地 震 研 究 所 彙 報
Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 80 (2005) pp. 43-52

Development of a database of shear-wave splitting of the crustal earthquakes, *OpenSWS*

Takashi Mizuno* and Misato Nakai

Institute of Geology and Geoinformation, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology

Abstract

Information on shear-wave splitting of crustal earthquakes can be used to infer the stress state of the upper crust. Since the late 1980's, shear-wave splitting of crustal earthquakes has been investigated by many researchers. In addition, recent developments of high-density and high-sensitivity seismic networks provide us with a great opportunity to investigate a detailed stress field using shear-wave splitting. To manage and use large amounts of previous and forthcoming shear-wave splitting data, a database of shear-wave splitting is required. We developed OpenSWS, an online database system offering public access to shear-wave splitting data in Japan. Because users can access the database through a Web page, they only require a web browser and Internet access. At present, the database stores bibliographic information of 23 papers and shear-wave splitting data from 270 stations.

Key words: relational database, Internet, shear-wave splitting, direction of maximum horizontal compression

1. Introduction

The main cause of shear-wave anisotropy in the upper crust has been explained by the Dilatancy Anisotropy model introduced by Crampin (1978): A preferred orientation of micro cracks in response to a local stress field causes anisotropy (Fig. 1). When a shear wave enters the cracked medium, shear-wave splitting (SWS) occurs: a shear wave splits into 2 quasi shear-waves with different polarizations and velocities (Fig. 1). If the maximum and the minimum compressional stress correspond to the maximum and the minimum horizontal compressional stress, the polarization angle of the leading shear wave (LSPD) is in the direction of maximum horizontal compression (Shmax) (Fig. 1). Because SWS is integrated in effects from hypocenter to station, we can infer the direction of Shmax in the crust using SWS. Recently, Boness and Zoback (2004) reported that the LSPD corresponded to the direction of Shmax using geophysical logs from the SAFOD Pilot Hole. Mizuno *et al.* (2001) analyzed SWS obtained at borehole stations around the source region of the Kobe earthquake in 1995, and reported that the LSPD corresponds to the direction of Shmax inferred from stress measurements at the same borehole.

Several researchers have investigated the direction of Shmax using SWS (e.g., Kaneshima, 1990). Spatial (e.g., Mizuno *et al.,* 2001) and temporal variations (e.g., Saiga *et al.,* 2003) of the stress field associated with a large earthquake were investigated by SWS. Mizuno *et al.* (2005) studied the stress accumulation process at the Atotsugawa fault, central Japan, using SWS, and indicated local stress accumulation due to localized flow or slip along the deep extension of the fault. The researchers will accelerate studies on SWS since recent developments of high-density and high-sensitivity seismic networks provide a great opportunity to investigate the stress field in detail using SWS.

To manage and use large amounts of previous and forthcoming SWS data on the upper crust, a SWS database is required. Although The World Stress

* e-mail: takashi.mizuno@aist.go.jp (AIST Tsukuba Central 7, Higashi 1-1-1, Tsukuba, Ibaraki 305-8567, Japan.)

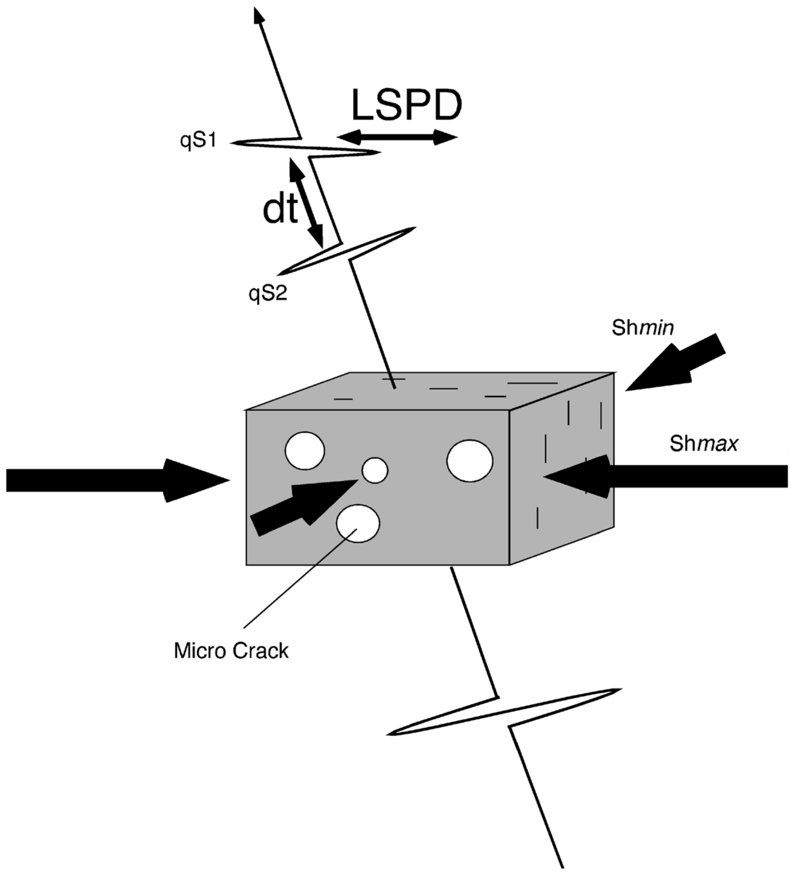


Fig. 1. Schematic view of crack-induced anisotropy in response to an anisotropic stress field. We assume that Shmax and Shmin correspond to the maximum and minimum compressional stresses in this region, respectively. In such a case, micro cracks will be aligned parallel to the direction of Shmax and normal to Shmin. Since the total elastic property of a medium with parallel-aligned cracks can be dealt with as an anisotropic medium, two shear waves with different velocities should be propagating in this medium. In addition, two shear waves, qS1 and qS2, are polarized parallel and normal to the crack plane, respectively. In case of near vertical incidence, qS1 arrives faster than qS2, since the phase velocity of qS1 is faster than qS2. Hence, LSPD corresponds to the direction of Shmax in case of near vertical incidence.

Map project (e.g., Zoback, 1992) is compiling a global database of contemporary *in situ* stresses in the crust using a variety of geophysical and geological measurement techniques, the SWS data are not stored in a database. In the present study, we developed OpenSWS, a web-based database of shear-wave splitting in Japan. We report on the structure of the database and the data stored in this system at present.

2. Requirements of OpenSWS

We designed the database to meet the following requirements.

A. This database manages the following information.
   a. Shear-wave splitting data, including direction of LSPD, delay time, average intensity of anisotropy, and number of SWS data.
   b. Location of observatory, including station code, name, latitude, longitude, and elevation.
   c. Article information, including article title, author name, journal name, volume, page, and publication date.

B. The information is distributed through the Internet since this database is being developed to encourage cooperation and sharing of contemporary data.

C. This service is open to the public because large numbers of specialists on seismology, geodesy, and disaster-prevention agencies have great interest in crustal stress fields.

D. User-friendly interfaces and User-friendly

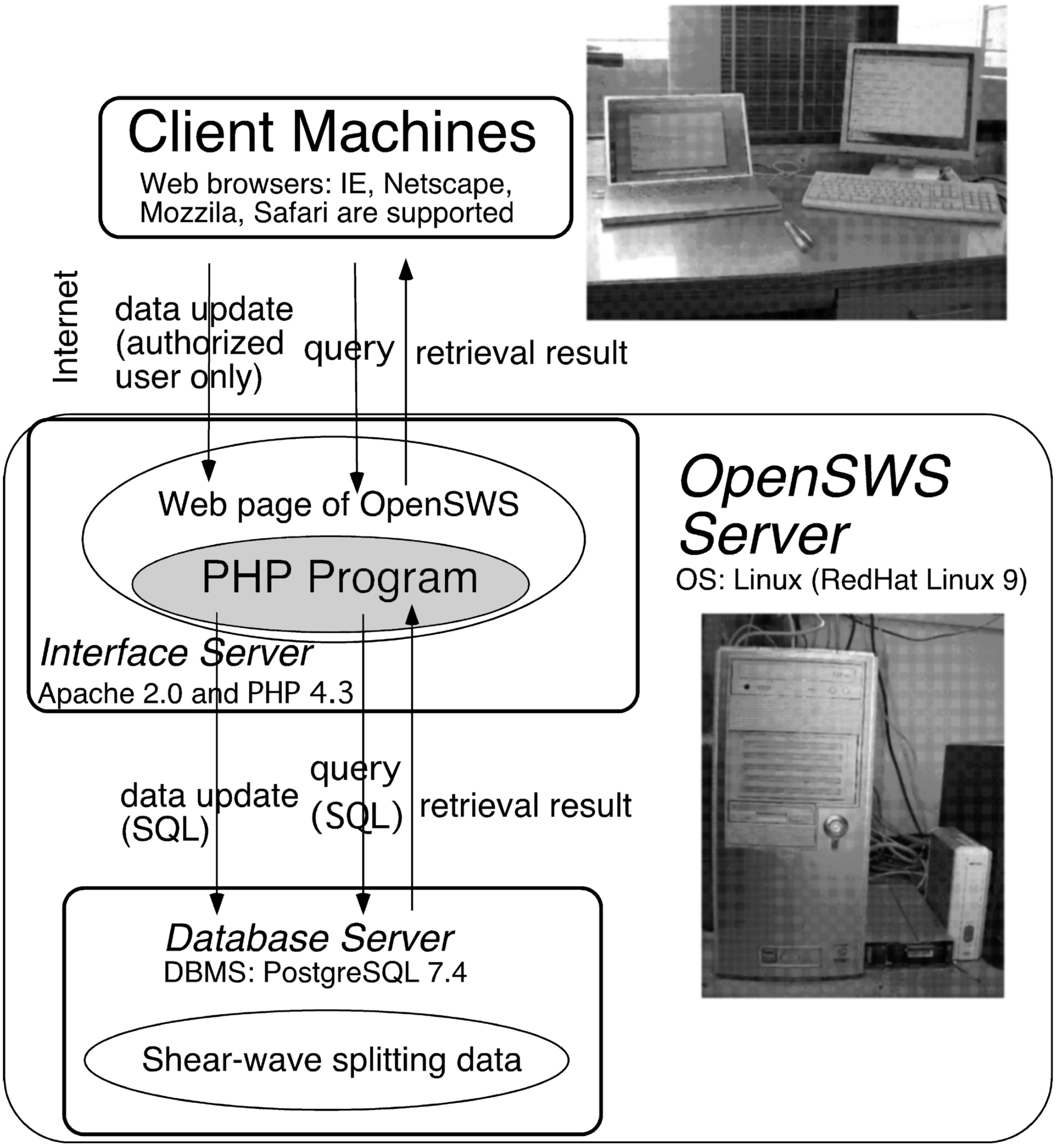


Fig. 2. Block diagram of the database system, OpenSWS. This system provides all of the services on the web page with the interface server.

search functions make the data accessible to users.

E. Users can use the database without any special software at the client side.

F. Efficient use of freeware software to reduce maintenance costs.

G. Remote update of the database should be supported for registered users since a comprehensive database cannot be maintained without active contributions from researchers who are willing to share information on shear-wave anisotropy in Japan, and support efforts to keep the database up-to-date.

3. Structure of OpenSWS

As shown in Fig. 2, OpenSWS consists of a combination of (a) database server and (b) interface server. Users access the interface server to retrieve SWS data stored in the database server.

3. 1. Database server

The task of the database server is to manage the database and respond to queries from the interface server (Fig. 2). In the present study, we selected freeware software, PostgreSQL (http : //www.postgresql.org), a relational database management system (e.g., Codd, 1970 ; Jackson, 1988). The database manages 3 tables as shown in Fig. 3. The "paper"

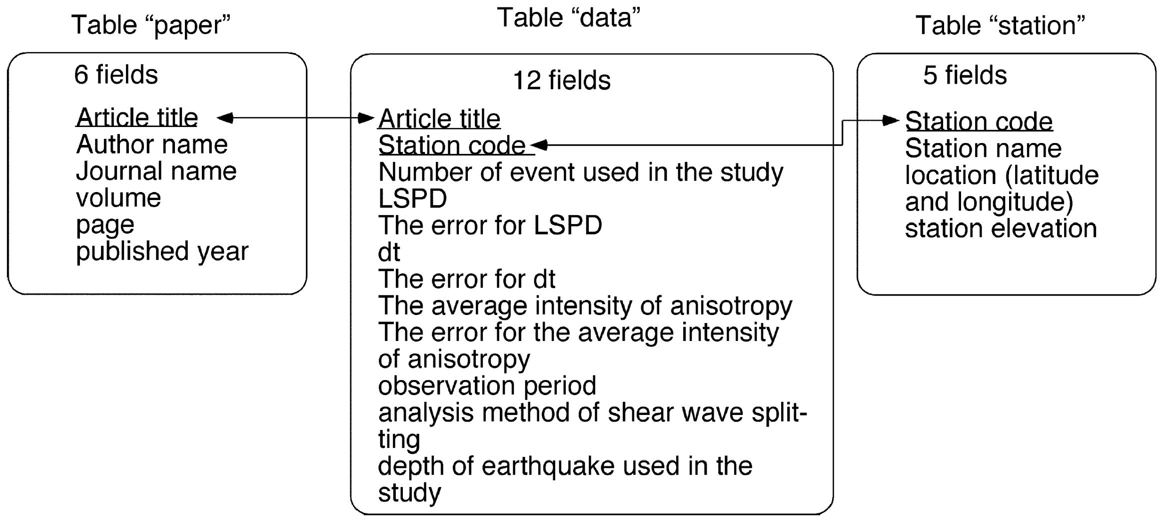


Fig. 3. The structure of tables used in the present system. Each table can be related to other tables (allowed in the figure) using “key” in each table (underlined).

table consists of 6 fields on bibliographic information of each paper, including title of article, author name, journal name, volume, page, and publication year. The “station” table consists of 5 fields on the location of each seismogram, including station code, station name, latitude, longitude, and elevation of station. The shear-wave splitting data is gathered in the “data” table. This table consists of 12 fields, including title of article, journal name, station name, number of data, LSPD and its error, delay time and its error, and intensity of anisotropy and its error. While the shear-wave splitting can be expressed by 2 parameters, LSPD and dt (Fig. 1), we also include γ, the average intensity of anisotropy, to express the degree of anisotropy in the following form :

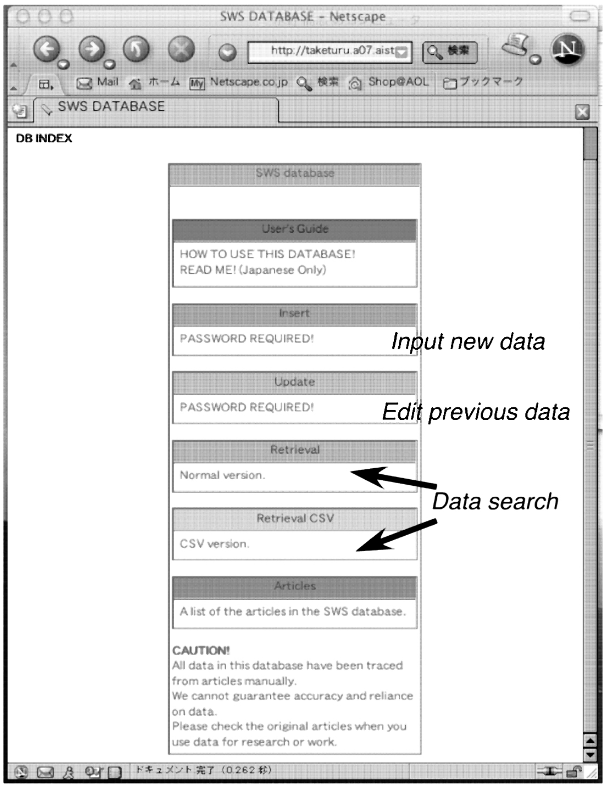
$$\lambda = \frac{Vs}{L} dt, \tag{1}$$

where Vs, L represents the shear-wave velocity of the matrix medium and the length of the lay-path from hypocenter to station, respectively. If the average intensity of anisotropy does not appear in an article, we calculate it using parameters in the article, if possible. Each table is related to other tables using “key”. The relation between tables of data and papers is accomplished using the “Article title” key, and the relation between tables of data and station is accomplished using “Station code” key (Fig. 3).

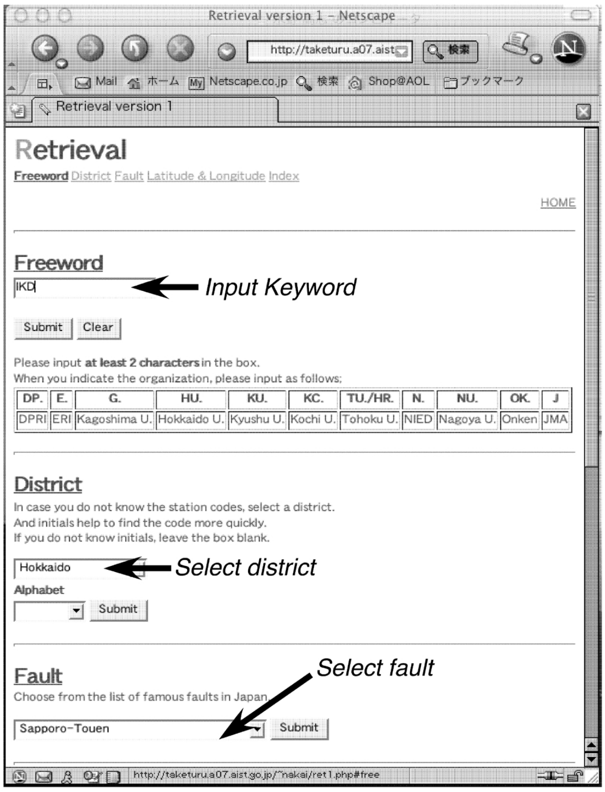
3. 2. Interface server

The web-based system cannot be provided with PostgreSQL alone, because it does not have a web-based interface. To provide a web-based database service, interface server access to the database server in response to a user request on the web page is required. We use Apache and PHP for the interface server. Communicating with the database, sending a query, and receiving retrieval results are accomplished with a program written in PHP, which is a server side script language embedded in HTML on Apache web server (Fig. 2). Once the user enters key words in a query on the web page of the interface server, the PHP program embedded in the web page generates a query written in SQL and submits it to the database server (Fig. 2). Then, the database server responds to the query, and sends the response to the interface server (Fig. 2). Updating of splitting data is also accomplished by the PHP program embedded in HTML (Fig. 2).

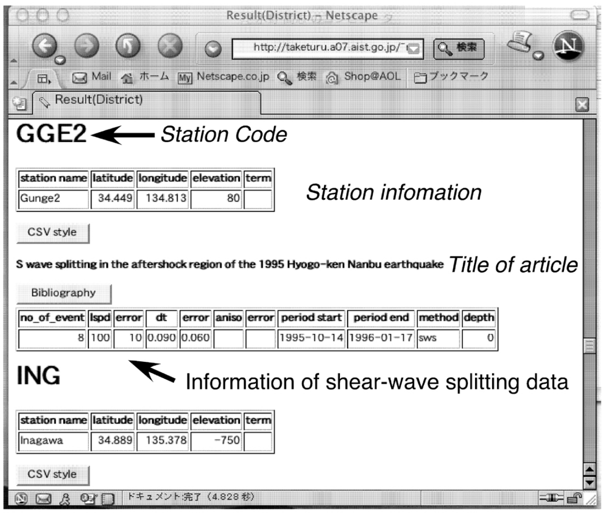
The present system was developed using PostgreSQL 7.4, apache 2.0, and PHP 4.3, and it is running on the PC Linux (RedHat 9.0) machine. Fig. 4 (a) shows the main portal to the web pages. Fig. 4 (b) shows the web page for retrieval. A user who would like to retrieve SWS data, enters keywords and pushes the “submit” button. Then, the PHP program is executed, and the query is submitted to the database server (Fig. 2). The database server generates a response to the query and transfers it to the web server (Fig. 2). The user can also select the station by choosing the district and the major tectonic zone



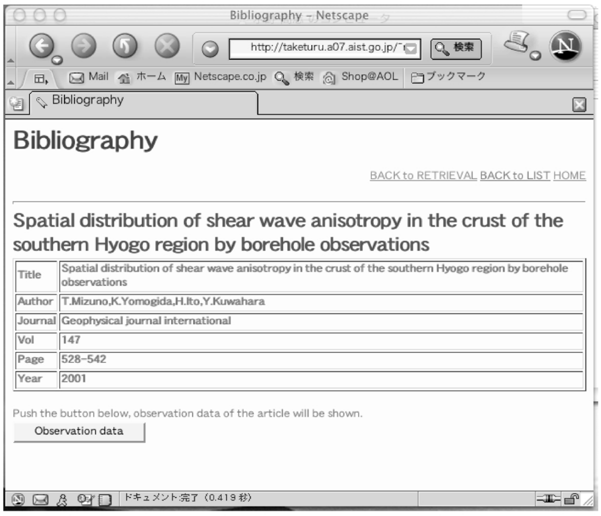
(a)



(b)

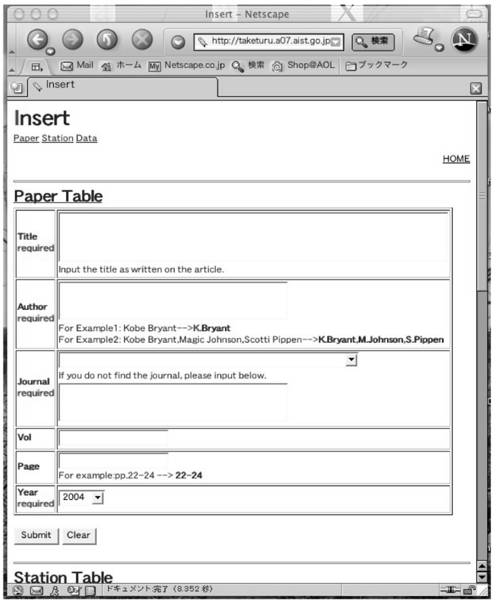


(c)



(d)

Fig. 4. Views of the web page of OpenSWS. (a) The main portal to OpenSWS. User selects a suitable web page. (b) Web page for retrieving records. User can retrieve data on the shear-wave splitting by the following three methods. Freeword : User inputs at least head 2 characters of a station code or an organization code to specify a station. District : Users can retrieve records for all stations located within the selected districts. Fault : There is a pulldown menu for selecting famous active faults and tectonic zone. The database returns data obtained at stations neighboring the specified fault or tectonic zone. Latitude & Longitude : The database returns records within the specified region. (c) Web page for results retrieved. (d) Web page for bibliographic information. From this page users can enter retrieval results page. (e) Web page for updating records. We can update records through the web page. However, access to this web page is only permitted to registered users for security reasons.



(e)

Fig. 4. (Continued)

where the station is located. Fig. 4 (c) shows an example of retrieval results, including station code, station name, latitude and longitude of station, splitting parameters, and title of article. We can also retrieve detailed bibliographic data on this page (Fig. 4 d), since the relations between data table and paper table have been accomplished (Fig. 3). If there are no splitting data for a query, the information on station code, station name, and latitude and longitude are presented. We prepared another version of the retrieval interface, which returns retrieval results in CSV style (comma separated values) for use with other applications, such as GMT (Wessel and Smith, 1991). Fig. 4 (e) shows the web page for entering new records. Access to this web page is restricted to registered users for security reasons.

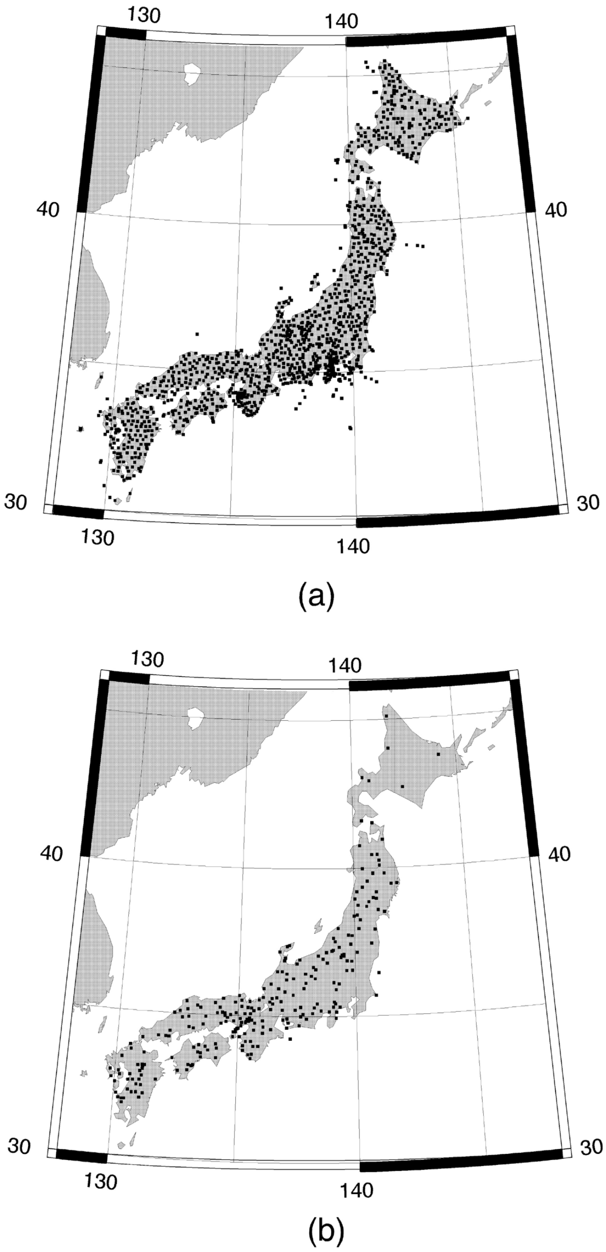


Fig. 5. (a) Distribution of permanent seismic stations deployed by national institutes and universities in Japan to date. (b) Distribution of seismic stations used in the previous analysis for shear-wave splitting.

4. SWS data stored in the database

Fig. 5 (a) shows the distribution of permanent seismic stations deployed by national institutes and universities in Japan. A total of approximately 1400 stations are in operation. Since the station spacing is approximately 20 km for the current seismic network, we have the potential to infer the direction of Shmax with a 20-km spacing using SWS. Fig. 5 (b) shows the distribution of seismic stations used for analyzing SWS. The number of these seismic stations is approximately 270, 20% of the total. Fig. 6 shows the direction of LSPD at each station. To use statistically reliable data, we selected a study that used at least 5 seismic records to obtain the average splitting parameter. The number of seismic stations that determined LSPD using at least 5 earthquakes is approximately 100, 7% of the total.

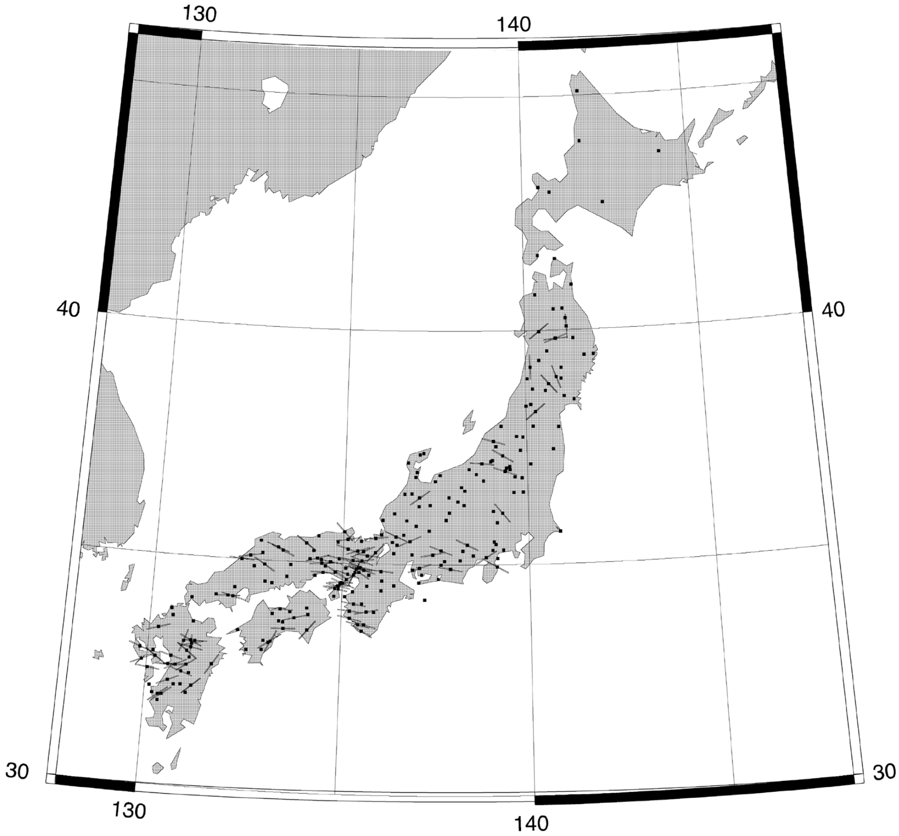


Fig. 6. Spatial variation of LSPD. The solid square denotes seismic stations used in previous studies. The solid bar represents the LSPD for a station that determined LSPDs using at least 5 earthquakes.

5. Verification of direction of maximum horizontal compression inferred from SWS—as one example of using OpenSWS—

To verify the direction of Shmax inferred from shear-wave splitting, LSPDs had been compared with the direction of the maximum horizontal compression inferred from geodetic measurements and focal mechanisms (e.g., Kaneshima, 1990). In this study, we compare the LSPD with the direction of Shmax inferred from *in situ* stress measurement, which was deployed in the vicinity of the seismic station. We retrieved LSPD information around the stress-measured site using OpenSWS. Table 1 and Fig. 7 show comparisons between LSPD and direction of Shmax inferred from *in situ* stress measurements near the seismic station. In addition, comparisons between LSPD and direction of Shmax inferred from strain measurements are also represented. Most of the pairs show good consistency, indicating LSPDs can be recognized as a good indicator of Shmax direction around a seismic station in most cases. However, LSPDs at stations NMZ and TDRT are not comparable with the direction of Shmax inferred from *in situ* stress measurements. Tadokoro *et al.* (1999) measured the LSPD at station TDRT, and indicated that the LSPD at TDRT represents micro fractures associated with the fault structure. However, there are no active faults in the vicinity of the NMZ. As mentioned in section 1, the LSPD corresponds to the direction of Shmax for the stress type that enhances the strike-slip type earthquake. Fukuyama *et al.* (2001) represented the nationwide crustal stress state map using an automatic CMT solution, and indicate that the thrust-type earthquake dominated around station NMZ. Hence, the LSPD at NMZ might not represent the direction of maximum horizontal compression. While measuring of shear-wave splitting is convenient for estimating the direction of maximum compression, it sometimes leads to false estimation. Hence, it is important to verify the direction of maximum horizontal compression inferred from shear-wave splitting, especially near the

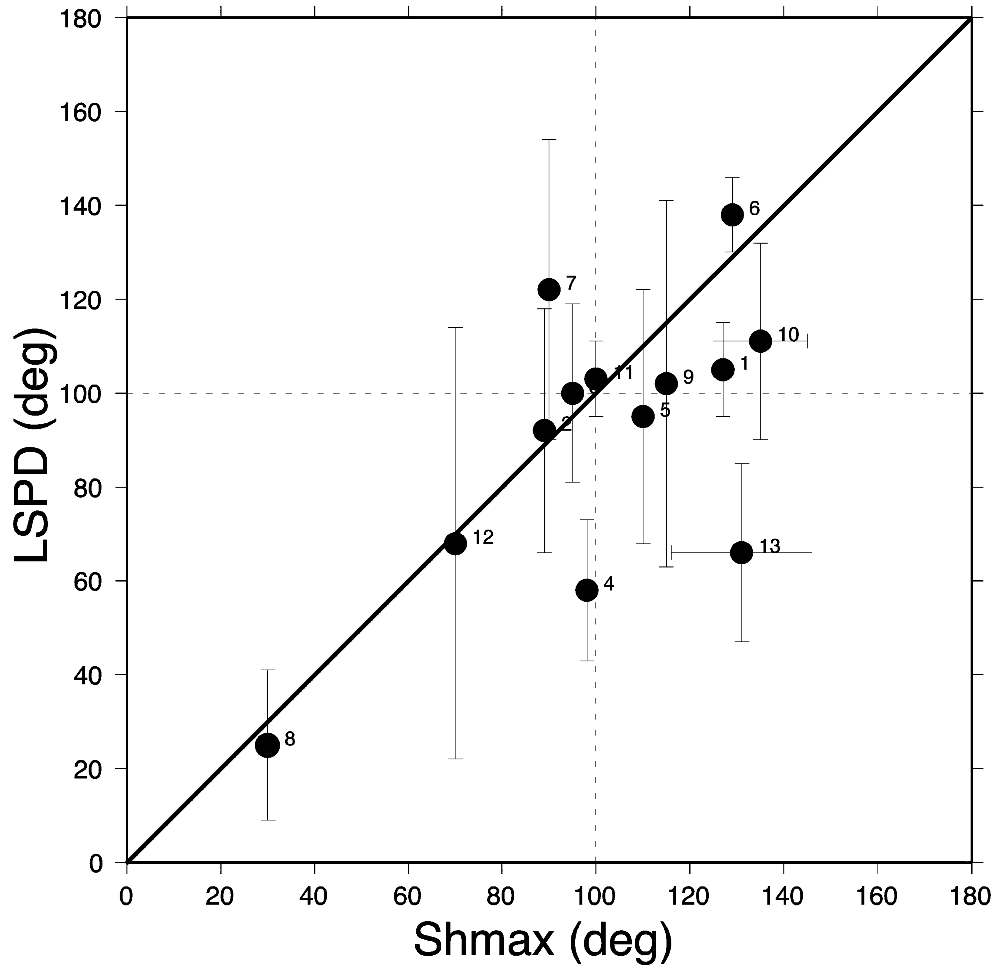


Fig. 7. The relationship between LSPD and the direction of the maximum horizontal compression inferred from in-situ stress and strain measurement. The ID corresponds to the site number in Table 1. The dots on the solid line indicate that the LSPD shows good consistency with the direction of the maximum horizontal compression inferred from the *in situ* stress and strain measurement.

Table 1. Comparisons between LSPD and the direction of the maximum horizontal compression inferred from *in situ* stress and strain measurement.

Shear wave splitting						Stress and strain measurements				
Site number	Station Code	Latitude (deg)	Longitude (deg)	LSPD (deg)	Paper ID	Site name	Latitude (deg)	Longitude (deg)	Direction of Shmax	Paper ID
1	KMP	32.816	130.65	105±10	s1	Miike	–	–	127	i1
2	DOI	33.961	133.398	92±26	s1	Sazare	–	–	89	i1
3	NKMH	34.128	135.327	100±19	s2	Nagamine	–	–	95	i1
4	NMZ	35.158	138.846	58±15	s1	Izu-Nagaoka	–	–	98	i2
5	KWNH	37.17	138.747	95±27	s2	Kan'etsu	–	–	110	i3
6	NRKH	38.856	140.655	138±8	s2	Kawatabi	–	–	129	i2
7	IKD	34.815	135.439	122±32	s3	IKD	34.815	135.439	90	i4
8	TKZ	34.818	135.335	25±16	s3	TKZ	34.818	135.335	30	i4
9	ING	34.889	135.378	102±39	s3	ING	34.889	135.378	115	i5
10	IWY2	34.572	135.009	111±21	s4	Iwaya	–	–	135±10	i6
11	MYG	36.344	137.189	103±8	s5	SGR	36.348	137.185	100	i7
12	IKH	34.51	134.899	68±46	s3	IKH	34.51	134.899	70	i8
13	TDRT	34.558	134.953	66±19	s4	Hirabayashi	–	–	131±15	i6

Paper ID : The ID of the reference of each study. s1 : Kaneshima (1990), s2 : Sakakibara (2004), s3 : Mizuno *et al.* (2001), s4 : Tadokoro *et al.* (1999), s5 : Mizuno *et al.* (2005), i1 : Tanaka (1986), i2 : The research group for crustal stress in eastern Japan (1984), i3 : Saito *et al.* (1988), i4 : Ito *et al.* (1997), i5 : Satoh *et al.* (1997), i6 : Ikeda (2001), i7 : Kuwahara (2003) personal communication, i8 : Kuwahara and Ito (2000).

fault zone and tectonic area where a strike-slip type earthquake does not dominate.

6. Concluding remarks

To manage and use large amounts of shear-wave splitting data, OpenSWS, a web-based database of shear-wave splitting has been developed. In order to view the information, users only require a Web browser and Internet access. Remote updating of the database is supported to receive contributions from researchers around the world. Bibliographic information of 23 papers and shear-wave splitting data of 270 stations are stored in the database at present.

Acknowledgements

The present study was inspired by discussions at the 2-day meeting "Reliable Measurement of Crustal Stress—Existing Techniques and Problems to be Solved—"held in June 2004 at the Earthquake Research Institute, the University of Tokyo. We are grateful to Dr. Atsuki Kubo of Kochi University for his help for correcting the research articles on the crustal anisotropy and for discussions on database during its development. We thank Dr. Yasuto Kuwahara of National Institute of Advanced Industrial Science and Technology for supporting this project. Ms. Akiko Tanaka (now at the National Institute of Earth Sciences and Disaster Prevention) helped the development at the begging of the project. This database has been constructed using software packages under BSD and GNU Public Licenses. We would like to express our gratitude to all of the software professionals who have contributed to the development of these programs. The comments of 2 anonymous reviewers are greatly appreciated. This study is partly supported by the Grant-in-Aid for JSPS Fellows (No. 15.1522) financed by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan (T. Mizuno). Takashi Mizuno is a postdoctoral research fellow of the Japan Society of Promotion of Science.

References

Boness, N.L. and M.D. Zoback, 2004, Stress-induced seismic velocity anisotropy and physical properties in the SAFOD Pilot Hole in Parkfield, CA, *Geophys. Res. Lett.,* **31**, L15S17, doi : 10.1029/2003GL019020.

Codd, E.F., 1970, A relational model of data for large shared data banks, *Comm. ACM,* **13**, 377–387.

Crampin, S., 1978, Seismic-wave propagation through a cracked solid : polarization as a possible dilatancy diagnostic, *Geophys. J. R. Astr. Soc.,* **53**, 467--496.

Fukuyama, E., A. Kubo, H. Kawai and K. Nonomura, 2001, Seismic remote monitoring of stress field, *Earth Planets Space,* **53**, 1021–1026.

Ikeda, R., Y. Iio and K. Omura, 2001, In situ stress measurements in NIED boreholes in and around the fault zone near the 1995 Hyogo-ken Nanbu earthquake, Japan, *The Island Arc,* **10**, 252–260.

Ito, H., Y. Kuwahara and O. Nishizawa, 1997, Stress measurements by the hydrautic fracturing in the 1995 Hyogoken-nanbu earthquake source region, in "*Rock Stress*", edited by Sugawara and Obara, Balkema, Rotterdam, Netherlands, pp. 351–354.

Jackson, G.A., 1988, *Relational database design with microcomputer application,* Prentice Hall.

Kaneshima, S., 1990, Origin of crustal anisotropy : Shear wave splitting studies in Japan, *J. Geophys. Res.,* **95**, 11121–11133.

Kuwahara, Y. and H. Ito, 2000, Strain field around the earthquake faults of the 1995 Hyogo-ken nanbu earthquake (2), *Programme and Abstracts of the Seismol. Soc. Jpn.,* P 023.

Mizuno, T., K. Yomogida, H. Ito and Y. Kuwahara, 2001, Spatial distribution of shear wave anisotropy in the crust of the southern Hyogo region by borehole observations, *Geophys. J. Int.,* **147**, 528–542.

Mizuno, T., H. Ito, Y. Kuwahara, K. Imanishi and T. Takeda, 2005, Spatial variation of shear-wave splitting across an active fault and its implication for stress accumulation mechanism of inland earthquakes : the Atotsugawa fault case, *Geophys. Res. Lett.,* **32**, L20305, doi : 10. 1029/2005GL023875, 2005.

Saiga, A., Y. Hiramatsu, T. Ooida and K. Yamaoka, 2003, Spatial variation in the crustal anisotropy and its temporal variation associated with a moderate-sized earthquake in the Tokai region, central Japan, *Geophys. J. Int.,* **154**, 695–705.

Saito, T., T. Ishida, M. Terada and Y. Tanaka, 1988, The general tendency of initial stress state in Japan with the data of in-situ measurements, *Proc. Jpn. Soc. Civil. Engineers,* **III-9, 394**, 71–78 (in Japanese with English abstract).

Sakakibara, Y., 2004, Nation-wide upper crustal anisotropy distribution beneath the Japan islands, *Master Thesis,* Nagoya University.

Satoh, T., K. Kusunose, A. Cho, T. Kiyama, F. Yamada and T. Aizawa, 1997, A crustal stress measurement just above the focal region of Inagawa earthquake swarm, *Zisin,* **50**, 57–65 (in Japanese with English abstract).

Tadokoro, K., M. Ando and Y. Umeda, 1999, S wave splitting in the aftershock region of the 1995 Hyogo-ken Nanbu earthquake, *J. Geophys. Res.,* **104**, 981–991.

Tanaka, Y., 1986, State of crustal stress inferred from in situ stress measurements, *J. Phys. Earth,* **34**, S57–S70.

The research group for crustal stress in eastern Japan, 1984, Measurements of crustal stress in Eastern Japan (1), *The report of the coordinating committee for earthquake prediction, Japan,* **32**, 396–402.

Wessel, P. and Smith, W.H.F., 1991, Free software helps map and display data, *EOS Trans. AGU,* **72**, 441.

Zoback, M.L., 1992, First and second order patterns of stress in the lithosphere : The World Stress Map Project, *J. Geophys. Res.,* **97**, 11703–11728.

(Received October 27, 2004)
(Accepted April 4, 2005)