Advances in Geological Science

Mitsuhiro Toriumi

Global Seismicity Dynamics and Data-Driven Science

Seismicity Modelling by Big Data Analytics

MOREMEDIA

Springer

Advances in Geological Science

Studies in the twentieth century uncovered groundbreaking facts in geophysics and produced a radically new picture of the Earth's history. However, in some respects it also created more puzzles for the research community of the twenty-first century to tackle. This book series aims to present the state of the art of contemporary geological studies and offers the opportunity to discuss major open problems in geosciences and their phenomena. The main focus is on physical geological features such as geomorphology, petrology, sedimentology, geotectonics, volcanology, seismology, glaciology, and their environmental impacts. The monographs in the series, including multi-authored volumes, will examine prominent features of past events up to their current status, and possibly forecast some aspects of the foreseeable future. The guiding principle is that understanding the fundamentals and applied methodology of overlapping fields will be key to paving the way for the next generation.

More information about this series at http://www.springer.com/series/11723

Mitsuhiro Toriumi

Global Seismicity Dynamics and Data-Driven Science

Seismicity Modelling by Big Data Analytics

Springer

Mitsuhiro Toriumi
Japan Agency of Marine-Earth Science
and Technology
Yokohama, Kanagawa, Japan

ISSN 2524-3829 ISSN 2524-3837 (electronic)
Advances in Geological Science
ISBN 978-981-15-5108-6 ISBN 978-981-15-5109-3 (eBook)
https://doi.org/10.1007/978-981-15-5109-3

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Natural phenomena of the earth are still mysterious even if there are accumulating huge amount of observation data because of complex and diachronous process. To understand them, it may require to discover macroscopic invariances embedded in huge amounts of measured information in nature.

Earthquakes and volcanic eruptions are representative phenomena of solid earth dynamics, and they are often serious disaster for human society in the world. Though they occurred frequently in the world, scientists have not succeeded in earthquake prediction except for the case that the earthquake is associated with the obvious signatures before its event. Actually, almost always giant earthquakes occurred at the plate boundary, and intraplate large faults took place suddenly without any signals. In spite very wide regions around the giant earthquakes are damaged seriously not only on person but also society with huge amounts of infrastructure, it should be surprising that no signals before earthquake can be found in the recent investigations except for several rare examples.

Recent investigations on earthquake researches are based on the global networks of the precise wide-band digital seismometers, and on the foundation of dense network system seismometer stations in Japan at 1998 and USA after 1990, and later the ocean bottom geophysical stations network such as Dense Ocean Floor Network for Earthquake and Tsunami (DONET) system founded at 2011 in Japan and NEPTUNE of Canada at 2009. By these global and regional network systems established after 1980, the detailed structures of solid earth interior are possibly determined by the tomography technology from crust to deep mantle and core. As the results, the whole seismic velocity structure of the earth interior is inferred in detail though there are some inconsistencies in the seismic velocity structures in the mantle and crust in the active plate boundary. It may be due to the fact that the tomography images by present inversion method are based on the optimization with grid search technique but not global minimum search using Markov chain Monte Carlo method (MCMC). Recent investigation of seismic tomography has been developed with MCMC Bayesian inversion method for the synthetic data case. Then, near future should open the precise seismic tomography applicable to the real solid earth interior and give us the detailed seismic structure required for the determination of epicenters of the large to micro-earthquakes.

Global seismic networks are providing huge amounts of seismic data to scientists and person in various fields of the world, and due to this open sourcing of data, it is possible to carry the cross-checks by many different investigations that the proposed models on seismicity dynamics of earth interior are available for fundamental relations and predictions of seismicity both in the world and districts. Furthermore, it also provides the necessity for prediction where and what are important observation and seismic stations in the present districts and world. Huge amounts of monitoring and accumulating data should involve the fundamental earth mechanics laws in the long-term and short-term phenomena though these contain abundant noisy fluctuation. Today, the scientific tools for investigation of hidden fundamental processes governing the earth mechanics take methods for huge amounts of data and many different kinds of data in the real time scales by means of data-driven scientific methods involving machine learning and several regularization techniques and artificial intelligence. In addition, there are many techniques for data assimilation between the large-scale simulation experiments with huge number of parameters and observation big data in the present scientific environments. In the fields of global and regional climatology and oceanic dynamics, the integrated dynamics of ocean and atmosphere with cloud generation is well running on precise experimental equations governing the weather and climate in the world with deep learning technology and data assimilation programs using the monitoring data by satellite gravity (GRACE) and many oceanic buoys network system (ARGO). The solid earth mechanics field should be facing with the time to investigate the comprehensive studies on the global and regional seismicity dynamics based on the now accumulating monitoring data from the global and regional geoscience observation networks and scientific vehicles.

In this book, the author intends to introduce the global and regional seismicity dynamics based on the huge amounts of global and regional seismic source data possibly acquired from the world open databases by means of the data-driven sciences which should be a potential clue for the predictive investigation of the large earthquakes and mitigation of the giant disaster by them. This book may be useful for learning the recent and future data-driven scientific and machine learning methods applicable for many interdisciplinary studies of earth and planetary sciences.

In this book, the author intends to propose a new method based on machine learning of huge amount of accumulating seismic data both in the global and regional scales of solid earth, and thus, he think of importance of the open data sources made from established global and regional databases on seismicity by himself. Therefore, in order to access the database used here by readers, the author prepared the open database in Electronic Supplement Materials (ESM) in Springer.

Yokohama, Japan Mitsuhiro Toriumi

Contents

Chapter 1
Introduction

Abstract Since the last centuries, many giant earthquakes exceeding magnitude 9 associated with giant tsunami took place in the circum-Pacific coastal areas in the world. These natural disasters brought huge amounts of damages in our human communities. Most of the scientists deeply felt a necessity of fundamental understanding of global and regional mechanical behavior of earth process.

Keywords Giant earthquakes · GR law of earthquakes · Earthquake disaster

1.1 Introduction

In 2004 and 2011, the giant plate boundary earthquakes occurred in the wide ranges of Sumatra and Northeast Japan, and their magnitudes of the giant earthquakes reached over M 9.0 (Kanamori 2006; Fujiwara et al. 2011). The source faults of the Sumatra earthquake exceed 1000 km length and 20 m displacement along the Indian (Indo-Australia) plate (Satake and Atwater 2007), and the Tohoku-Oki giant earthquake ranges 500 km length and 300 km width along the plate boundary between the Pacific plate and the Japanese islands arc crust. The post-seismic displacement reaching 70 m at the edge of the overriding island arc crust displayed first eastward and then changed westward after one year, suggesting the recoupling of Pacific plate and island arc crust (Fujiwara et al. 2011). Giant plate boundary earthquakes exceeding M. 9 occurred six times during recent hundred years even around the Pacific Ocean: Kamchatka Peninsula earthquake, Alaska earthquake, Chile earthquake, Sumatra earthquake, and Tohoku-Oki earthquake (Fig. 1.1). The maximum slip extended about 1000 km along the Chile trench at the case of 1960 Chile earthquake but at the case of Tohoku-Oki earthquake, the scale of earthquake generating plate boundary zone reached 500 km $\times$ 300 km with the slip length of 70 m eastward.

Electronic supplementary material The online version of this chapter (https://doi.org/10.1007/978-981-15-5109-3_1) contains supplementary material, which is available to authorized users.

M. Toriumi, *Global Seismicity Dynamics and Data-Driven Science*,
Advances in Geological Science,
https://doi.org/10.1007/978-981-15-5109-3_1

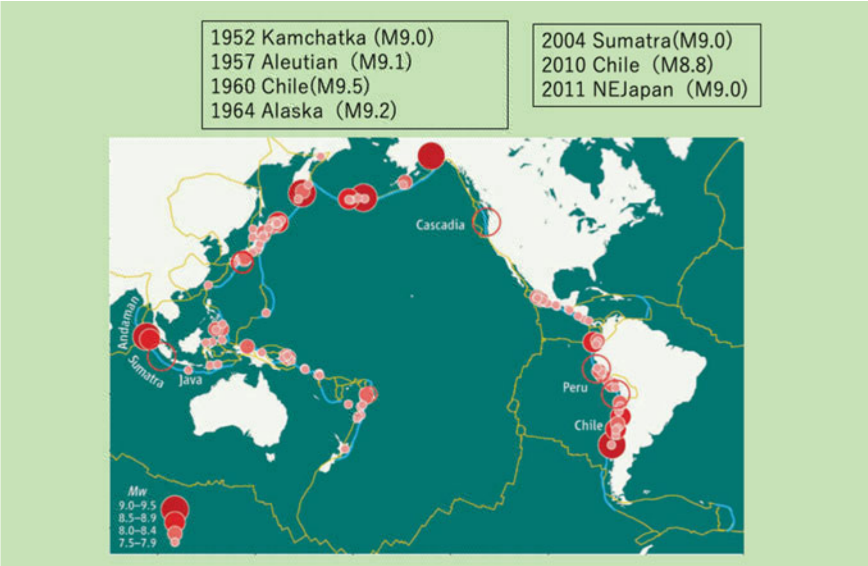

Fig. 1.1 Recent occurrence of giant earthquakes at the subduction zones around the Pacific Ocean from 1900 to 2016. (Personal communications of Dr. Sugioka of Kobe University)

Huge amount of damage by these giant disasters took a strong negative impact not only on regional community but also worldwide economy and social system because of destructive deficient effects about social system and social capitals together with many persons failed. In the case of Sumatra 2004, the plate boundary giant earthquake brought much wide disaster against the many coastal cities and towns around the Indian Sea from eastern Indian Sea even to the western area of the Indian Sea. At the same time, the giant tsunami with 10–30 m height generated from the Sumatra earthquake and attacked the coastal areas around the Indian Sea and persons over 300,000 died. In the case of Tohoku-Oki 2011 earthquake, very large tsunami reaching 30 m high also attacked the coast areas of Pacific side of the Tohoku District and persons over 25,000 died and lost.

As noted in many literatures, there were abundant giant earthquakes along the plate subduction boundaries of our planet which gave the great negative effects on human community and society. And it often gave a heavy damage-inducing the perfect destruction of one city or town. At the time of the Tohoku-Oki giant earthquake, the giant tsunami attacked the many small towns along the Sanriku District, and then those small cities were perfectly destroyed by the giant tsunami.

Today, the giant earthquake is considered to be generated by high-speed slippage along the large scale thrust faults and many of them occurred at the active plate boundaries, especially at the subduction plate boundary. The earthquake at the plate boundary is responsible for the unstable slip in the wide range of slip velocity, slip area, slip distance, depth of slip plane, and slip angle with other many parameters such as water film along the boundary plane as pointed out by Scholz (1982). Recent detailed investigations of the earthquakes occurred in the plate boundary zone show a manifestation that there is a wide variation of timescales of the durations characterizing the earthquakes ranging from subseconds to years. The very short time durations are characteristic in the case of very small magnitudes, but in the case of long-term durations of slip events the earthquakes appear wide variations of the magnitude reaching M 9. The relations between durations of the earthquakes and their magnitudes are recently suggested to be classified into two types by Ide and Shelly (2007): One is normal (regular) earthquake and another is slow slip event and tremor types. In the normal type, the magnitude seems to be proportional to the logarithmic duration time of the earthquake, and thus, the giant earthquakes arise generally long-term oscillation of the ground.

The earthquake is the elastic oscillation within the solid and fluid earth (Aki and Richards 1980). Thus, the earthquake is observed as the elastic oscillation of the ground, of the air, and of the seawater. Although the oscillation of the air and water is the sound itself showing the elastic body wave in the case of solid earth, it results in the elastic shear wave and body wave against the advancing direction of the elastic wave. The body wave is the oscillation of compression and expansion of the solid and fluid medium of the earth but shear wave is the oscillation of shear displacement of the solid medium normal to the advancing direction of the wave, and it is called as optical mode because of the oscillation geometry.

Elastic wave in the solid materials is primarily generated by the change of slip velocity of rock masses along on the slip plane (Aki and Richards 1980). Stable slip makes the elastic wave but almost always at the beginning of the slip or at the cessation of the slip the elastic wave is propagated and the timescale of the unstable slip corresponds to the frequency of the elastic wave. In general case, the slip velocity increases from zero to a finite value and then decreases to zero, indicating the maximum velocity change at the meantime of the slip motion along on the discontinuous plane. Then the observed oscillation of elastic shear wave at the ground station displays the mode of double couple of mutually orthogonal shear waves because of no rotation condition of the rock masses around the shear plane. However, it should be noted that the elastic wave generated by the explosion or implosion of rock masses such as phase transition of minerals and fluid phases appears to be compression and dilation modes, but it should be transformed into random orientation of double couple shear wave mode.

The earthquakes generating points are called as the hypocenter, but it means some extent of the slip plane area, being correlated with the magnitudes of them. The intensity of the earthquake is expressed by the magnitude (M) or moment magnitude defined by the following equation;

$$M = log\,(moment\;of\;earthquake) = log\,(du\;G\;S) \tag{1.1}$$

in which du is the shear displacement, G is the shear modulus (rigidity) of the rock, and S is the surface area of the shear slip plane (Aki and Richards 1980). Thus, it follows that the intensity of the earthquake shows those of the fracture area and displacement of the slip. Therefore, the unit increase of the magnitude corresponds

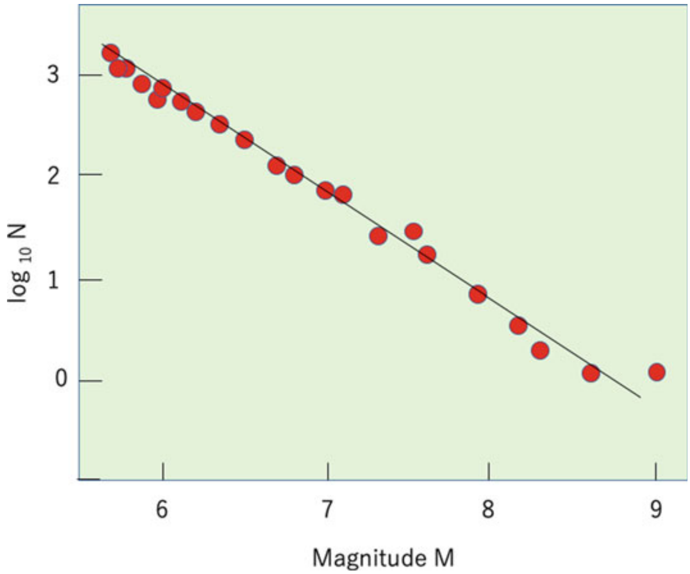

Fig. 1.2 Gutenberg and Richter law of the relation between magnitude and cumulative number of the earthquakes

to the ten times of the slip area in the case of constant slip displacement means 1/10 of that of earthquake magnitude. The total moment release by the M9 earthquake should be then 10^8 times of those of M1 earthquakes.

The logarithmic cumulative frequency of the earthquakes is proportional to the moment (i.e., the magnitude) as well-known Gutenberg–Richter law (Fig. 1.2),

$$N(M) = 10^{-bM} \tag{1.2}$$

This type of law is called as the scaling law, and the above GR law is satisfied in the very wide range of the seismic magnitude from M2 to M9. It is still strange in the physical mechanism of the very wide scale-free process in the natural solid earth mechanics as discussed by many authors (Allegre et al. 1982; Bak and Tang 1989; Ito and Matsuzaki 1990; Brown et al. 1991).

Combining these relations, it is obvious that in the large volume and time of earthquakes statistics the logarithmic cumulative frequency of the shear crack is proportional to the sizes of the shear cracks. Therefore, it seems that the very small shear cracks corresponding to M1 are very common in the crust and shallow mantle of the plate boundary zone, judging from that the 10^8 times of frequency compared with the M9 earthquakes. Therefore, if we consider the number density of micro-earthquakes below magnitude 2–3, the mechanical states and its time variation represented by density function of the very small shear cracks activated by small increase of the shear stress in the crust and mantle are possibly inferred in the global and regional solid earth. In addition, the mechanical state referring to the shear stress which is critical for propagating the shear cracks should be responsible for triggering the large giant earthquakes along the plate boundary and intraplate fault zones. In this book, the author would like to introduce the global seismicity dynamics by means of the characteristic features of the time series of density functions of micro-to-small earthquakes events in the global plate boundaries zones and highly seismic active subduction zone in the Japanese islands region and transform fault zone of Northern California region from 1990 to 2019 AD. The huge amounts of seismic data studied here are acquisited from seismic source data stored in the various databases in the USA (USGS, FDSN and Berkeley Seismicity Center and Japanese seismic open data centers (ERI of University of Tokyo, NIED, and JMA).

References

Aki K, Richards PG (1980) Quantitative seismology: theory and methods. W.H. Freeman, San Francisco, California, p 948

Allegre CJ, LeMouel JL, Provost A (1982) Scaling rules in rock fracture and possible implications for earthquake prediction. Nature 297:47–49

Bak P, Tang C (1989) Earthquakes as a self-organized critical phenomenon. J Geophys Res 94:15635–15637

Brown SR, Scholz CH, Rundle JB (1991) A simplified spring-block model of earthquakes. Geophys Res Lett 18:215–218

Fujiwara T, Kodaira S, No T, Kaiho Y, Takahashi N, Kaneda Y (2011) The 2011 Tohoku-Oki earthquake: displacement reaching the trench axis. Science 334:1240–1240. https://doi.org/10.1126/science.1211554

Ide S, Shelly DR (2007) A scaling law for slow earthquakes. Nature 447:76079. https://doi.org/10.1038/nature05780

Ito K, Matsuzaki M (1990) Earthquakes as self-organized critical phenomena. J Geophys Res 95:6853–6860

Kanamori H (2006) Lessons from the 2004 Sumatra-Andaman earthquake. Phil Trans R Soc A 364:1927–1945

Satake K, Atwater BF (2007) Long-term perspectives on giant earthquakes and tsunamis at subduction zones. Annu Rev Earth Planet Sci 35:349–374

Scholz CH (1982) Scaling laws for large earthquakes and consequences for physical models. Bull Seismol Soc Amer 72:1–14

Chapter 2
Nature of Earthquake in the Solid Earth

Abstract Earthquake is an oscillation of the solid and fluid of the earth interior, and it is excited by fracture of rocks. The modes of fracture and nature of medium, therefore, govern the propagation of elastic wave of earthquake, and thus, the nature of the earthquake is manifested by the global process of fracture in the earth interior.

Keywords Global distribution of earthquakes · Shear instability · Classification of earthquakes

2.1 Global Earthquake Distribution and Plate Tectonics

The plate tectonics has been founded by the global distribution patterns of earthquakes as discussed by Sykes (1967) and Isacks et al. (1968), together with magnetization anomaly of the ocean floor basalt as a kinematic model of rigid spherical plates along on the solid earth: The dense occurrence of many earthquakes appears in the narrow zone of the plate boundaries as shown in Fig. 2.1, and on the other hand, the rare occurrence of earthquakes apart from the plate boundaries except for large collision zone of the continents such as Tibet and southern Eurasia regions is as seen in the same figure (Fig. 2.1). The frequency of earthquakes along the mid-oceanic ridge zones, however, is lesser than those along the subduction boundaries (arc–trench). The ratio of the frequency between them reaches about 100–1000, and the maximum magnitude of the ridge zone is less than about 7 but that of the trench zone about 9.

The observations of earthquakes at many stations clarify the characteristics of the slip geometry of the shear cracks such as shear crack vectors composed of the shear plane and slip vector by the observed nodal planes by orientation of ground motions. The one of the shear cracks is the thrust type, second type is the transcurrent

Electronic supplementary material The online version of this chapter (https://doi.org/10.1007/978-981-15-5109-3_2) contains supplementary material, which is available to authorized users.

M. Toriumi, *Global Seismicity Dynamics and Data-Driven Science*, Advances in Geological Science,
https://doi.org/10.1007/978-981-15-5109-3_2

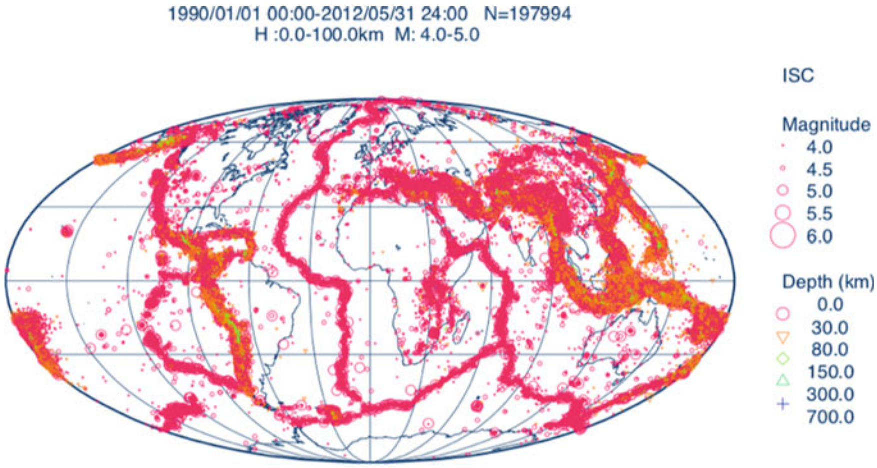

Fig. 2.1 Inhomogeneous distribution of earthquakes along global subduction zone and oceanic ridge zone

fault type, and third is the normal fault type. The difference of these three types is resulted from that of the stress geometry against gravity. The case of the maximum stress normal to the gravity and minimum one parallel to gravity is the thrust type, but the case of maximum stress parallel to the gravity and minimum one normal to the gravity is the normal fault type. Third case of transcurrent fault type corresponds to the intermediate stress parallel to the gravity. During the foundation stage of the plate tectonics from 1967 to 1970, it was stressed that modes of earthquakes in the subduction zone are characterized by the thrust-type and transcurrent-type faults, but in the ridge zone, the normal fault type is predominant.

The distribution patterns of earthquakes in the three-dimensional framework display sharply the oblique subduction of the oceanic plate behind the trench, which is called as Wadachi–Benioff zone from the ocean bottom level to 700 km depth. The characteristic frequency of earthquakes along the subducting oceanic plate is composed of the shallow maximum and the deep maximum as indicated by Sykes (1967) and as shown in Fig. 2.2. The former is called as shallow focused earthquakes and the latter as deep focused ones. The seismic mechanisms of both types have been investigated in the long time, and it seems that both are followed by double coupled type responsible for shear slip motion. However, the fracture mechanics suggests that the fracture strength becomes very large over several GPa in the 700 km depth, and shear cracks cannot be active by simple differential stress conditions under several MPa. Recent studies show that the deep focused earthquakes should occur by the rapid transformation of wadsleyite and ringwoodite after olivine incorporated with water in the 400–700 km depth (Green and Burnley 1989).

On the other hand, the seismicity of the ridge is characterized by the shallow earthquakes above 10 km depth, and almost always, it is represented commonly by

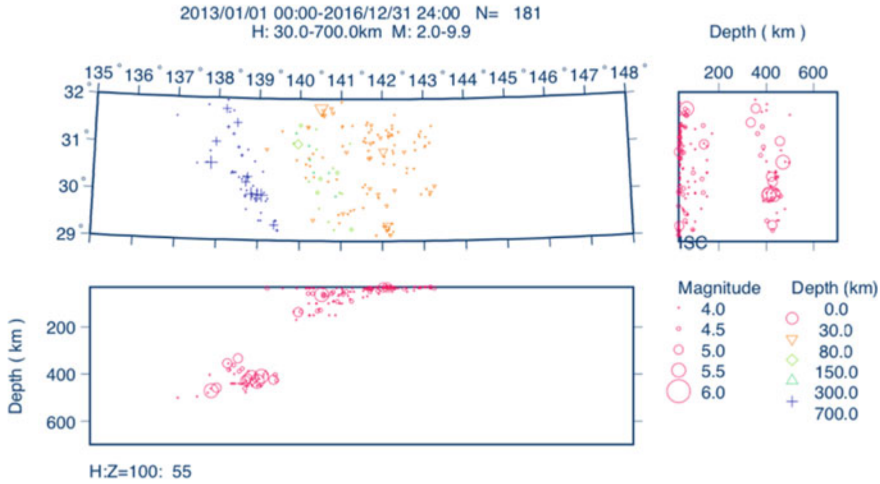

Fig. 2.2 Three-dimensional distribution of earthquakes under the Izu–Bonin arc, showing the two clusters of seismicity of the deep slab and shallow one of the Pacific plate

normal fault type. Such features are possibly considered to be due to high temperature conditions near the ridge and at large stress level should result in the yielding plastically at the relative shallower depth. Besides, the extensional stress field should be responsible for the low differential stress fracturing. Along the transform fault zones, the transcurrent fault type seismicity is common as manifestation of the plate tectonics kinematics (Isacks et al. 1968).

In summary, the global-scale earth mechanics is represented by seismicity patterns of the surficial solid earth with deep subduction zone at the narrow zones of the plate boundaries. Furthermore, this seismicity is caused by the pre-existing cracks growing associated with plate motion. The seismic wave as the earthquakes is emitted by the case that the shear cracks propagate with unstable mode indicating the shear instability in terms of solid mechanics (e.g., Rice 1993). In the next chapter, we will see the detail of the shear instability in the rock and solid mechanics resulting the earthquakes.

2.2 Earthquake Propagation and Shear Instability

Generally speaking, the seismic slip along shear cracks emitting elastic wave occurs unstably due to accumulating stress or strain in the solid earth. When slip in the solid earth takes place in the stationary constant speed, it leads stable slip, and it is responsible for permanent deformation by faults. Unstable slip phenomena of the pre-existing shear crack are resulted from the velocity softening and/or from the strain softening that is defined by the negative $\mathrm{d}F/\mathrm{d}V_s$ or $\mathrm{d}F/\mathrm{d}\varepsilon$ along on the slip zone, in which F is the force (shear stress) on slippage. Considering the frictional slip on the shear crack, the shear stress acting on the shear plane is followed by Coulomb–Navier law as,

$$\tau = \mu\,\sigma_n + c \tag{2.1}$$

Here, τ is the shear stress, μ is the frictional coefficient, and σ_n is the stress normal to the shear plane, respectively, and c is constant. The above criterion is the condition of frictional slip of the precut plane of the solid materials and rocks, but it does not suggest the unstable slip. The differentiation of right hand side that we obtain is in the case of unstable slip,

$$\mathrm{d}\tau/\mathrm{d}V = \mathrm{d}(\mu\,\sigma_n)/\mathrm{d}V = \mathrm{d}\mu/\mathrm{d}V < 0 \tag{2.2}$$

On the other hand, based on many experimental data of frictional slip of the rocks, Dietrich (1979, 1994) and Ruina (1983) obtained the rate and state equation of slip as follows;

$$\begin{aligned} &\mu(\theta, V) = \mu_o + a\ \ln(V/V_o) + b\ \ln(V_o\theta/D_c) \\ &\mathrm{d}\theta/\mathrm{d}t = 1 - V\,\theta/D_c \end{aligned} \tag{2.3}$$

where θ and μ are the state parameter and frictional coefficient of the slip, respectively, and V and D_c are the slip velocity and critical distance of slip, respectively. V_o is the normalized parameter of slip velocity.

In these equations, we obtain $\mathrm{d}\mu/\mathrm{d}V$ under the condition of $\mathrm{d}\theta/\mathrm{d}t = 0$ as follows

$$\mathrm{d}\mu/\mathrm{d}V = (a - b)/V$$

and

$$\tau = \sigma\,\mu \sim \sigma(a - b)\ln\ V \tag{2.4}$$

Therefore, the unstable condition of the slip is the case of negative value of $(a - b)$. The $(a - b)$ depends on the surrounding conditions such as pressure, temperature, fluid pressure, and other physicochemical parameters. Recently, Leeman et al. (2016) summarized the wide spectrum of slip instability of natural earthquakes phenomena from regular type to slow slip types as the marginal instability near the stable slip at $(a - b) \sim 0$. Unstable slip in the case of Eq. (2.4) should take place with softening by increasing slip velocity V as shown in Fig. 2.3.

The marginal instability near $(a - b) \sim 0$ then shows the instability of slips with various frequencies of critical slip distance (Ohnaka and Matsu-ura 2002), suggesting that the several long-term unstable slips may be coupled with each other and make some degree of resonance between them and start the unstable slip under the noisy fluctuations.

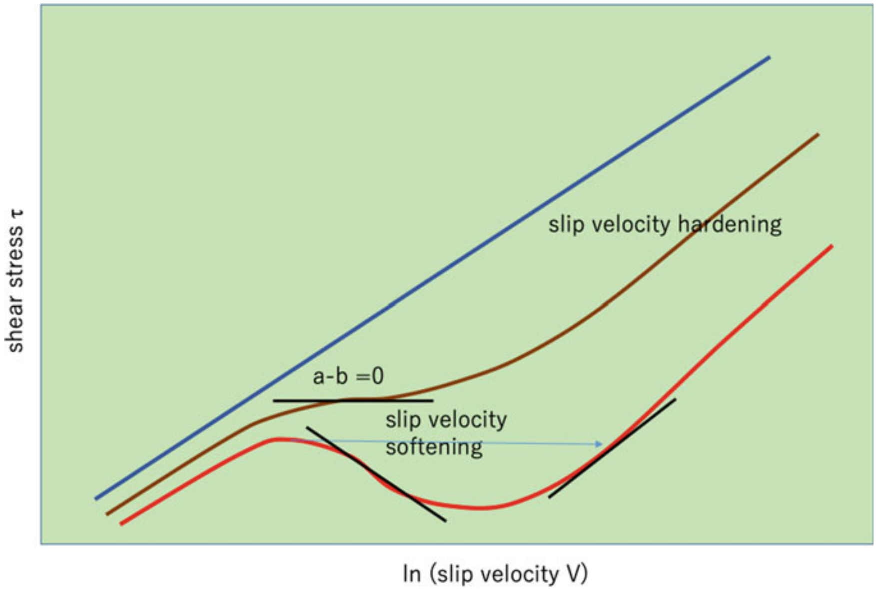

Fig. 2.3 Friction law of the shear slip plane with increasing normal stress from red to blue curve. The slip velocity softening appears in the negative slope of the curve and the hardening does in the positive slope regime. The critical condition at $a - b = 0$ occurs in the case of brown curve

By the way, we next consider the various types of network system of many slider block units as proposed by Burridge and Knopoff (1967) and later Brown et al. (1991), having the velocity v_i and displacement x_i as follows:

$$\begin{aligned} \mathrm{d}v_i/\mathrm{d}t &= k_i x_i + k_j x_{ij} + r_i v_i + \text{noises} \\ \mathrm{d}x_i/\mathrm{d}t &= v_i \end{aligned} \tag{2.5}$$

Here, k_i and r_i are the elastic constant and viscous resistance of the unit, respectively.

First, we consider the circular network system of simple slider blocks as shown in Fig. 2.4.

In order to investigate the network effects of multiple slider blocks connected by elastic and viscous stress such as the situation of the plate subduction zones around Pacific Ocean, the cases of the constant elastic modulus and viscosity and their fluctuated values are simulated. The system size is kept in the 100 units configured as the circular network of their connection. It follows that the block motion is characterized by the apparent random velocity and displacement, but the correlated motions of many slider blocks appear as the large-scale and long-term cooperative displacement along the circular connection as shown in Fig. 2.5. In this study, the correlated motions of the circular-connected slider blocks are processed by means of deterministic PCA method described in the later chapter.

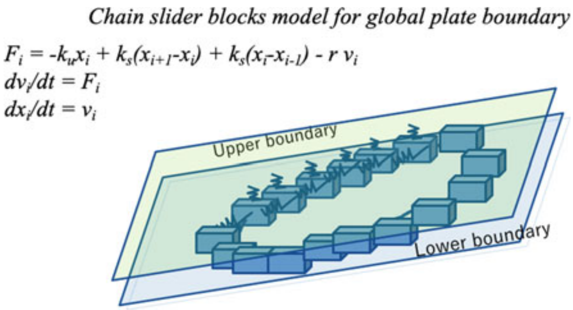

Fig. 2.4 Circular connected slider–spring block model showing the subduction zone slippages at the plate boundary. The upper boundary is of the subduction plate and overriding plate, and the lower one is with the asthenosphere underneath the subduction plate

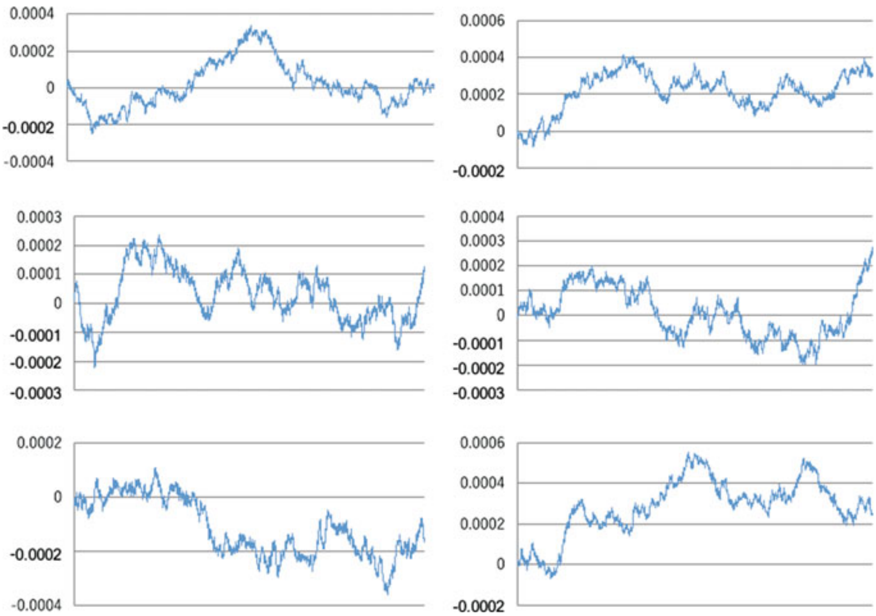

Fig. 2.5 Representative time series of the displacement of representative blocks (simulation; 5000 steps) on the circular connected slider block model. The vertical axis is the normalized displacement, and horizontal axis is the time step

On the other hand, the two-dimensional arrays of slider blocks shown in figures are simulated in the same parameter conditions as those of the chained slider blocks (Fig. 2.5). The correlated motions of the arrayed slider blocks can be seen clearly in the large-scale and long-term modes of combined individual blocks as shown in Fig. 2.6. By these simulation studies, clustered motions of the connected slider blocks are generated having the long-term oscillation modes.

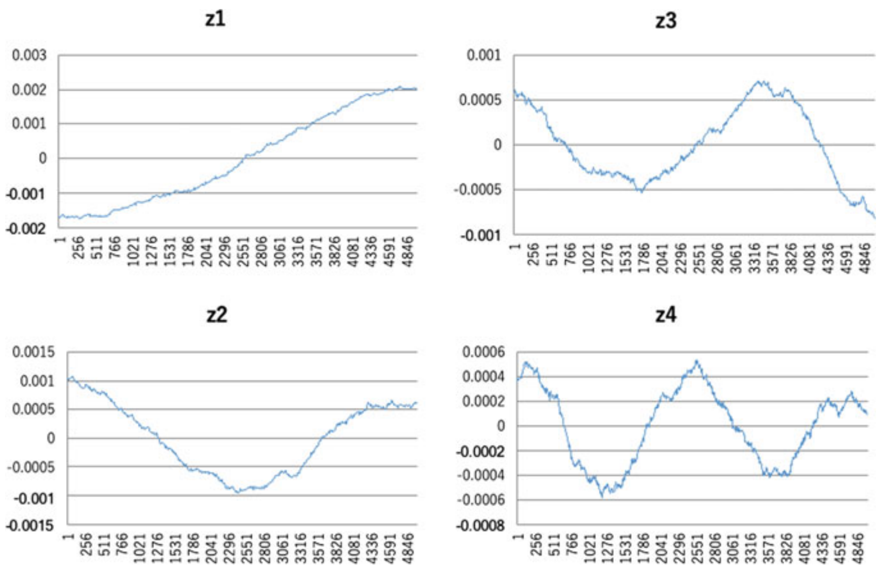

Fig. 2.6 Time series of major correlated displacements of z_1 to z_4 determined by principal component analysis of simulated blocks motion in the circular connected slider–spring block model of Fig. 2.4

2.3 Earthquakes and Global Network of Seismic Stations

In order to clarify the layered structure and the short- and long-term seismic activity of the solid earth, the global and regional digital seismometers have been founded in the world, and methods of automatic hypocenter determination by global networks are developed as CMT centroid moment tensor method by Harvard University group from 1980 (Dziewonski et al. 1981). The network stations are distributed as shown in Fig. 2.7, and global CMT hypocenters determined by these networks are stored in the global databases in the USGS earthquake center.

On the other hand, the Japanese regional networks of digital seismometers have been founded at 1998 after Hanshin–Awaji earthquake of 1995 as shown in Fig. 2.8. The database of seismicity in the Japanese islands regions is stored in database of JMA-1 by Japan Meteoritic Agency and National Institute of Earthquake Disasters. The database of seismic hypocenters involves earthquakes of M1 to M9 from 1998 to 2019. The area covers the hypocenters of Japanese islands regions from Okinawa to northern Hokkaido and Ogasawara islands. Recent ocean-bottom seismic networks of DONET I and II and also SNET are founded in the Off Kii and Shikoku regions of Nankai Trough and in the regions along the Japan Trench from Off Chiba to Off Hokkaido in order to monitor the near-field activity above Philippine Sea plate and Pacific plate, respectively. The DONET has the station nodes with seismometers and hydro-pressure gauges. The dense networks of sensitive hydro-pressure gauges can take the signals of the slow slip events and non-volcanic tremors along the plate

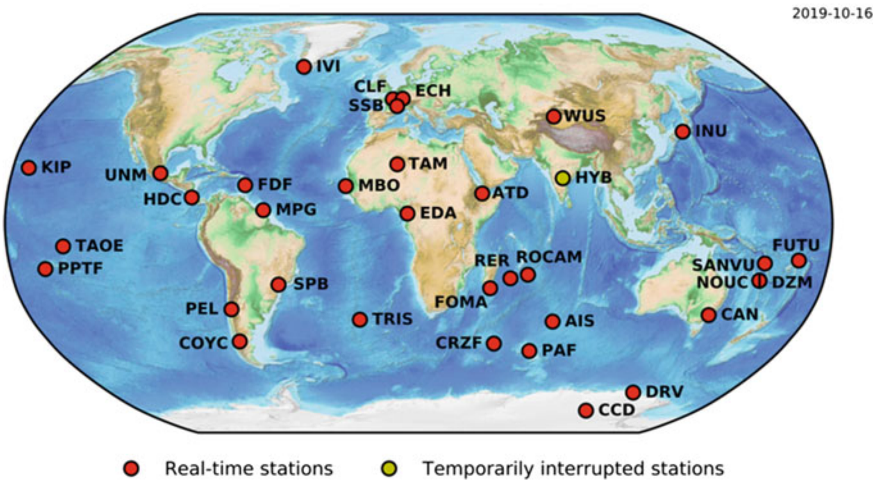

Fig. 2.7 Map showing the global network system of the seismicity of the solid earth cited from https://fdns.edu

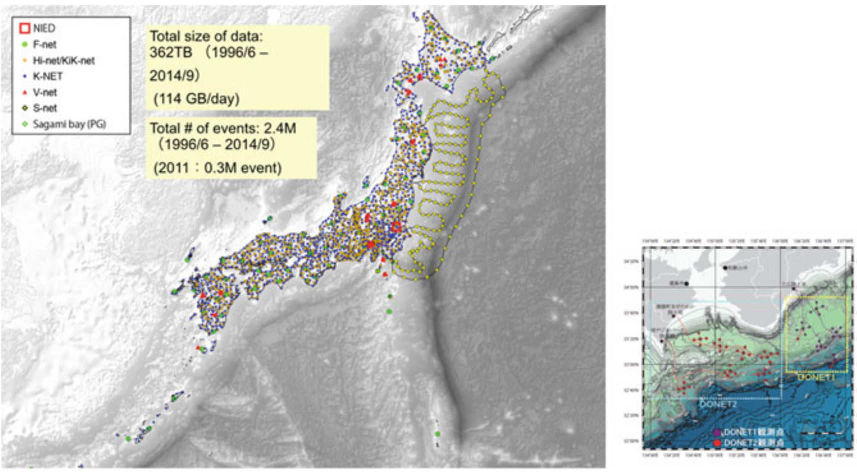

Fig. 2.8 Maps of regional network system of digital seismic stations and DONET ocean-bottom seismicity and tsunami observation system Off Kii and Shikoku in Japan (https://www.jamstec.go.jp/donet/j/donet/donet2.html)

subduction boundary and within the accretionary prism as being referred to Japan Agency of Marine Science and Technology (JAMSTEC) and National Institute of Earthquake Disaster (NIED) of Japan.

Regional networks of precise digital seismometers have been founded in various areas where large-scale transcurrent faults are active like the San Andreas Faults along west coast regions of US. The maps of the regional networks of seismic stations

Fig. 2.9 Map of digital seismograph stations in Northern California cited from Northern California Earthquake Data Center, UC Berkeley Seismological Laboratory. Data set. https://doi.org/10.7932/ncedc: http://ncedc.org/berkeley-networks.html

are shown in Fig. 2.9, as being cited from International Federation of Digital Seismograph Networks (FDSN networks). These network databases are very useful for investigating the inner solid earth structures and various seismic activities related to the seasonal variations of rainfall and snow loading and unloading stresses and/or tidal force variation. The hydro-loading and unloading stresses can be evaluated precisely from the meteoritic databases of NOAA and from the gravitational variations observed from satellite observation systems (GRACE; Chanard et al. 2018). The data from the telemetric variations of continent—continent and hot spots—continent distances are also open accessed in database of VLBI centers of National Astronomical Observatory of Japan (ONAOJ; GSI home page (Geospatial Information Authority of Japan) 2019).

References

Brown SR, Scholz CH, Rundle JB (1991) A simplified spring-block model of earthquakes. Geophys Res Lett 18:215–218

Burridge R, Knopoff L (1967) Model and theoretical seismicity. Bull Seismol Soc Amer 57:341–371