Development of a *Slow Earthquake Database*

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Abstract

This paper describes a database that provides various catalogs of slow earthquakes that list the times and the locations of the events together with additional information depending on the catalog. Since these catalogs are provided by a variety of documents in different formats, previous studies that use them must repeat complex procedures for preparing data. To make it more convenient to use such multiple catalogs and to promote research on slow earthquakes, we have compiled a number of catalogs into a standardized format in a single repository, the *Slow Earthquake Database*, at the University of Tokyo (http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/) given in "Data and Resources." Users can visualize the source locations of multiple slow earthquakes in the database in map views on the website. Convenient access to the database encourages researchers to work on slow earthquakes regardless of their backgrounds. We also expect the database to foster collaboration among researchers in various fields and further the understanding of the mechanisms, environmental conditions, and underlying physics of slow earthquakes. Through the compilation of this database, we have established a global standard of slow earthquake catalogs.

Introduction

The scope of this paper includes describing a database on slow earthquakes (Ide et al., 2007), a new type of fault slip. The deployment of seismic and geodetic networks in the late twentieth century contributed to the first discovery of slow earthquakes in southwest Japan (e.g., Hirose *et al*., 1999; Obara, 2002). Since then, slow earthquakes have been widely detected in the world, especially in subduction zones along the Pacific Rim (Peng and Gomberg, 2010; Obara and Kato, 2016). Because slow earthquakes usually occur both on the deeper and shallower sides of megathrust seismogenic zones, slow earthquakes may interact with huge earthquakes. Therefore, revealing the generation mechanisms, environmental conditions, and principles of slow earthquakes should promote our understanding of all earthquake processes, ranging from slow transients to fast ruptures in faults.

Slow earthquakes are characterized by slower fault slips than ordinary earthquakes but faster than stable sliding with various characteristic time scales ranging from seconds to years. For seismic signals of slow earthquakes, tectonic tremor with a dominant frequency of 2–8 Hz in their waveforms is observed by high-sensitivity seismometers (Obara, 2002) or ocean bottom seismometers (OBSs) (Obana and Kodaira, 2009; Yamashita *et al*., 2015). Tremor is considered to be a continuous signal of low frequency earthquakes (LFEs) (Shelly *et al*., 2006) that is an element of tremor, and isolated pulses of tremor have also been identified as LFEs (Katsumata and Kamaya, 2003). Broadband seismometers record very low frequency earthquakes (VLFEs) with a dominant period of a few tens of seconds (Ito *et al*., 2007), and geodetic networks such as the Global Navigation Satellite System (GNSS), tiltmeters, and strainmeters detect slow slip events (SSEs), lasting from days to years (Hirose *et al*., 1999; Rogers and Dragert, 2003).

Researchers have used a number of methods to estimate the source locations of LFEs, tremors, VLFEs, and SSEs. Catalogs of slow earthquakes, which list the times and the locations of the events together with additional information depending on the catalog, were detected by different researchers and became available in different formats. They are available from each original paper, which provide catalogs created upon publication, or through a website such as the Interactive Tremor Map (Wech, 2010) and the World Tremor Database (Idehara *et al*., 2014), which provide updated catalogs with the most recent events. However, to investigate slow earthquakes, researchers must download catalogs from different sources with different formats, a complex-, time-consuming process. Thus, to mitigate this problem and provide a more convenient source of information, we have released the *Slow Earthquake Database*, given in “Data and Resources,” a standardized compilation of slow earthquake catalogs. This paper introduces an overview of the database, including its construction, contents, and availability along with the underlying issues and future possible updates.

Database construction and overview

The construction of the *Slow Earthquake Database* entailed the following procedure (Fig. 1). We began by compiling information about slow earthquake such as occurrence times, locations, magnitudes, and source mechanisms of events from peer-reviewed papers and institutional reports. We used every slow earthquake catalog in the database with permission from the corresponding author(s) to include it to the database and then converted the format of the catalogs to a unified format mentioned in the “Download and catalog format” section. After the conversion, we stored all of the catalogs in a single repository at the University of Tokyo that is currently open to the public via the *Slow Earthquake Database* (http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/). The database consists of 29 catalogs, including five LFE, thirteen tremor, five VLFE, and six SSE catalogs (as of December 4, 2017; Table 1).

The source locations of LFEs are usually determined based on the manually picked arrival times of P and S waves (Katsumata and Kamaya, 2003; Arai *et al*., 2016) or their difference (S-P time). For example, the Japan Meteorological Agency (JMA) routinely determines the hypocenters of LFEs in Japan. The catalog compiled by the JMA includes both volcanic and tectonic LFEs along the subducting plate (Katsumata and Kamaya, 2003). The method of locating tremor involves the relative time differences of S wave arrivals detected by a cross correlation analysis of waveform envelopes, or the envelope cross-correlation method (ECM) (Obara, 2002; Wech and Creager, 2008; Ide, 2010; 2012). To determine the hypocenters of LFEs along the Ryukyu subduction zone, several studies adopted ECM and the S-P time (Arai *et al*., 2016; Nakamura, 2017).

The ECM is fundamentally used to determine the source location of worldwide tremor such as that in southwest Japan (Obara, 2002; Obana and Kodaira, 2009; Yamashita *et al*., 2015), Cascadia, Parkfield, Mexico, Chile, New Zealand, and Taiwan (Idehara *et al*., 2014). By combining the ECM and information related to the squared tremor amplitudes, Maeda and Obara (2009) identified the tremor hypocenters in southwest Japan. These methods can determine one source location within a short time period (e.g., one minute). Since tremors can be continuous signals, tremor sources for a continuous period are sometimes clustered into one or two centroid locations (Obara *et al*., 2010; Annoura *et al*., 2016). For example, the National Research Institute for Earth Science and Disaster Resilience (NIED) routinely constructs catalogs of "clustered" tremor with a maximum duration of one hour. In northeast Japan, tremor signals were observed by ocean bottom seismometers (OBSs) (Ito *et al*., 2015). However, since the OBS station was insufficient for locating tremor, we used the locations of the OBSs that recorded tremor signals in the catalog instead of the source location (Ito *et al*., 2015).

Since the observed waveforms of VLFEs are dominant in low frequency bands of 0.05 Hz, researchers often conduct centroid moment tensor inversion analyses (Ito *et al*., 2007) by comparing synthetic and observed waveforms using an appropriate velocity structure. Several studies have applied this approach to locate VLFEs along the Japan Trench (Matsuzawa *et al*., 2015) and to both deep (Ito *et al*., 2007; 2009; Takeo *et al*., 2010) and shallow (Sugioka *et al*., 2012) VLFEs in the Nankai subduction zone. Nakamura and Sunagawa (2015) employed the maximum amplitudes of surface waves recorded by broadband seismometers to detect the epicenters of VLFEs in the Ryukyu area. Their method, however, was incapable of accurately determining the source depth.

The *Slow Earthquake Database* includes the source parameters of SSEs in northeast and southwest Japan, represented by a single rectangular fault model. Assuming a homogeneous half space, we inferred the source parameters of the faults (Okada, 1992) to explain the observed GNSS displacement vectors (Heki and Kataoka, 2008; Nishimura *et al*., 2013; Nishimura, 2014; Takagi *et al*., 2016; Tu and Heki, 2017), tilt changes (Sekine *et al*., 2010), strain changes (Ito *et al*., 2013), and pressure changes on the seafloor (Ito *et al*., 2013).

At the time of its first release, the database included catalogs of slow earthquakes detected mainly in Japan, where this phenomenon is vigorously investigated. However, we are currently in the stage of compiling more catalogs in the world in cooperation with various researchers. Among them are catalogs of LFEs in Cascadia (Bostock *et al*., 2015) and Nankai (Ohta and Ide, 2017), tremors in California (Chao *et al*., 2012a), Taiwan (Chao *et al*., 2012b; 2017) and Japan (Chao and Obara, 2016; Imanishi *et al*., 2016), global triggered tremor (Chao *et al*., 2013), VLFEs in Nankai (Baba *et al*., 2018), and SSEs in Nankai (Itaba and Ando, 2011) and Mexico (Rousset *et al*., 2017). In addition, we are planning to add catalogs of repeating earthquakes as indicators of slow slip along faults, such as those in northeast Japan (Uchida and Matsuzawa, 2013). Therefore, the number of catalogs in the *Slow Earthquake Database* will continue to increase in the future. We welcome researchers to contribute by adding their published slow earthquake catalogs to our database. In addition, now that the accessibility to the data presented in published papers has become an essential requirement for a number of journals, researchers can refer to our database as a tool with which they share their catalogs. Any requests and questions regarding the details of sharing the catalogs through our database can be addressed to sloweq-ctlg-hq@eri.u-tokyo.ac.jp.

Use of the *Slow Earthquake Database*

Catalog selection

Figure 2 presents a screenshot of the *Slow Earthquake Database* website. After logging on to the database, users select the time span of interest (A in Fig. 2a); that is, users choose the first day of the time span and its duration or the last day of interest. Next, from a table (B in Fig. 2a) users select which slow earthquake catalog(s) they wish to use. The catalogs are sorted by region and the category of slow earthquake, that is, the characteristic duration.

Visualization

Users can view source locations of their selected slow earthquakes at the same time in Google Maps (C in Fig.2b). The catalogs are plotted by color in the default configuration. They can change the color scale to represent the source depth or the occurrence time of the events. The number of events in each catalog in the selected time span are also indicated below the map (D in Fig. 2b). Plate boundaries in Google Maps come from Bird (2003).

Download and catalog format

The database provides the slow earthquake catalogs in a unified or standardized format or the user's preferred format, which the user can specify in the download part. Four format options available (E in Fig. 2c). The first three are the commonly used formats for LFEs or tremor, VLFEs, and SSEs, and the other contains all information in a default format that can be customized by users. A summary of the labels in the format appear in the "Data Format" part (F in Fig. 2c). By clicking the "Download" button, users can download the selected catalogs in a specified format as a single comma-separated-value (CSV) file. Figure 3 presents a downloaded CSV file in the case of all labels selected in the format for JMA-LFE, Annoura2016-Tremor, YoshiIto2009-VLFE, and Sekine2010-SSE catalogs on March 5, 2008 (Katsumata and Kamaya, 2003; Ito *et al.*, 2009; Sekine *et al.*, 2010; Annoura *et al.*, 2016). The first 26 columns (columns A–Z in Figs. 3a and 3b) list occurrence times (columns A–I in Fig. 3a), source locations (columns J–L in Fig. 3a), and mechanisms (columns M–Z in Fig. 3b), respectively. The following six columns (columns AA–AF in Fig. 3c) list the information of source uncertainties in both time and space. The last seven columns list (columns AG–AM in Fig. 3c) the notices in the catalog. A description of each column is summarized in the "Data Format" on the website (F in Fig. 2c). The properties that are not included in the original catalog remain to be blank.

Database availability

The *Slow Earthquake Database* is an open database. Users of the database must comply with our general and individual policies. The general policy (see Fig. 4a) describes the general rules formulated for all catalogs, such as how to cite or acknowledge a database. They also outline the responsibility of the user, a prohibition of the redistribution of catalogs, and an explanation of future possible updates. In addition, each catalog has an individual policy set by the corresponding author. Figure 4b presents an example of an individual policy corresponding to the tremor catalog provided by NIED (Maeda and Obara, 2009; Obara *et al*., 2010). Individual policies generally include citation information, the data period, and short notices about the usage of the catalog. All of the policies are summarized in the database.

Underlying issues and future updates of the database

The *Slow Earthquake Database* compiles a variety of slow earthquake catalogs from a number of sources, and the information provided in each catalog differs from one source to another. For example, the source locations of LFEs, tremor, and VLFEs are estimated as corresponding to point sources. In contrast, those of SSEs are estimated as finite faults. Therefore, information about the source mechanism such as strike, dip, rake, length, width and slip are included only in the SSE catalogs. This comes from the difference of event size and duration of interest, or originally from the difference in the types of observations used for identifying and characterizing the events. At the same time, the information may vary, even within the same category of slow earthquakes. For example, while the LFE catalog provided by JMA determines the magnitude of events, the LFE catalog in Nakamura (2017) does not. To date, our database does not clearly indicate which information is provided in each catalog; such information, however, will be included in a near future. The quality of catalogs also varies, depending on the detection method, which ranges from fully automatic to manual detection. In addition, the time periods covered by each catalog can significantly differ. We are planning to incorporate such information to the webpage in the future.

There are also several issues specific to the catalogs of particular types of slow earthquakes that are currently not fully addressed in our database. For one, LFEs are often detected based on template matching, which identifies new events by comparing the similarity between observed waveforms and those of a template event. In the near future, the database will provide catalogs that have been determined by such methods (e.g., Bostock *et al*., 2015); such catalogs, however, are not currently included in the database. As this type of catalog consists of overlapping locations corresponding to events detected using the same template, visualization on Google Maps would be difficult. In addition, the unified format does not include information for template events. Therefore, we are preparing a “bulk download” page that will provide original catalogs including the template information. This page will be an addition to the download page with the unified format mentioned in this paper. As this issue could be problematic for other categories of slow earthquakes, we will treat it in the same way.

Tremor catalogs are roughly divided into two types in terms of duration. Since tremor can be observed as a continuous signal, the definition of tremor duration is somewhat complex. Some catalogs estimate one source location based on recorded waveforms within a short period (e.g., one minute). Clustering catalogs, however, treat estimated source locations of tremor as one or two centroid location during a longer period such as one hour. While the former catalogs enable us to examine shorter time-scale tremor activity, the latter ones can be used for investigating only longer time-scale tremor activity. Users should be mindful of such issues in handling tremor catalogs and are advised to consult the corresponding references.

At the stage of the initial release of the database, our database provided only SSE catalogs that represented the source of an SSE as a single rectangular fault. After all, the formatting and visualization of slip distributions for SSEs, including the temporal evolution of slips, is a complex issue currently under discussion. SSE catalogs that include fault slip distribution and temporal evolution will be available for download in the "bulk download" page in their original format.

The database sometimes faces a problem when users attempt to plot or download a large number of catalogs. The maximum number of catalogs that can download from the database in one time depends on the selected format, and will be notified in the database.

Although users who wish to share new catalogs must contact us before including it in the database, we plan to construct a semi-automatic system for uploading catalogs to the database in the future. Newly submitted as well as automatically updated catalogs will be released on a monthly basis.

Summary

We have constructed the *Slow Earthquake Database* by compiling a wide variety of seismically and geodetically detected catalogs on slow earthquakes from the peer-reviewed papers and institutional reports and converted their original formats to a unified format. Based on the agreement of the corresponding authors of the original catalogs, we converted and stored the catalogs in a single repository. Users can download the multiple catalogs in either the unified format or their preferred format. This database is available all users as long as they follow the general policy and the individual policy of each catalog. In addition, users can visualize the source distribution in Google Maps before downloading the data, which assures users that events have occurred during the selected time span.

The constructed database enables users to find where, when, and what type of slow earthquakes have occurred. Comparisons of catalogs, especially comparisons between seismically and geodetically detected slow earthquakes, will promote a more comprehensive understanding of slow earthquake activity such as the spatial relationship among different types of slow earthquakes and regional differences among slow earthquake activity. Such comparison can also help researchers characterize the differences among source locations found by various detection methods. Another advantage of the database is that users can download multiple catalogs as a single compiled catalog in the unified or preferred format. The unified catalog contains references to the original catalogs so that users can refer to them for more detailed information. As a result of such standardization, researchers will find it more convenient to access the findings of previous studies, which will promote research on slow earthquakes that may foster future collaboration among researchers from various fields and further our understanding of the mechanisms, environmental conditions, and underlying physics of slow earthquakes. Furthermore, we expect that the database will play a leading role in establishing a global standard of slow earthquake catalogs. In cooperation with many researchers, we are now compiling more catalogs, which will result in a more and more comprehensive database.

Data and resources

The *Slow Earthquake Database* is available at http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/ (last accessed January 25, 2018) and open to everyone as long as users follow the general policy of our database and the individual policy of each catalog. The most recent update of the database was on December 4, 2017, when this paper was submitted. If users have any feedback or comments, or wish to share their catalogs, they should contact sloweq-ctlg-hq@eri.u-tokyo.ac.jp.

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Figure 1. Schematic illustration of the database construction.

Figure 2. Screenshot of the webpage showing (a) database selection and the Policy tab for the catalog references and policies, (b) interactive map and (c) download sections. Contents related to labels shown by the red characters are mentioned in the main text.

Figure 3. Example of the downloaded CSV format, which lists (a) occurrence times (columns A–I), source locations (columns J–L), (b) source mechanisms (columns M–Z), (c) source uncertainties in both time and space (columns AA–AF), and the notices in the catalog (columns AG–AM). A description of each column is summarized in the “Data Format” on the website (F in Fig. 2c). The properties that are not included in the original catalog remain to be blank.

Figure 4. (a) General policy and (b) an example of the individual policy, from the NIED-Tremor catalog.

Table

Table 1. Catalogs in the *Slow Earthquake Database* available December 4, 2017.

*Source locations are not estimated.

“+” in the Time Span indicates that the catalog will be updated.

Category	Name	Region	Time Span	Observations used for source estimation	Reference(s)
LFE	Arai2016_ECM	Japan	2013-2014	Envelope waveform	Arai *et al.*, 2016
	Arai2016_tomoDD	Japan	2014	P and S arrival times	
	JMA	Japan	1999-2017+	P and S arrival times	Katsumata and Kamaya, 2003
	Nakamura2017_ECM	Japan	2004-2016	Envelope waveform	Nakamura, 2017
	Nakamura2017_ECM+SP	Japan	2004-2016	Envelope waveform + S-P time	
Tremor	Annoura2016	Japan	2004-2015	Envelope waveform	Annoura *et al.*, 2016
	NIED	Japan	2001-2017+	Envelope waveform + Average squared amplitude	Maeda and Obara, 2009 Obara *et al.*, 2010
	Obana2009	Japan	2003	Envelope waveform	Obana and Kodaira, 2009
	WTD-Cascadia	Cascadia	2005-2014	Envelope waveform	Idehara *et al.*, 2014
	WTD-Chile	Chile	2005-2007		
	WTD-Kyushu	Japan	2004-2013		
	WTD-Mexico	Mexico	2005-2007, 2009-2013		
	WTD-Nankai	Japan	2004-2013		
	WTD-NewZealand	New Zealand	2004-2012		
	WTD-Parkfield	San Andreas	2005-2012		
	WTD-Taiwan	Taiwan	2006-2009		
	Yamashita2015	Japan	2013	Envelope waveform	Yamashita *et al.*, 2015
	YoshiIto2015	Japan	2011	N/A*	Ito *et al.*, 2015
VLF	Matsuzawa2015	Japan	2005-2013	Maximum amplitude of surface waves	Matsuzawa *et al.*, 2015
	Nakamura2015	Japan	2002-2014	Full waveform	Nakamura and Sunagawa, 2015
	Sugioka2012	Japan	2008-2009	Full waveform	Sugioka *et al.*, 2012
	Takeo2010	Japan	2008	Full waveform	Takeo *et al.* 2010
	YoshiIto2009	Japan	2003-2008	Full waveform	Ito *et al.* 2009
SSE	Nishimura2013	Japan	1996-2012	GNSS displacement	Nishimura *et al.*, 2013
	Nishimura2014	Japan	1997-2013	GNSS displacement	Nishimura, 2014
	Sekine2010	Japan	2001-2008	Tilt change	Sekine *et al.*, 2010
	Takagi2016	Japan	2004-2013	GNSS displacement	Takagi *et al.* 2016
	Tu2017	Japan	1997-2016	GNSS displacement	Heki and Kataoka, 2008 Tu and Heki, 2017
	YoshiIto2013	Japan	2008-2011	Strain and pressure change	Ito *et al.*, 2013