hawaiian Kilauea volcano eruption, and several earthquakes in Turkey) and then outline our strategy to apply our data gap backfilling methods on an international scale.*

## 1. Introduction

The Center for Engineering Strong Motion Data (CESMD) is a collaborative initiative that emerged from the partnership between the US Geological Survey (USGS) and the California Geological Survey (CGS). Its fundamental objective is the integration of strong-motion earthquake data collected from diverse sources, including the CGS California Strong Motion Instrumentation Program, the USGS National Strong Motion Project (NSMP), and the Advanced National Seismic System (ANSS) (USGS,2017). CESMD offers a comprehensive repository of raw and processed strong-motion data specifically designed for use in earthquake engineering applications. In recent years, it has increased accessibility to these seismic waveforms via web application programming interface (Web API) (Hagos et al., 2024). This transformative change presents an opportunity to bolster the global earthquake engineering community's efforts in evaluating seismic hazards and improving design to earthquake resilient infrastructure. The utilization of the CESMD API promotes accessibility of comprehensive datasets, provides a standard format for our user community, and enriches the resources available for ground motion modelling.

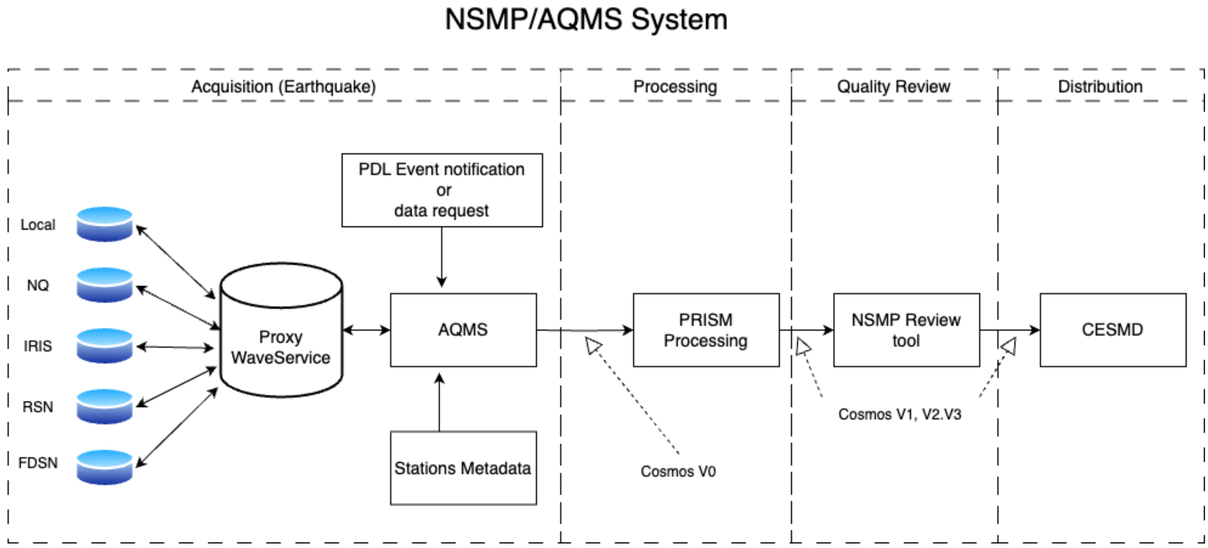



*Figure 1. The USGS NSMP/AQMS system automatically acquires, processes, reviews, and posts SM data (Steidl et al., 2022)*

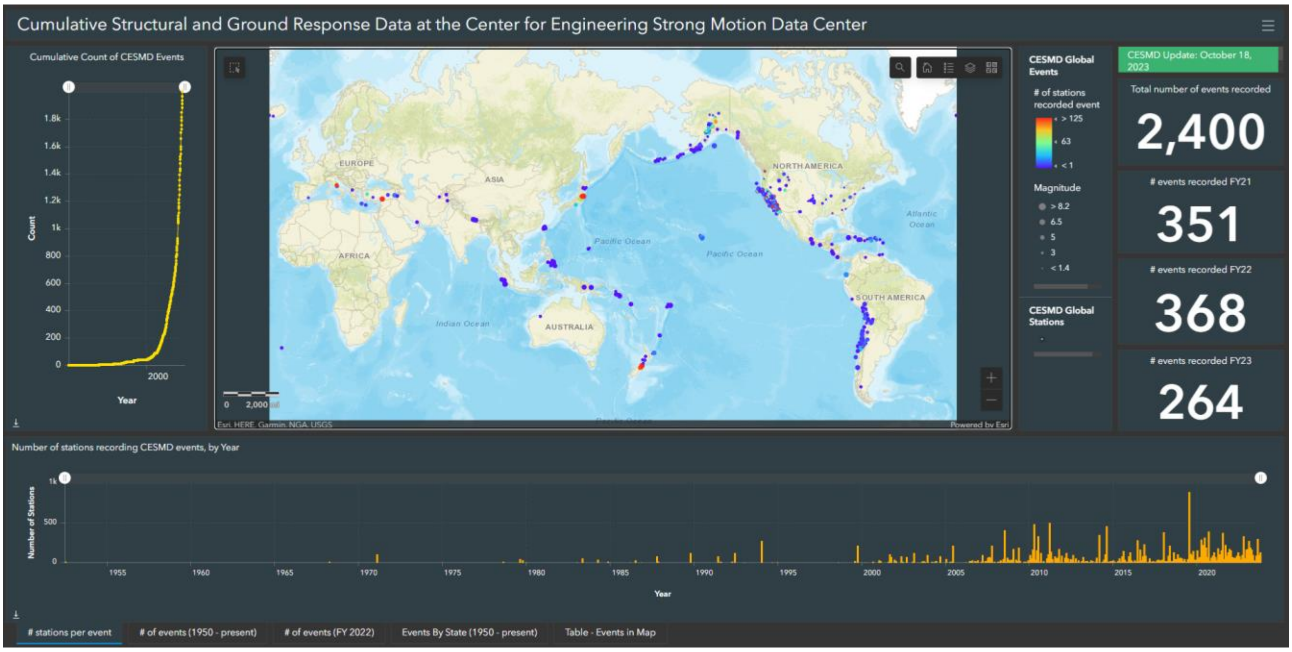



*Figure 2. CESMD Earthquake Dashboard. This is a cumulative dashboard for CESMD. It shows the number of events available from CESMD. The map demonstrates the events' location and magnitude. The number of events is represented by size and the number of stations is represented by colour.*

In 2018, the NSMP established an optimized procedure to integrate the PRISM (Processing and Review Interface for Strong Motion data) (Jones, J.M 2019), processing engine with the ANSS Quake Monitoring System (AQMS) (Steidl et al., 2022). When event alerts are sent out via the USGS Product Distribution Layer (PDL) messaging platform and the events meet magnitude and proximity thresholds, the system autonomously acquires data, encompassing both data and metadata, from these stations (Steidl et al., 2022). The data is gathered from various data repositories along with station metadata in the formats of Federation of Digital Seismic Networks StationXML and Dataless SEED Standard for the Exchange of Earthquake Data. The data and metadata are converted into the COSMOS V0 raw data format, then transferred to PRISM for the creation of COSMOS V1, V2, and V3 data products (Steidl et al., 2022). To ensure data quality, it is reviewed before being made publicly available on CESMD (Steidl et al., 2022). The complete workflow is shown in Figure 1. The primary goal of this study is to programmatically identify gaps within CESMD's archives in the United States (US) and on a global scale, and acquire, process, review, and distribute raw and processed strong-motion data to the CESMD archive through the NSMP AQMS system. CESMD has archived over 2,400 earthquakes and more than 5,000 stations (Figure 2). In the past three years, this effort about 1,000 events to CESMD through the AQMS system.

## 2. Methodology to Identify Missing Events and to Put Recovered Data Into CESMD.

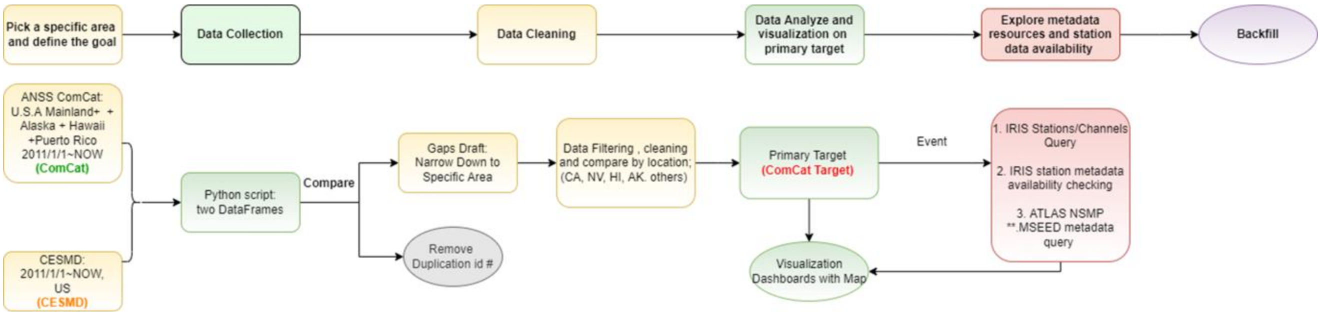



*Figure 3. Project workflow. This workflow shows the six phases of the project in the United States. Internationally, we use the same workflow and change the parameters in each step.*

The comparative analysis between the CESMD data catalog and the ANSS Comprehensive Catalog (ComCat) is a crucial step in the approach (USGS,2017). By utilizing web APIs, the scripts meticulously examines earthquake events recorded in both catalogs, with a particular focus on 1) discrepancies in the number of earthquakes within the same time frame, 2) the existence of different earthquake identifiers for the same events, and 3) inconsistencies in earthquake source parameters such as magnitude values. This comparative analysis aims to highlight and document any significant differences observed between the CESMD and ANSS catalogs (Figure 3).

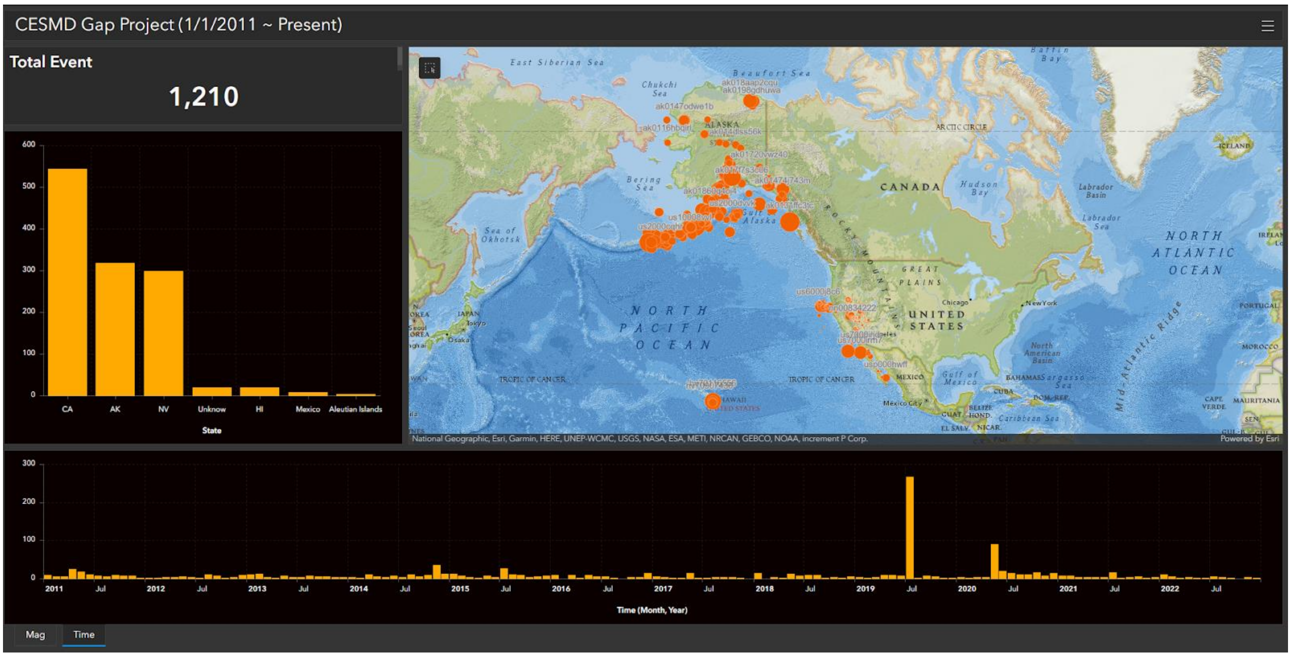



*Figure 4. U.S. CESMD Earthquake Gaps Dashboard (geoplatform.gov).*

In the data cleaning and visualization phase of the workflow, Tableau and ESRI's ArcGIS Online Dashboards are the major tools used to visually represent and perform statistical analysis. Figure 4 illustrates both the quantity and geographical distribution of earthquakes in the United States from January 1st, 2011, to September 1st, 2023, to consider adding to our processing workflow (ANSS Comcat). Due to the substantial volume of data involved, the work is divided into multiple sections based on regions, magnitudes, and time periods, each with its own priority. We aim to provide raw and processed strong-motion waveforms with PGA values greater than 0.1%g for magnitude 3.0 earthquakes and larger in California and M4.0 and larger within the conterminous US, Hawaii, Puerto Rico, and Alaska. Datasets of interest to the engineering and geophysics communities, such as event sequences in areas of induced seismicity and significant global events, are processed and posted at the CESMD at strongmotioncenter.org. For earthquake events outside the US, we seek to collaborate with the international strong-motion community for acquiring, processing, attributing, and making the data available through CESMD.

The other main part of the project is finding and processing metadata. We began by focusing our data infilling effort on the 2018 Anchorage Alaska earthquake sequence and the 2018 Hawaiian earthquakes associated with lava flows. These earthquake sequences are of unique seismic and geologic interest and were missed because of a brief system outage. The main sources of metadata are the International Federation of Digital Seismograph Networks (FDSN) web services, and a data inventorying database internal to USGS, comparable to the IRIS mseedindex application (IRIS). The FDSN is a global organization comprised of groups responsible for the installation and maintenance of seismographs and collaboration on data sharing. Internationally, the metadata collection has predominantly relied on FDSN tools by conducting targeted searches across various seismic monitoring stations to gather the necessary metadata. This collaborative effort facilitates global scientific research, primarily in the field of Earth Science, and more specifically, in the study of seismic activity across the globe. After integrating the data, the metadata are processed using AQMS and PRISM (Jones, J.M 2019), which generates plots of acceleration, velocity, and displacement time series, along with spectral response acceleration data and its associated information (Steidl et al., 2022). Finally, all the data products produced are distributed via CESMD, to allow instant access for users engaged in post-earthquake assessments and subsequent analyses.

## 3. Strategy for International Scale Implementation

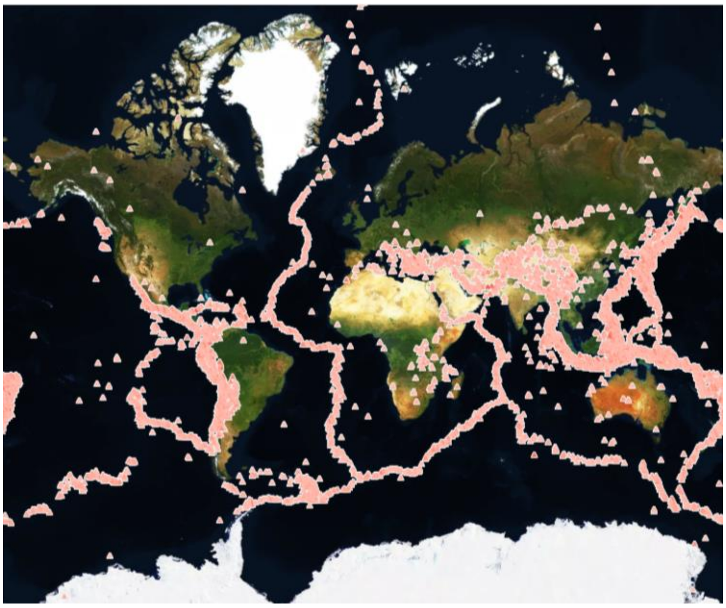


*Figure 5. International Missing Events Map (2011~2023, M >5.0).*

The process of recovering international earthquake events presents a considerably greater degree of complexity as compared to events within the United States. Upon the initial phase of data collection for the past 10 years, we found more than 19,000 potential missing earthquakes with M>5.0. They necessitate a strategic approach aimed at streamlining the investigative effort. As depicted in Figure 5, earthquakes exhibit a pronounced concentration pattern along well-defined seismic zones. To effectively navigate this vast dataset, a crucial step involves narrowing the investigative focus to specific regions or countries and increasing the magnitude threshold. This process serves to enhance the efficiency of data analysis and resource allocation. Figure 6 is a summary view of the overall initial targets. The majority of targets have a magnitude lower than 6.0. For the first phase of our backfilling effort, the prioritized target magnitude was increased to M7.0, which narrowed the targets down to 155 events. In the next phase, the targets were cross-referenced with the list of stations in the ShakeMap Atlas. (Marano, K.D.,2023). This process will help us pinpoint 'important' earthquakes, as events in the ShakeMap Atlas have been chosen based on human impact, population density, and the presence of at-risk-infrastructure, providing valuable insight for the project.

Yearly Summary With Number of Missing Events

| Mag (gro.. | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | Grand T.. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| > M7 | 19 | 16 | 17 | 10 | 15 | 10 | 6 | 12 | 9 | 5 | 15 | 7 | 14 | **155** |
| M6 | 184 | 110 | 117 | 134 | 118 | 123 | 94 | 105 | 126 | 92 | 123 | 97 | 97 | **1,520** |
| M 5 | 2,417 | 1,498 | 1,381 | 1,525 | 1,309 | 1,472 | 1,355 | 1,544 | 1,418 | 1,186 | 1,936 | 1,483 | 1,122 | **19,646** |

| Mag (gro.. | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | Grand T.. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| > M7 | 0.73% | 0.99% | 1.12% | 0.60% | 1.04% | 0.62% | 0.41% | 0.72% | 0.58% | 0.39% | 0.72% | 0.44% | 1.14% | **0.73%** |
| M6 | 7.02% | 6.77% | 7.72% | 8.03% | 8.18% | 7.66% | 6.46% | 6.32% | 8.11% | 7.17% | 5.93% | 6.11% | 7.87% | **7.13%** |
| M 5 | 92.25% | 92.24% | 91.16% | 91.37% | 90.78% | 91.71% | 93.13% | 92.96% | 91.31% | 92.44% | 93.35% | 93.45% | 91.00% | **92.14%** |

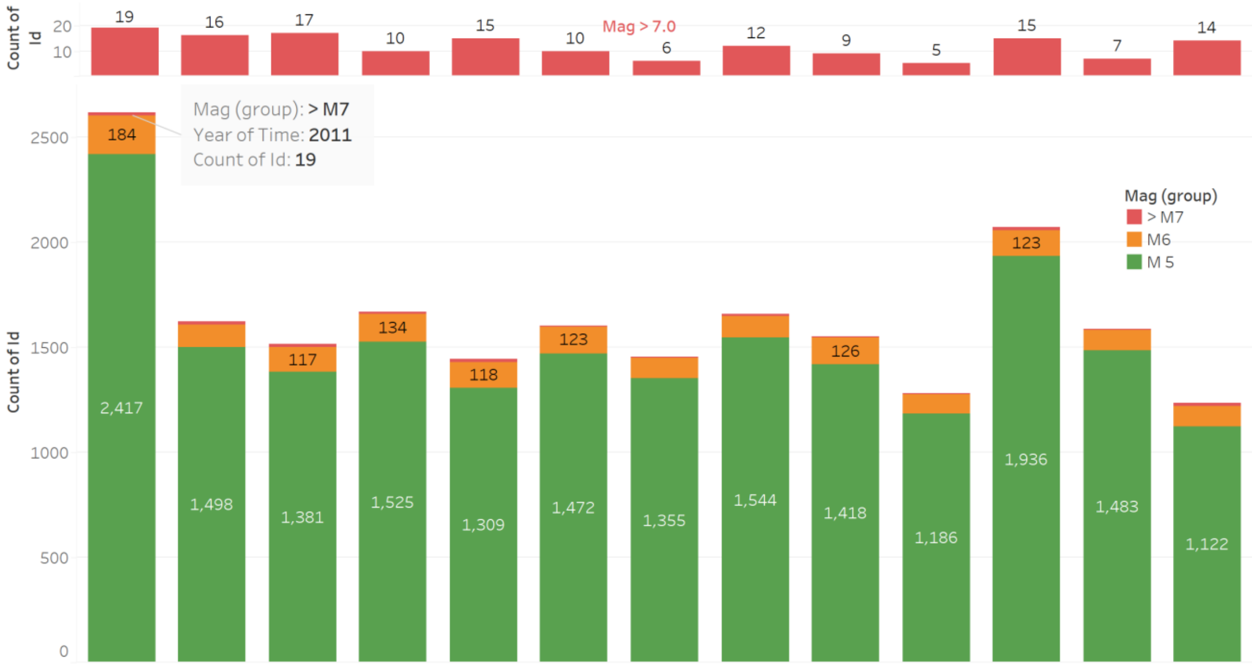



*Figure 6. International Events Missing Events Statistic Summary (2011~2023). Count of Id broken down by year vs magnitude* (USGS, 2023)

Exploring and accessing international metadata is a multifaceted endeavor that hinges on fostering collaborative relationships among a diverse array of organizations and effectively utilizing the FDSN DATASELECT application (SAGE,2024). This cooperative framework plays a pivotal role in facilitating the sharing of seismic data on a global scale. The query parameter for FDSN is showing in Figure 7, and the data are in mseed format. However, the landscape of seismic monitoring is highly diverse, with each nation and organization maintaining distinct systems and methodologies for data collection, management, and dissemination. This inherent diversity poses a significant challenge when it comes to international data exploration. The primary hurdle is the task of identifying and acquiring the pertinent metadata associated with seismic events. Additionally, given the inherent variations in data formats and structures utilized by different systems, a crucial component of the process involves transforming this data into formats that are compatible with the specific requirements of the respective systems. The effective exploration of international metadata necessitates not only cooperation and information sharing among stakeholders but also a remarkable degree of adaptability and data transformation skills to navigate the intricate web of diverse seismic monitoring systems and methodologies across the globe. Data standardization ensures interoperability and enhances the accessibility and utility of valuable datasets on a global scale. It promotes consistency, reliability, and a common understanding, fostering a more efficient and collaborative environment for researchers, scientists, and organizations involved in data exchange and analysis.

| Parameter | Alias | Support | Default | Allowed Values | Type | Unit |
|---|---|---|---|---|---|---|
| **starttime** | **start** | **required** | **[Any]** | **Any valid time** | **time** | **UTC** |
| | Limit results to time series samples on or after the specified start time | | | | | |
| **endtime** | **end** | **required** | **[Any]** | **Any valid time** | **time** | **UTC** |
| | Limit results to time series samples on or before the specified end time | | | | | |
| **network** | **net** | **required** | **[Any]** | **Valid network code or wildcard** | **string** | |
| | Select one or more network codes. Can be SEED network codes or data center defined codes. Multiple codes are comma-separated. | | | | | |
| **station** | **sta** | **required** | **[Any]** | **Valid station code or wildcard** | **string** | |
| | Select one or more SEED station codes. Multiple codes are comma-separated. | | | | | |
| **location** | **loc** | **required** | **[Any]** | **Valid location code or wildcard** | **string** | |
| | Select one or more SEED location identifiers. Multiple identifiers are comma-separated. As a special case '--' (two dashes) will be translated to a string of two space characters to match blank location IDs. | | | | | |
| **channel** | **cha** | **required** | **[Any]** | **Valid channel code or wildcard** | **string** | |
| | Select one or more SEED channel codes. Multiple codes are comma-separated. | | | | | |
| **quality** | | **optional** | **B** | **D, R, Q, M or B** | **string** | |
| | Select a specific SEED quality indicator, handling is data center dependent. | | | | | |
| **minimumlength** | | **optional** | **0.0** | **>= 0.0** | **float** | |
| | Limit results to continuous data segments of a minimum length specified in seconds. | | | | | |
| **longestonly** | | **optional** | **FALSE** | **TRUE or FALSE** | **boolean** | |
| | Limit results to the longest continuous segment per channel. | | | | | |
| **format** | | **optional** | **miniseed** | **miniseed** | **string** | |
| | Specify format of result, the default value is ***miniseed***. If this parameter is not specified the service must return miniSEED. | | | | | |
| **nodata** | | **optional** | **204** | **204 or 404** | **string** | |
| | Select status code for "no data", either ***204*** (default) or ***404***. | | | | | |

*Figure 7. Parameters for the query method (FDSN)*

## 4. Case Studies

### 4.1. 2018 Anchorage, Alaska earthquake sequence

This research entails gathering peak ground motion data from the 2018 M7.1 Anchorage earthquake and 33 intermediate-depth earthquakes with magnitudes equal to or exceeding 4.0 in the Cook Inlet region of southern Alaska (Moschetti, M.P. 2018). The map in Figure 8 displays the distribution of events. After applying filtering based on time and location, we identified 47 events associated with the main earthquake and initiated an in-depth exploration based on this foundation. The histogram in Figure 8 illustrates the 15 events involving the highest number of stations. By searching the FDSN, the internal NSMP and the USGS internal database, we successfully recovered data for 33 events. The metadata for the remaining events exhibits low quality, making it challenging to post them to CESMD.

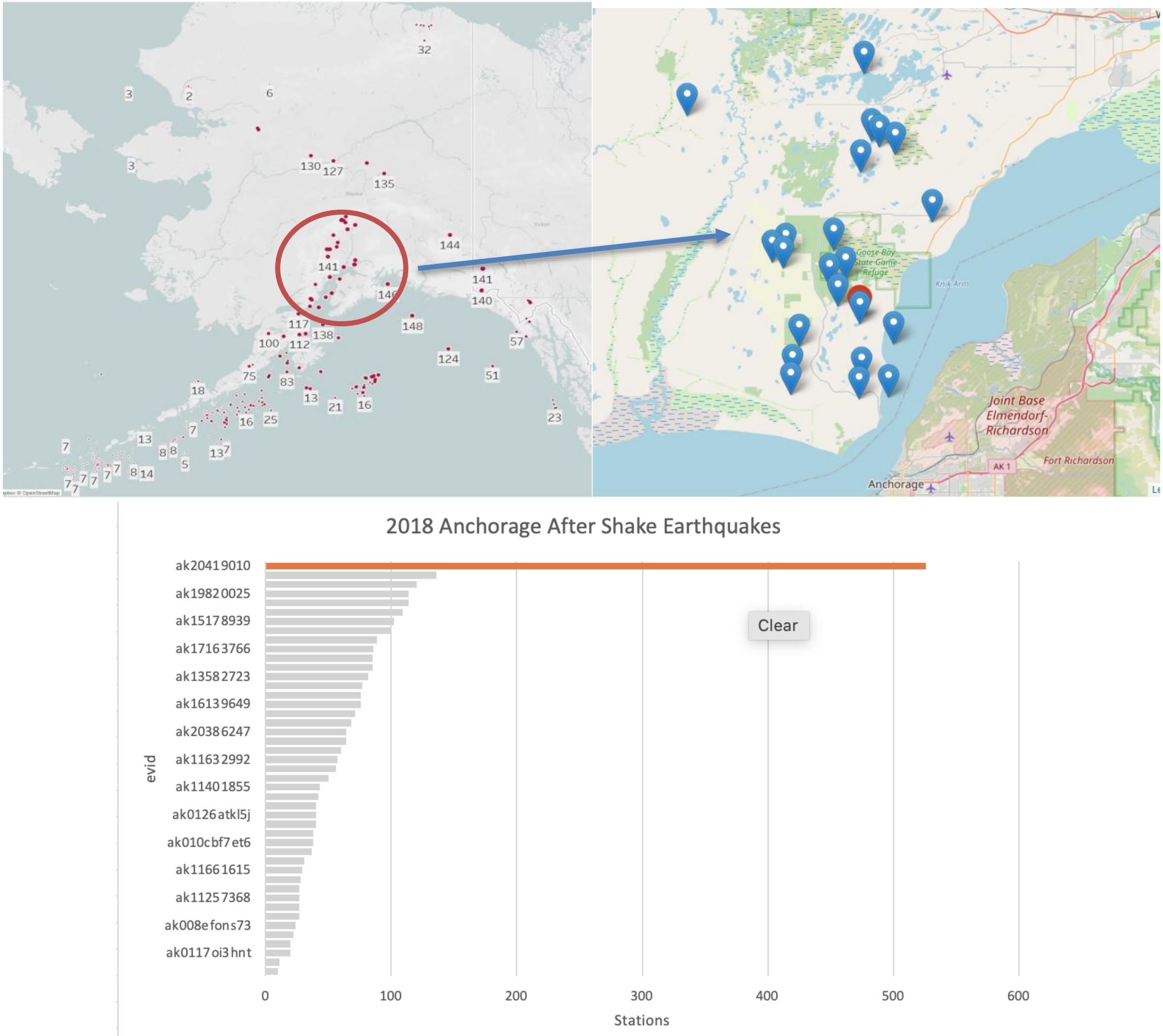



*Figure 8. Alaska 2018 Anchorage Earthquake Aftershocks (USGS ANSS Comcat, CESMD, 2023).*

### 4.2. 2018 Hawaiian lava flows

This study involves the aggregation of peak ground motion data originating from the 2018 earthquake with a magnitude of 6.9 in the vicinity of Leilani Estates, Hawaii, in addition to seismic occurrences associated with the eruption and summit collapse events of the Kilauea Volcano (Moschetti, et. al. 2018). After initial exploration, we identified a total of 56 events that occurred in 2018, and we successfully backfilled data for 38 of these events to CESMD. Since Hawaii has a small number of stations due to its compact landmass, a comprehensive list of stations located within a specific distance from the seismic center was created. Subsequently, an exhaustive metadata search was meticulously conducted station by station. This targeted data retrieval method has demonstrated its effectiveness in efficiently locating and transferring the metadata to the AQMS. As Figure 9 shows, Hawaii missing events decreased in number from 56 to 19.

| State.. | May 2018 | June 2018 | July 2018 | August 2018 |
|---|---|---|---|---|
| | Month of Time | | | |
| HI | 9 | 25 | 21 | 1 |

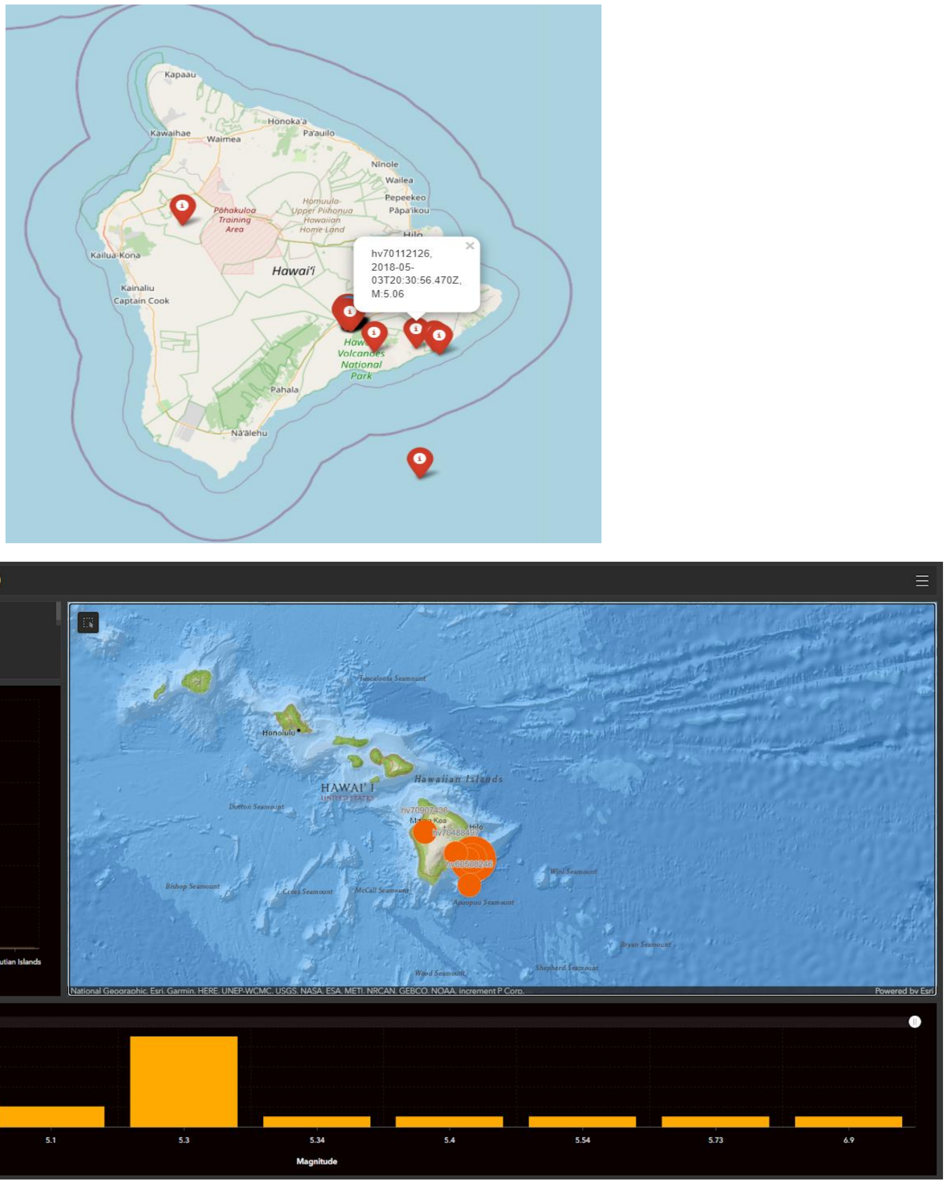
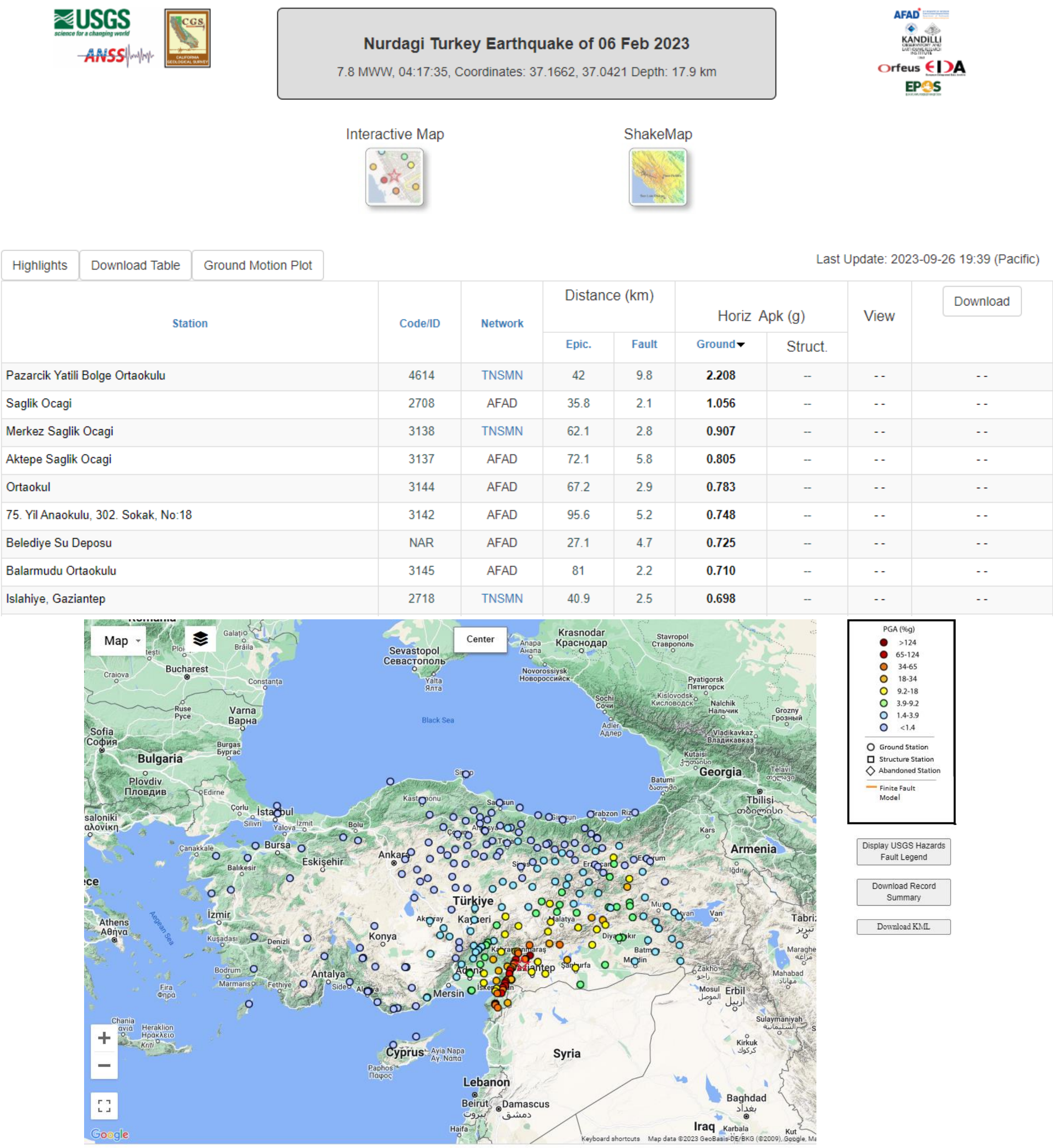



*Figure 9. 2018 Hawaiian lava flows ((USGS ANSS Comcat, CESMD, 2023)*

### 4.3. Türkiye

On February 6, 2023, a seismic event of magnitude 7.8 rocked the southern region of Türkiye, close to its northern border with Syria (USGS, 2023). Roughly nine hours later, another earthquake, measuring 7.5 in magnitude, occurred approximately 90 kilometers to the north. These substantial seismic events triggered a sequence of aftershocks in the area. Given the freshness of the data and the seismic activity in this region, it has been designated as one of the top-priority areas for data recovery efforts. We acquired waveform data and metadata from AFAD-TADAS, KOERI, ORFEUS/EIDA/ESM, and IRIS (FDSN, 2024)to ensure consistency, parametric data from the AFAD-TADAS and ORFEUS ESM event pages was populated to CESMD for the mainshock: We are currently working to incorporate data and metadata recorded by AFAD-TADAS (NetCodes TK and TU) (AFAD, 1973) alongside Kandilli Observatory and Earthquake Research Institute (KOERI, NetCodes KO) (KOERI, 2001) and the Global Seismographic Network (GSN) (Network = IU) into our NSMP processing workflow (Figure 1, Schleicher et al., 2024) to produce COSMOS products for

CESMD. Figure 10 illustrates the CESMD Internet Data Report for the M7.8 Nurdagi, Türkiye Earthquake of 6 February (“Nurdagi, Türkiye”). The page shows the stations table and serves as a getaway directing user to other related pages. To identify data centers offering metadata, their symbols are shown in the upper right corner, and a "Highlights” document provides detailed references to the datacenter and network.




| Station | Code/ID | Network | Distance (km) | | Horiz Apk (g) | | View | Download |
|---|---|---|---|---|---|---|---|---|
| | | | Epic. | Fault | Ground | Struct. | | |
| Pazarcik Yatili Bolge Ortaokulu | 4614 | TNSMN | 42 | 9.8 | 2.208 | -- | - - | - - |
| Saglik Ocagi | 2708 | AFAD | 35.8 | 2.1 | 1.056 | -- | - - | - - |
| Merkez Saglik Ocagi | 3138 | TNSMN | 62.1 | 2.8 | 0.907 | -- | - - | - - |
| Aktepe Saglik Ocagi | 3137 | AFAD | 72.1 | 5.8 | 0.805 | -- | - - | - - |
| Ortaokul | 3144 | AFAD | 67.2 | 2.9 | 0.783 | -- | - - | - - |
| 75. Yil Anaokulu, 302. Sokak, No:18 | 3142 | AFAD | 95.6 | 5.2 | 0.748 | -- | - - | - - |
| Belediye Su Deposu | NAR | AFAD | 27.1 | 4.7 | 0.725 | -- | - - | - - |
| Balarmudu Ortaokulu | 3145 | AFAD | 81 | 2.2 | 0.710 | -- | - - | - - |
| Islahiye, Gaziantep | 2718 | TNSMN | 40.9 | 2.5 | 0.698 | -- | - - | - - |

*Figure 10. CEMSD sample for the M7.8 Nurdagi, Türkiye Earthquake of 6 February 2023. The map is the interactive map that shows the stations related to the earthquake and the colours represent the PGA level (CESMD, 2023).*

## 5. Challenge

Throughout this entire process, numerous challenges inevitably arise. Following significant seismic events, some data connections may be disrupted, necessitating the physical presence of personnel on-site to retrieve the data. Due to unforeseeable and uncontrollable factors, this on-site data retrieval process can often be more protracted and intricate than initially anticipated.

For international events, the issues and challenges that need to be addressed are even more complex and multifaceted.

**5.1 Complexity:** Obtaining international metadata is often more complex than initially envisioned. International metadata may be stored in various databases and at different organizations. Limited familiarity with these databases and organizations adds to the challenge of obtaining metadata. This is because such metadata may be distributed among different organizations in different regions or stored in university databases. This dispersion makes the search and collection of metadata complex and time-consuming. Currently, FDSN provides a common method for accessing seismic data and metadata. However, its information is limited in some regions. Establishing contact and obtaining authorization from various organizations can be an alternative strategy to acquire the needed data.

**5.2 Data Format:** The input data format for AQMS is *mseed*. However, not all organizations or instrumentation types utilize or publish data in this format. During the process of developing automated conversion code, errors in units and formats may arise, leading to inaccuracies in the automatically generated output data. These errors can stem from disparities between different data formats, mismatched data units, or technical challenges encountered during the data conversion process. To address these issues, it is typically necessary to implement meticulous data format checks and conversion steps within the automated code. This may involve unit conversions, data standardization, detection, and rectification of anomalies, among other measures. We are developing the format conversion feature within the Ground-Motion Processing Software (gmprocess). It is a Python toolbox designed to fetch and process ground motion waveform data while extracting a range of metrics from metadata (Hearne et al., 2019). Furthermore, effective communication and coordination with data providers is crucial to ensure the quality and consistency of input data and to foster a shared understanding of specific data formats and units. When dealing with diverse data sources and formats, extra care should be taken to ensure data accuracy and reliability. This is essential for AQMS to function correctly and provide dependable quality monitoring. Our NSMP AQMS system may require ongoing improvements and adjustments to the automated code to accommodate various data sources and scenarios.

**5.3 Data Inconsistencies:** The metadata we used was directly sourced from the database and was primarily in mseed. In our reprocessing workflow, we lack the data quality control until the review step since we assume that the data is correct with our default configuration. This may lead to a metadata inconsistency issue and stations with missing channels. These inconsistencies may manifest in location and channel codes due to missing label or incorrect azimuths with the file. On the other hand, multiple methods of representing channel azimuths exist, and may cause inconsistencies during processing. For example, some databases might use a number to signify the azimuth while others might use a format like X, Y, Z In the process of matching numerals and characters, the variations may result in channel mismatching.

**5.4 Data Reviewing:** Incorrect metadata and missing provenance are another challenge for automatic process. Human expertise is required in manual review tools to ensure that the data is accurate for further process and public.

**5.5 Citation and Attribution:** Establishing accurate citations for the acquired data is crucial. Typically, APIs provided by FDSN are used to assist in constructing citations. However, due to practical constraints, data citations may sometimes be attributed to the organization's name rather than the database's name. This can pose challenges for software code. We show all the datacenters' symbols on the data page. Currently, we use "DataCite API", the same one used by FDSN, to generate citation and public in the "Highlight" section of the CESMD event internet data page.

**5.6 Data Authorization:** Ensuring authorization is obtained before handling international metadata is essential. This step is vital for protecting the legality and privacy of the data.

In summary, obtaining international metadata involves various challenges, including data distribution, citation, and authorization issues. These challenges can be addressed using appropriate methods and tools to ensure the acquisition of accurate metadata for scientific research.

## 6. Conclusion and Future work

The Python-based approach to backfill earthquake data holds significant promise as a valuable addition to CESMD. Its design as an automated detection method aimed at identifying potentially missed earthquakes that meet specific criteria and subsequently filling in the event details. This procedure, currently tested within the United States, is set to expand its coverage area, ensuring the comprehensive integrity of the CESMD database. At present, we have established a live dashboard that continuously tracks data gaps in real-time across the United States. We are also working towards extending this capability to international or specific regions using ESRI's ArcGIS. Through regional automated processing, we have effectively added aftershocks in the Alaska and Hawaii regions, thereby validating the method's feasibility. This process has the potential to provide more data resources to CESMD and enhance earthquake event monitoring and analysis. Turning to the exploration and retroactive data filling of international seismic events, the broad geographical distribution, potential uniqueness of events, and complexities associated with the data underscore the need for further discussions and research to devise effective and efficient retroactive filling strategies. To address current formatting issues, we are upgrading gmprocess to facilitate data format conversion. We aspire to bolster communication with diverse organizations, enhancing our understanding of international earthquake data.

### 7. Acknowledgments

We thank California Strong Motion Instrumentation Program (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. Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government

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