5^{th} IASPEI/IAEE International Symposium
Effects of Surface Geology on Seismic Motion
2016 August 15-17 Taipei Taiwan

ADVANTAGES OF BOREHOLE ARRAY DATA FOR BETTER UNDERSTANDING OF STRONG GROUND MOTION IN SEDIMENTARY BASINS

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温故知新（孔子）

Learn a lesson from the past /   or

Study the history, and obtain

the wisdom for tomorrow./

OUTLINE OF MY TALK TODAY (1):

Short History of Seismic Observations in the Underground (Borehole), Mostly in Japan

- Efforts of the First Stage in Japan (1887–1940)
- Developments of Borehole Seismometer and Observations (1950–1970)
- Increase of Borehole Observation Sites and Seismic Prospecting (1970–1995)

Non-linear, Q , Test sites: Do not touch today

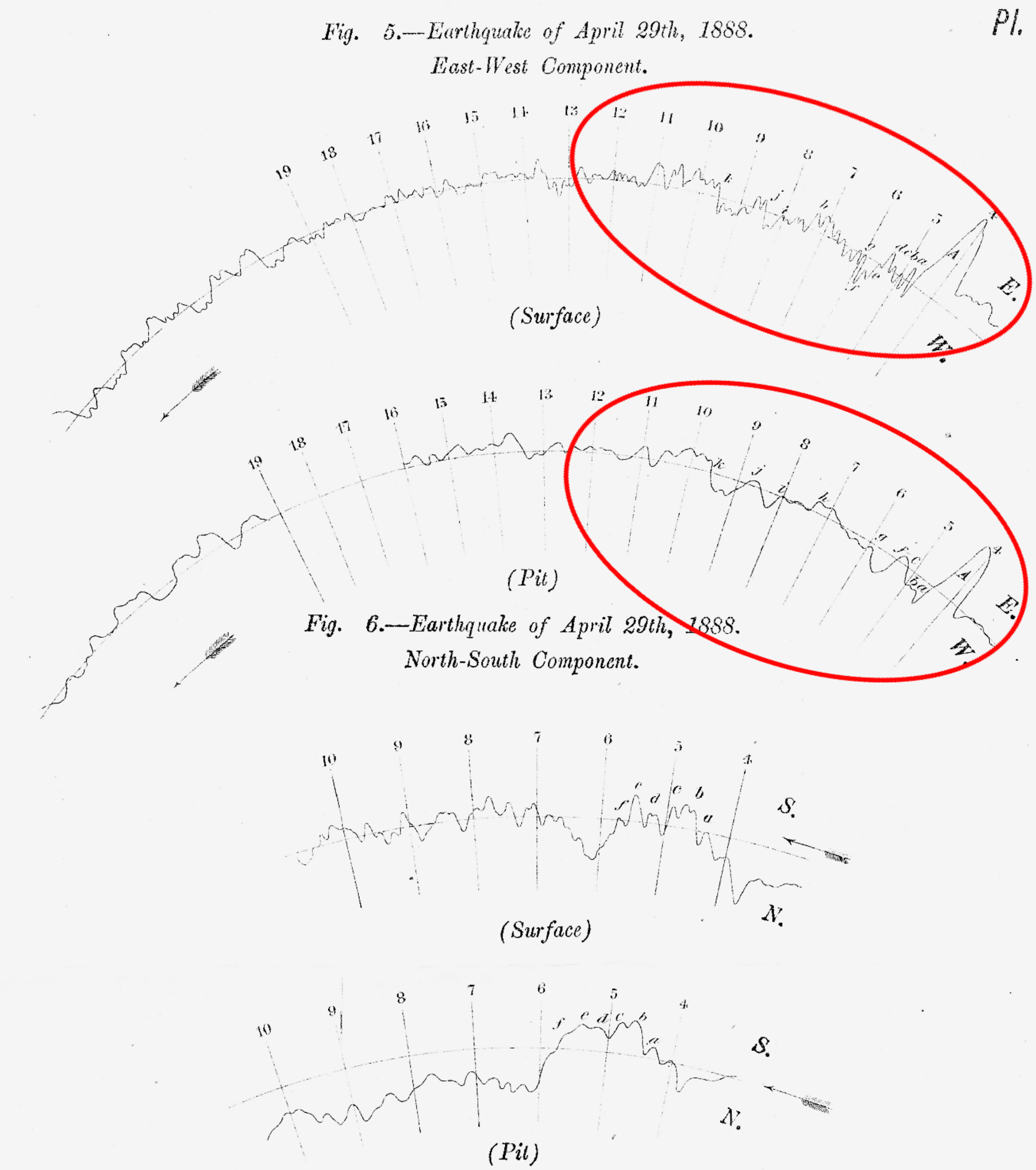
OUTLINE OF MY TALK TODAY (2):

Some Topics of Deep Borehole Observations, its History and Recent Issues

- Deep Borehole Observation in Sedimentary Basins
- Deep Borehole Observation at Stiff Soils or Rock Sites
- Contribution of the KiK-net from Deep Borehole sites
- Recent Unexpected Ground Motion and Deep Boreholes Observations in the Nuclear Power Stations in Japan

Borehole Observations at the Dawn of Seismology in Japan

Year	Authors	Site Name	Depths(m) of Instrument	Type of Instruments
1887	Milne	Kasumigaseki (Tokyo)	Surface & -3m	
1892	Sekiya and Omori	Hongo (Tokyo)	Surface & -5.4m	Ewing type horizontal seismograph
1934	Saita and Suzuki	Marunouchi (Tokyo)	Surface, -9.1m & -20.6m (two wells)	Ishimoto type accelerographs
1934	Inoue	Komaba (Tokyo)	Surface & -9m	Imamura's displacement seismograph, Ishimoto's Accelerographs, Tremor recorder
1951	Kanai and Tanaka	Hitachi Mine (Ibaraki Pref.)	Surface, -150m, -300m, and 450m	Horizontal displacement seismograph (To = 1 sec), Magnification = 150



- Sekiya and Omori(1891)

Surface: The ripple are very prominent

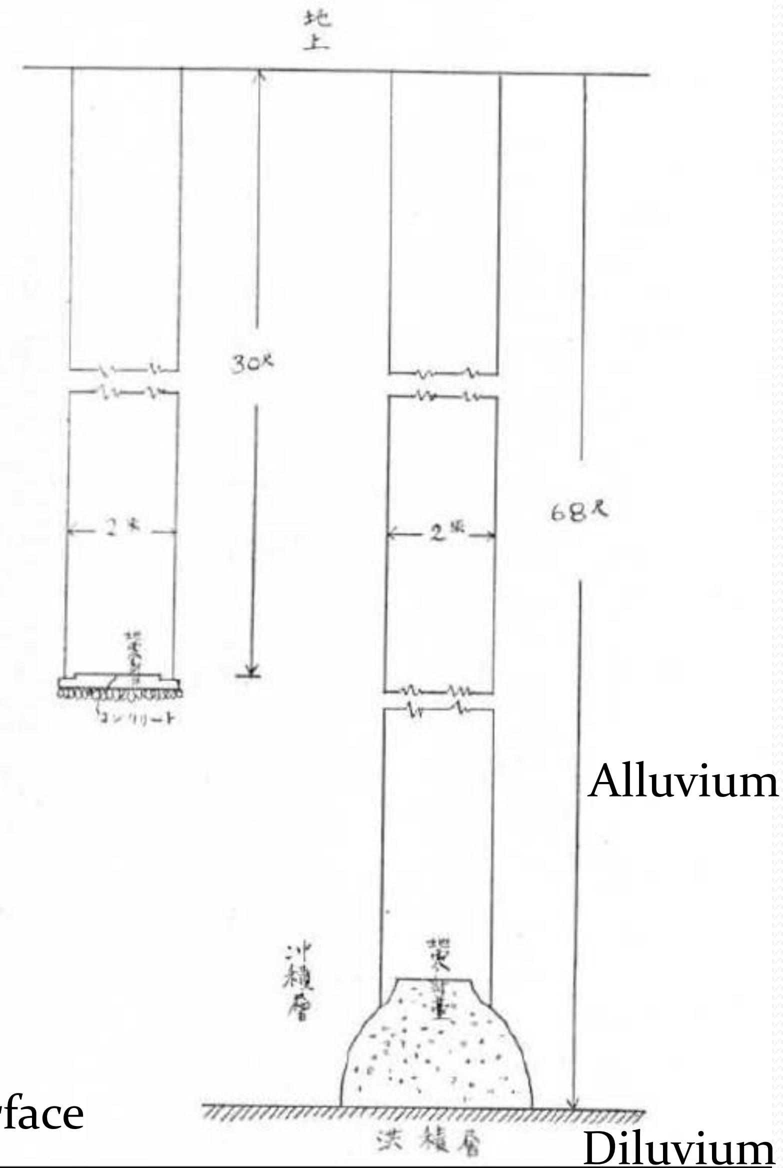
Pit: No ripples

Ripple are super imposed on slower undulation of 2 sec. (EW) and 3 sec. (NS)

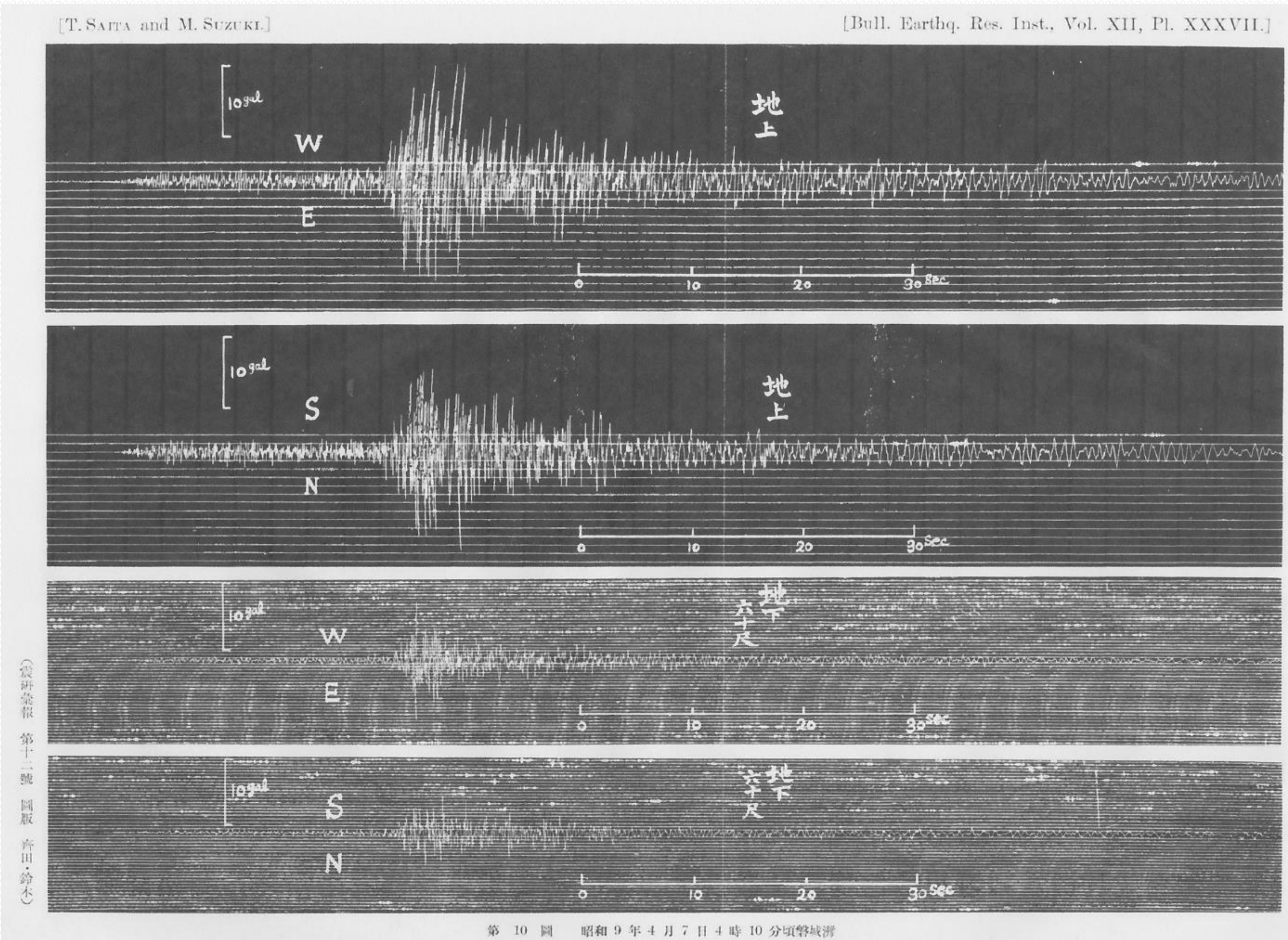
Observation pits used by Saita and Suzuki (1934)

第 2 圖　地下68尺の觀測所を地上より望む

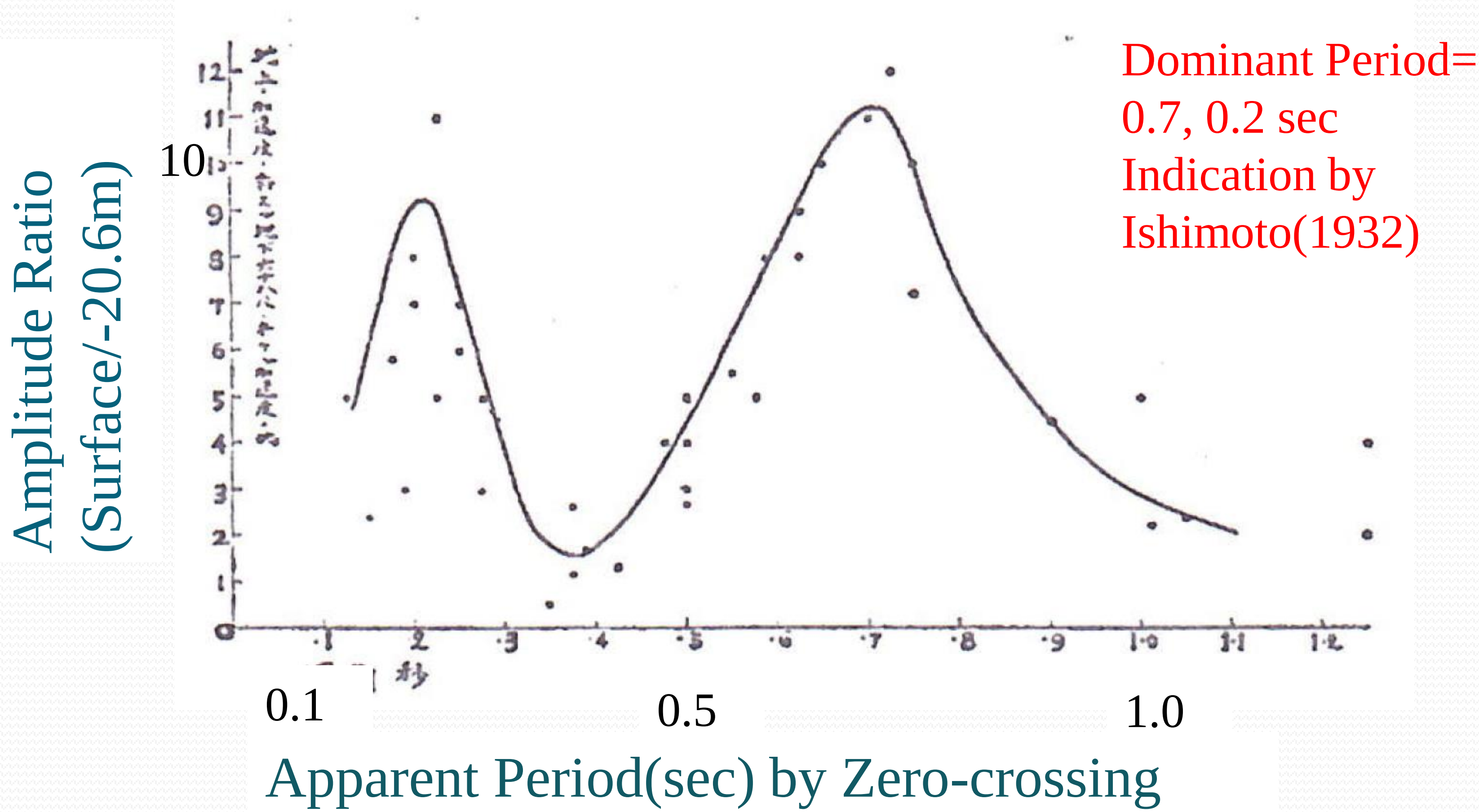
Look down the 68f (~21m) pit from the surface



Examples of records reproduced from Saita and Suzuki (1934) : Ishimoto's Accelerographs were used



Quasi Spectral Ratio of Ground Motions between Surface and Underground (-20.6 m)



Reproduced from Saita and Suzuki (1934) with additional explanations.

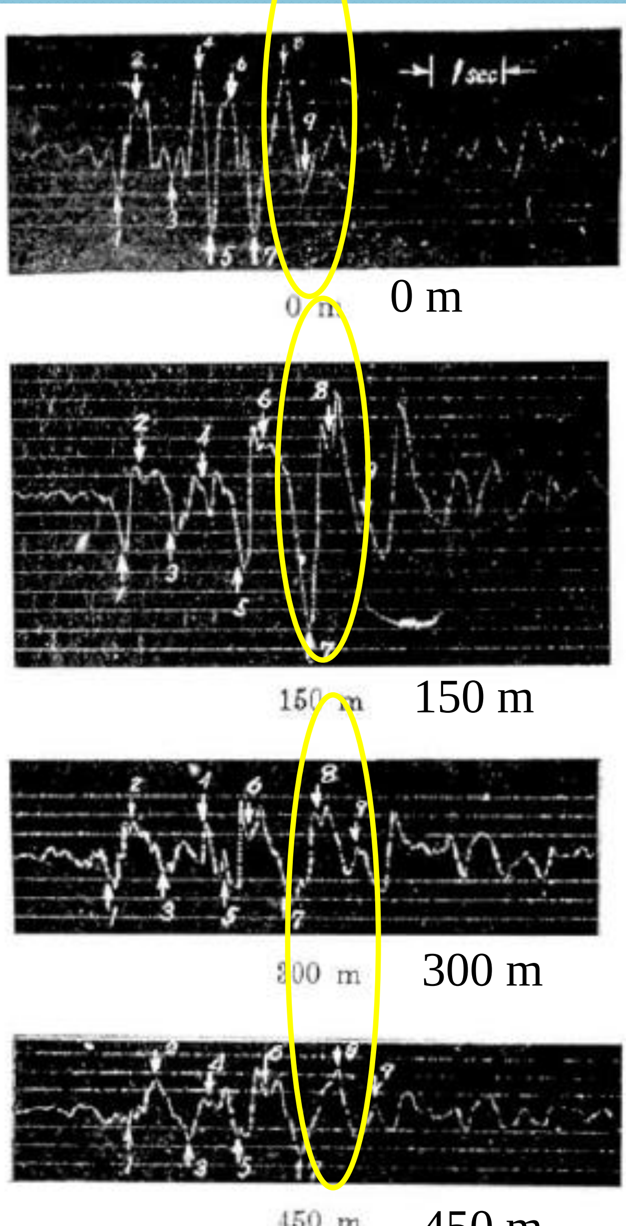


Fig. 6. Records of the early parts of the main shocks of the earthquake, 36.2° N; 141.2° E, $D=40$ km, $\Delta \doteqdot 70$ km, 1950 IV 14. Original × 3.5.

Deep underground observations led to the discovery of existence of the M_2 waves (Sezawa and Kanai, 1935)

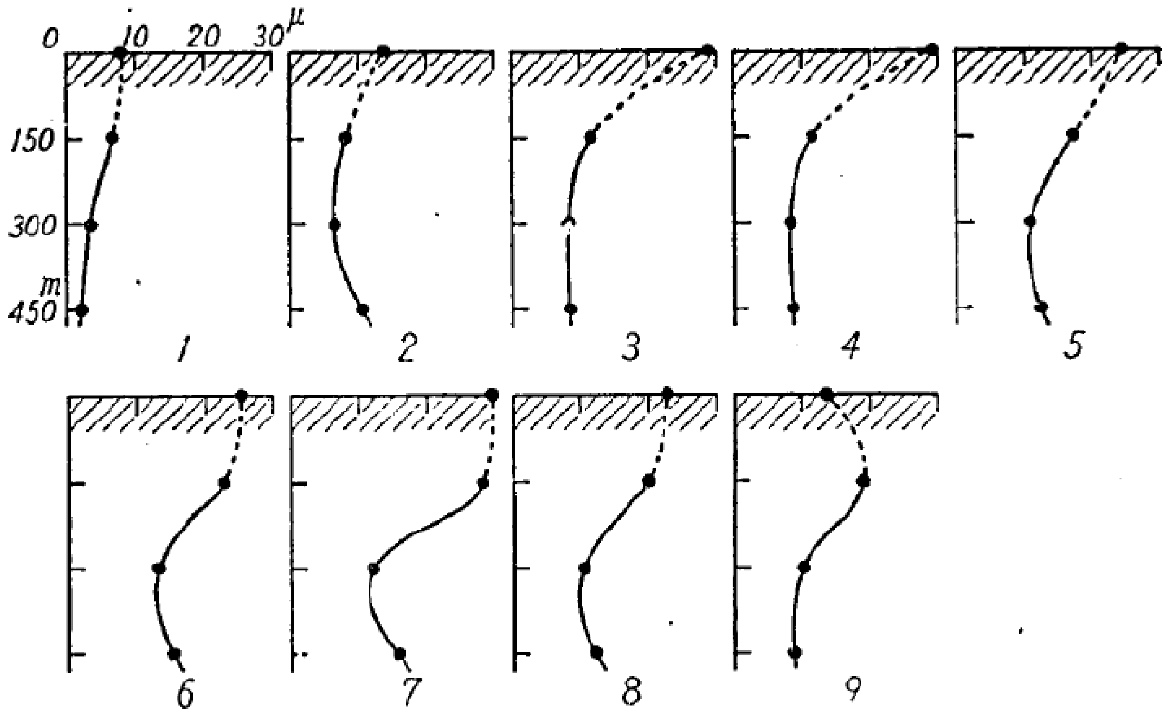


Fig. 11. The distributions of horizontal displacements at different depths of cases corresponding to Fig. 6.

Reproduced from Kanai and Tanaka (1951)

Developments of Borehole Seismometers (1960~1970)

＊Borehole seismometers (electromagnetic) were developed and they contributed to earthquake observation at various places and at some depths in a field of earthquake engineering.

＊Representatives of borehole seismometers are Kanai and Tanaka (1958) and Shima (1962). But, we had to wait the strong motion borehole sensor until the development of the servo-type accelerometers.

＊S-wave velocity measurements for quantitative evaluation of the effects of subsoil layers were one of a major topics. The special geophone for velocity logging developed by Kitsunezaki (1967) accelerated the site characterizations studies and measurements.

Comments on Studies after 1970s

- The works using the strong motion records at downhole sites have been reviewed taking the opportunity of the International Symposium on Effects of Surface Geology and other international symposiums/workshops (e.g., Finn, 1992; Archuleta and Steidl, 1998; Kawase, 2006).
- We cannot go into detail today, but the borehole measurements have played a significant role to understand the non-linear behavior of soils during destructive earthquakes occurred during 1980s and 1990s, including liquefaction of soils (Wen, et al., 1994; Iai et al., 1995, Kawase et al., 1996; Aguire and Irikura, 1997).

Deep Borehole Observation in Kanto Basin, Japan 1971~, by NIED

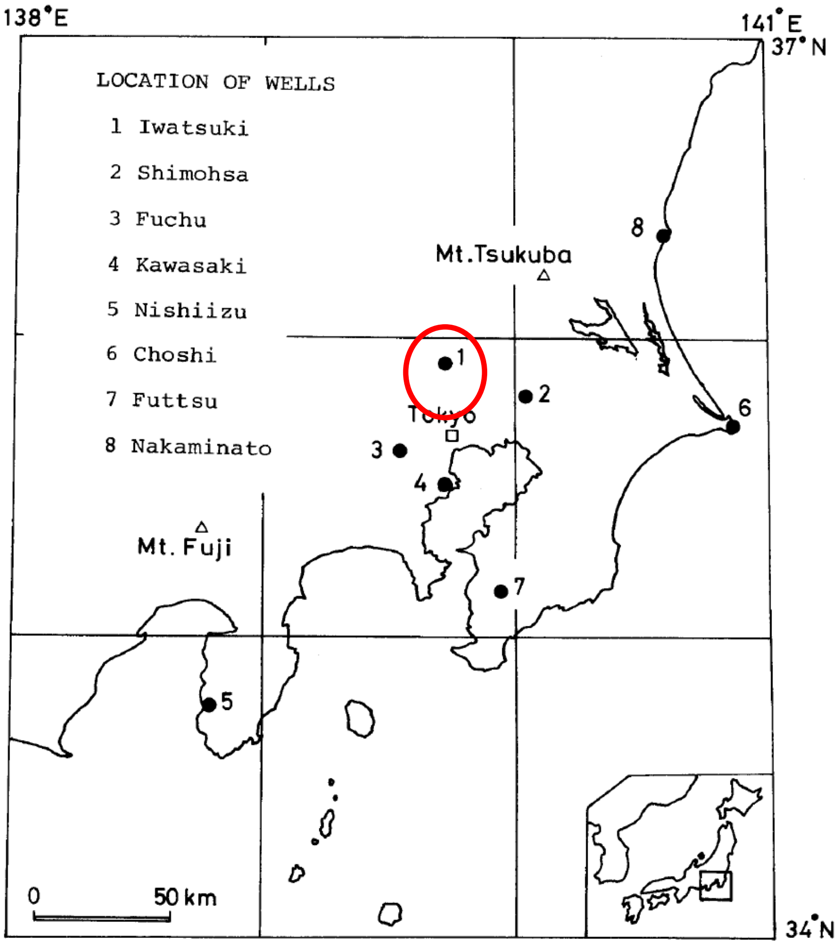


図1 孔井位置

Fig. 1 Location of wells.

Reproduced from Suzuki et al.(1981)

防災科学技術研究資料 第65号 1981年9月

岩 槻 (IWATSUKI)

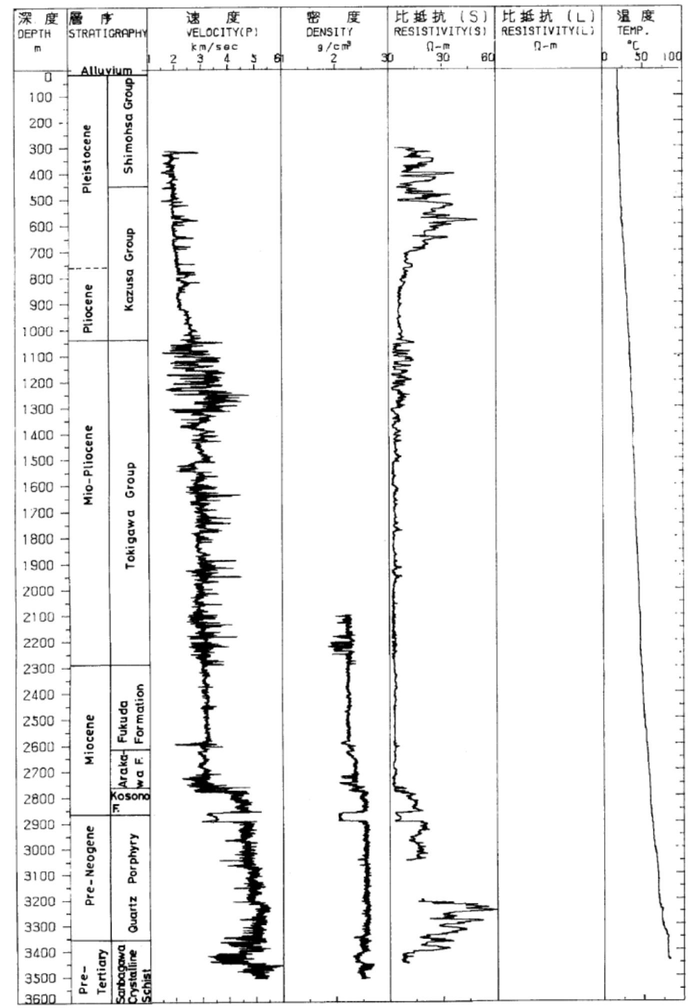


図3—1—B 岩槻孔井検層図

Fig. 3—1—B Well log (Iwatsuki).

Advantages of Deep Borehole(2000~3000m) in Seismology and Earthquake Engineering

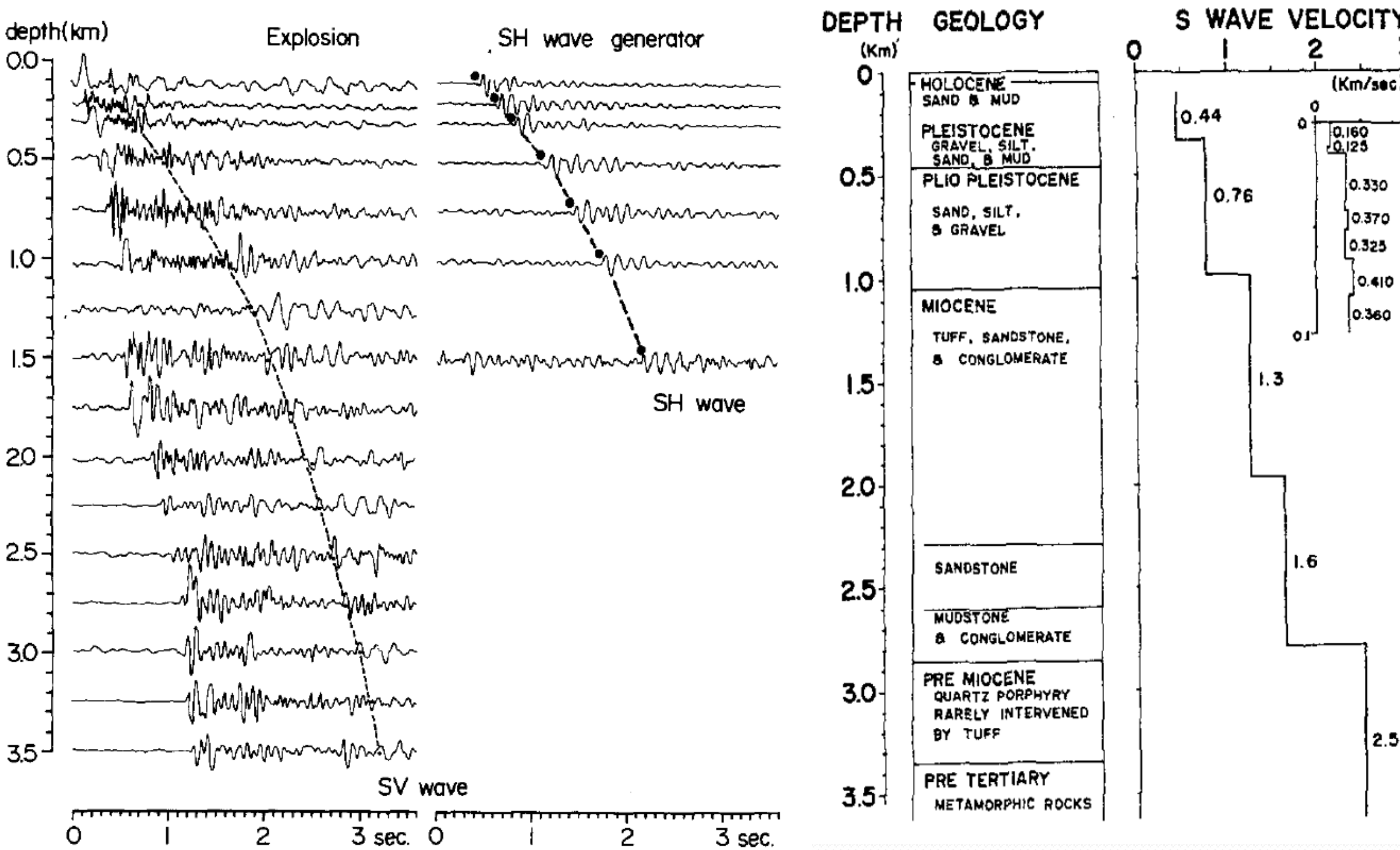
- Original purpose of deep borehole: Increase S/N, and related issues provided by the earthquake prediction research program.
- Advantages in the field of engineering seismology:

Direct understanding of amplification of long period ground motion taking the amplitude and/or spectral ratio between surface and deep ground.

Direct measurements of P- and S-wave velocities, Q values (e.g., Ohta et al., 1980; Kinoshita, 1986;······.)

Grasp the input (up-going) and reflected (down-going) waves, Kinoshita (1986).

Well-shooting Results at the Iwatsuki Deep Borehole



Reproduced from Ohta et al. (1980)

SH-Wave Generator-Gun (Cannon) by Shima and Ohta (1968)

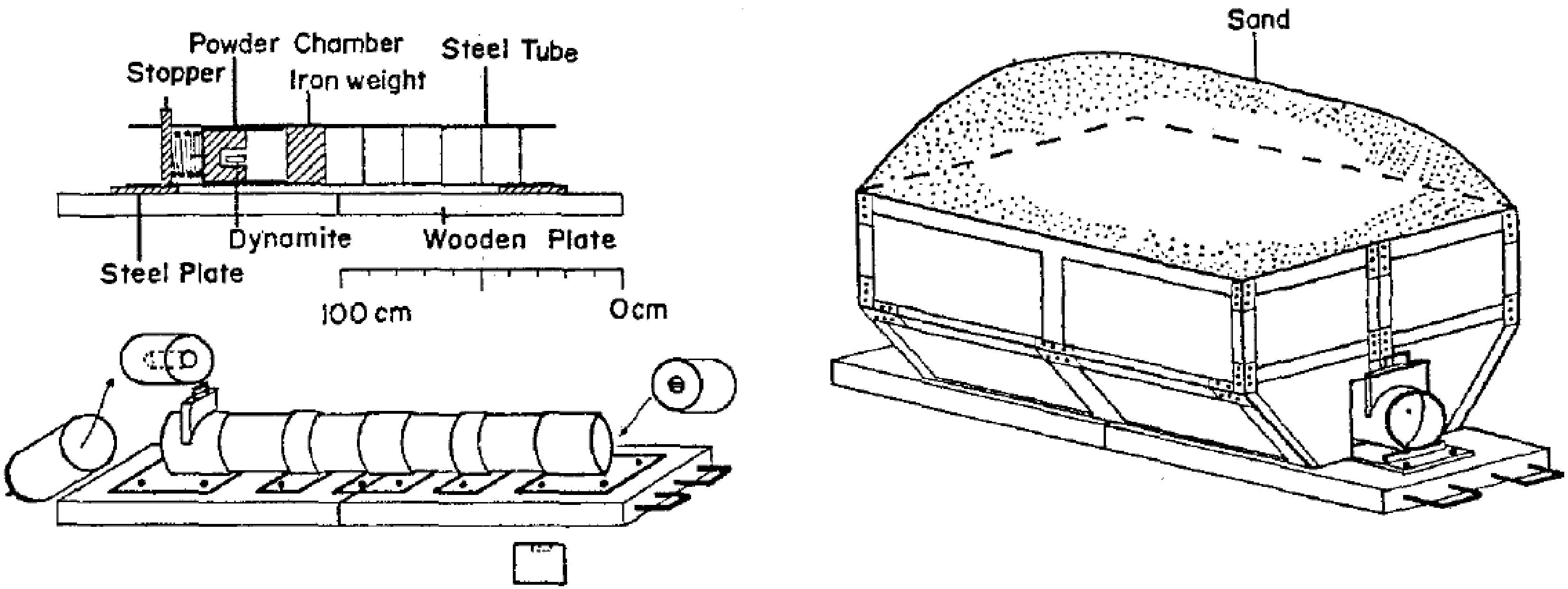
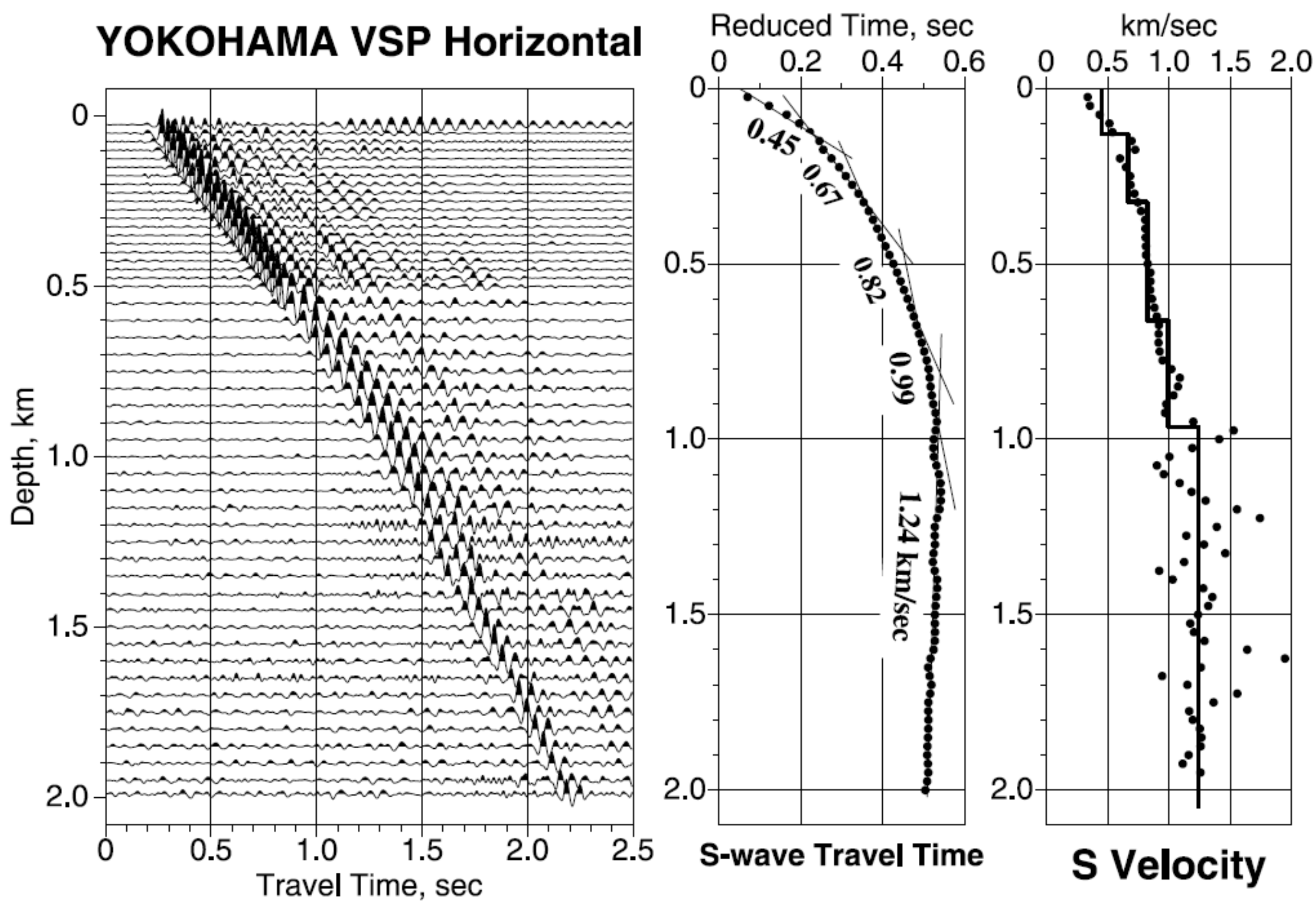


FIG. 3. *SH*-wave generator (Shima and Ohta, 1968).

Improvements by New Technology

- Suspension Method
- Stacking
- Source
- Multi-Receiver



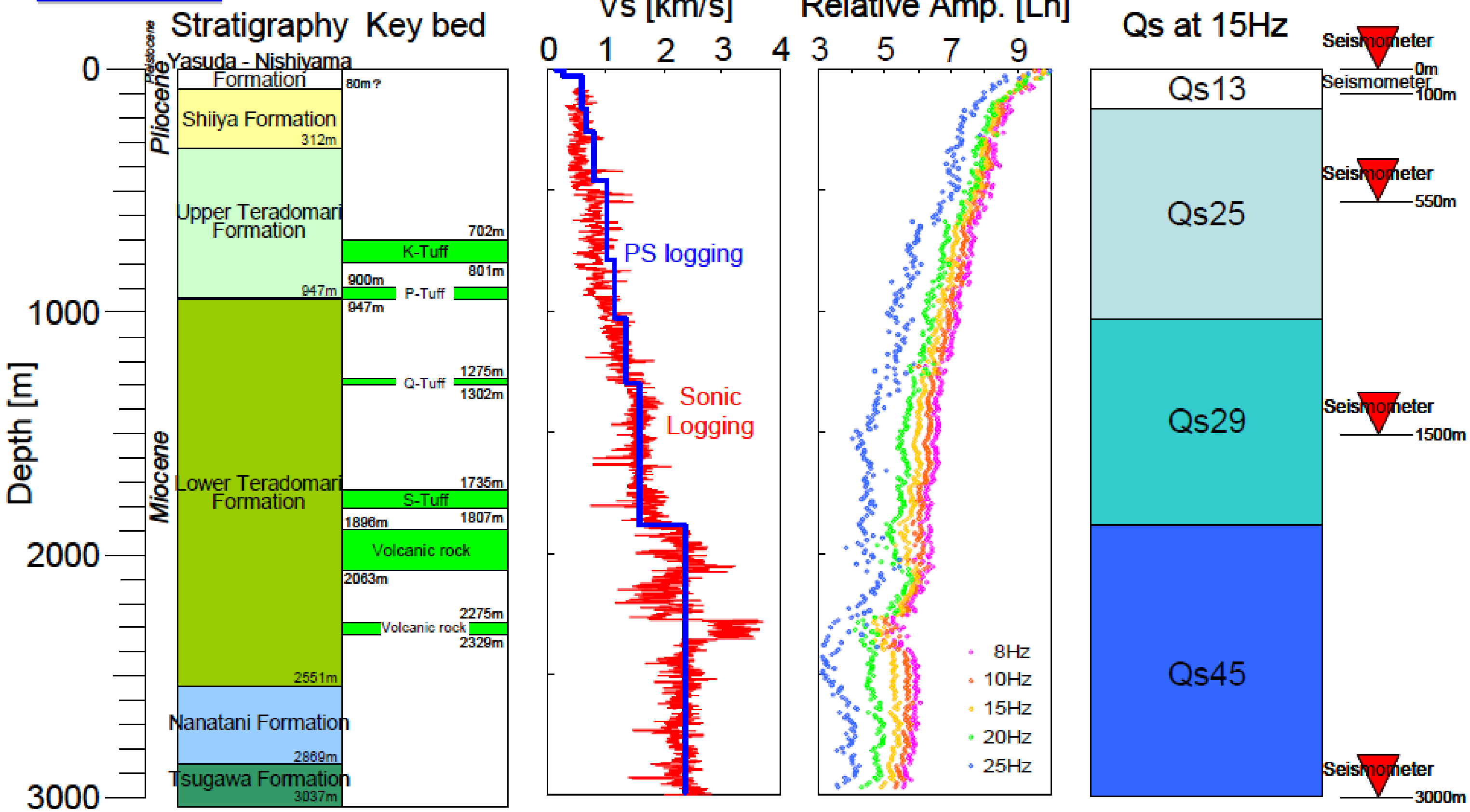
Reproduced from Yamamizu(2004)

Example of Recent Geotechnical Data

JNES

4. Overview of the Results (2/3)

A1. Deep Boring



【Achievement】 We carried out 3000m deep boring reaching to bedrock equivalent to seismic bedrock, geological investigation, various logging (PS logging, density logging etc.), and obtained verified data to construct site characteristics evaluation method at deep underground.

Reproduced from Kobayashi (2012)

Clear separation of up-going and reflected down-going waves; Determination of Q (Kinoshita, 1986)

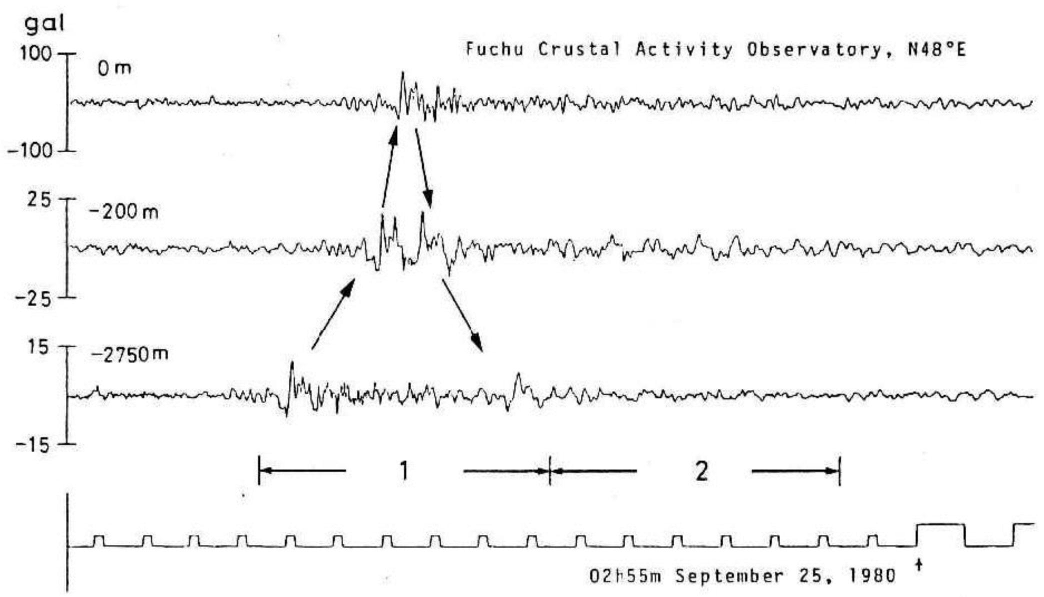


Fig. 3.5(a) Seismograms obtained by the down-hole array observation at FCH during the Central Chiba Pref. Earthquake of Sep. 25, 1980 (N48°E-component).

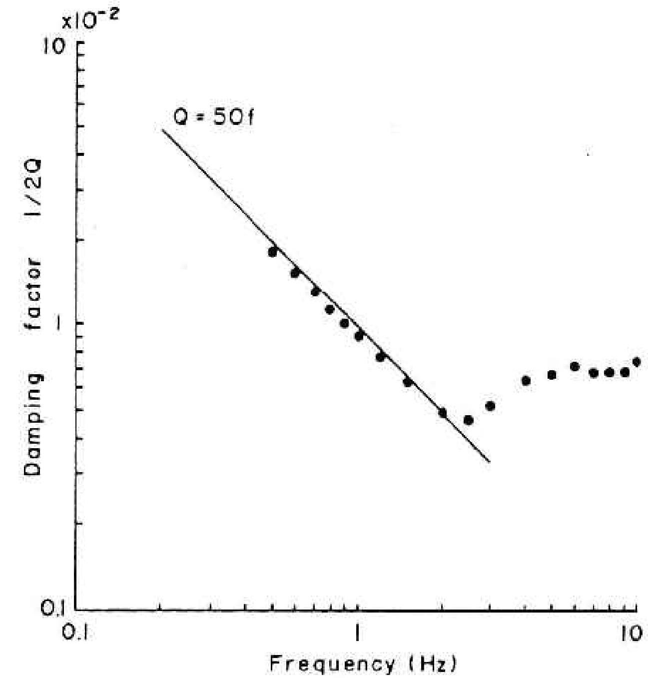


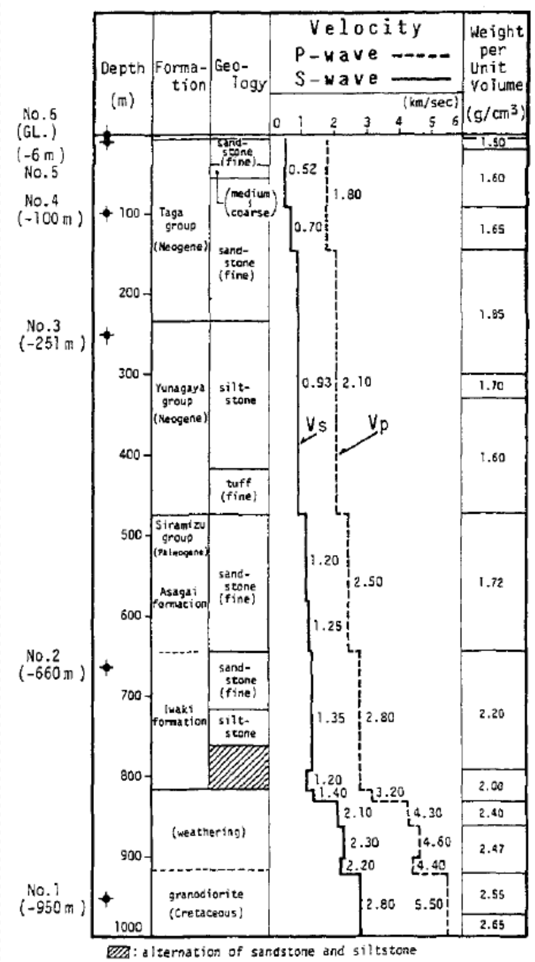
Fig. 3.6 Average damping factor of S-waves in a sedimentary layer at the Fuchu site. The results were obtained by using the spectral ratio of surface-reflected S-waves to its direct ones. No compensation function is taken into account.

Reproduced from Kinoshita (1986)

Deep Borehole Array Observation at Stiff Soils or Rock Sites

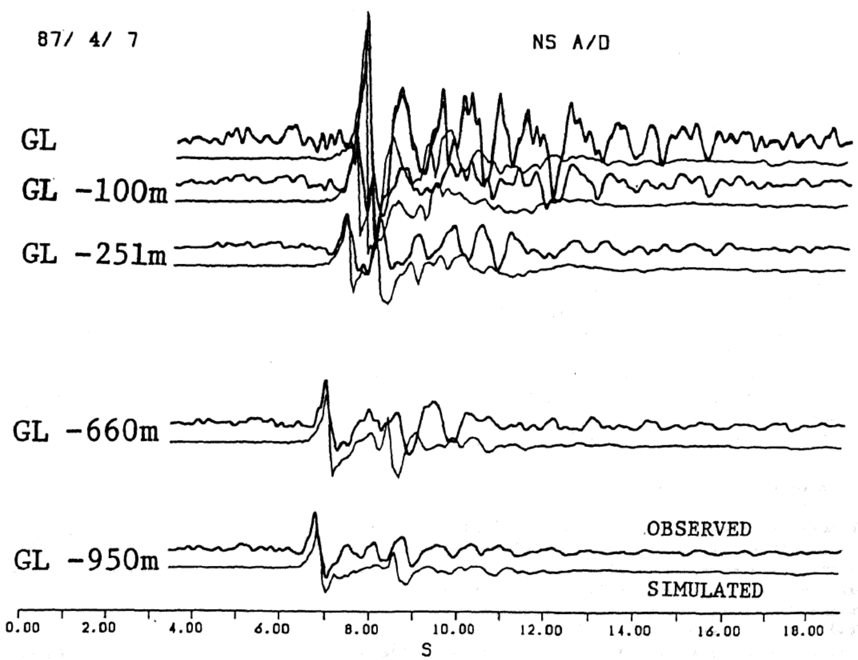
- Iwaki, Tomioka (Fukushima Pref., Japan)
  :Omote et al., (1984)
- Major targets was to understand the bedrock motion (or earthquake source nature) and amplification /attenuation (Q) in surface layers.
- Very important managements were that the observed data have been released on demand of users.
- The data contributed to present the empirical predictive model of bedrock motion, the evaluation of vertical motion, and others. Those are especially requested for assessing the ground motion for nuclear power stations.

Results: e.g., Takahashi et al., 1992; Takemura, et al., 1993; Noda et al., 2002,



Reproduced from Omote et al. (1984)

Deep borehole array records are significant to confirm the simulation techniques: good example for the records obtained at Tomioka borehole site



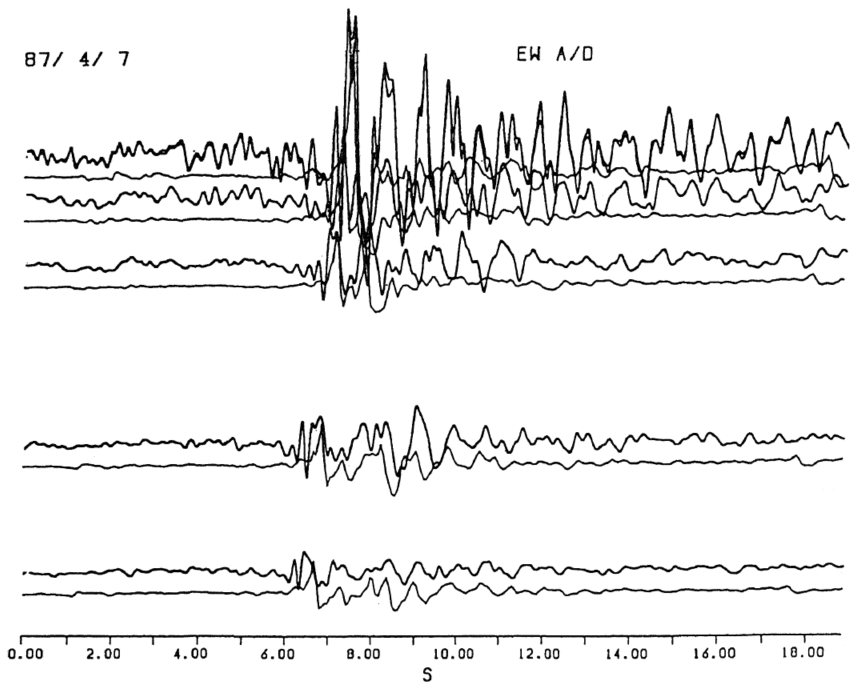
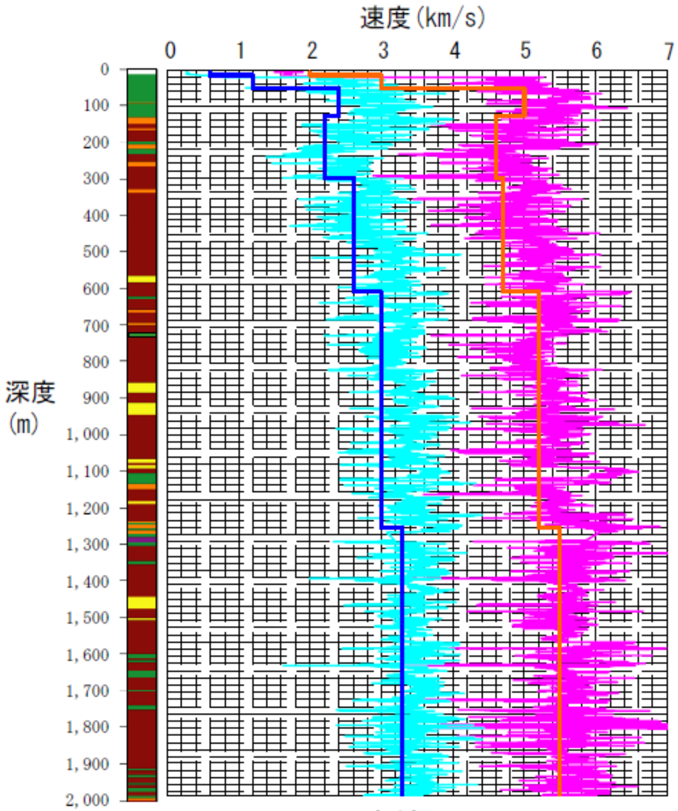


Fig.7 Simulated and observed velocity seismograms of EW and NS components. Thin lines show the simulation and thick lines, observation. (a) shows the NS component and (B) the EW component.

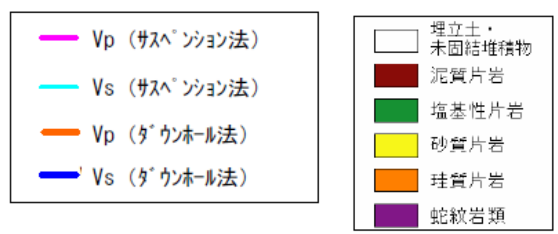
Reproduced from Iwata et al. (1992)

Lesson from hard rock site
- Ikata Nuclear Power Stations-

PS検層（サスペンション法）結果



・ダウンホール法およびサスペンション法による速度値はほぼ同等である。
・地下浅部から地下深部まで非常に速い速度（Vs=2.2～3.3km/s）を示し、深度方向に漸増するものの、地震動増幅の要因となるインピーダンス比は小さい。
・深度2,000mは地震基盤（Vs=3.5km/s）に相当する。



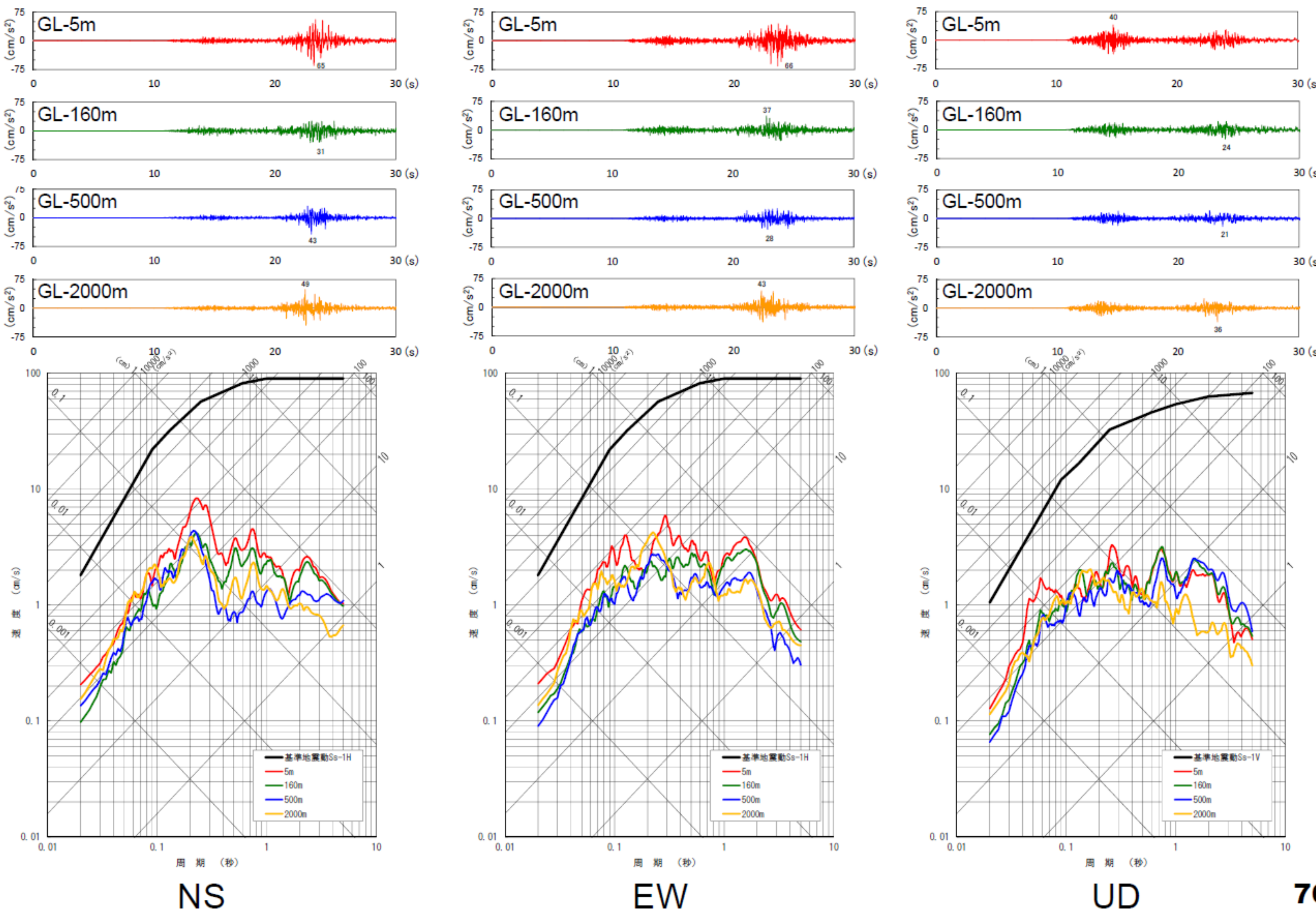
測定結果

（耐震バックチェックにおける地盤構造モデルでは深度2,000mでS波速度3.5km/s）

Reproduced from Shikoku Electric Power Co. (2013)

【参考：2】平成26年3月14日　伊予灘の地震

No.10　2014.3.14　伊予灘の地震　M6.2　（深部地震計）



Reproduced from Shikoku Electric Power Co. (2013)

Contribution of deep borehole data at hard rock sites

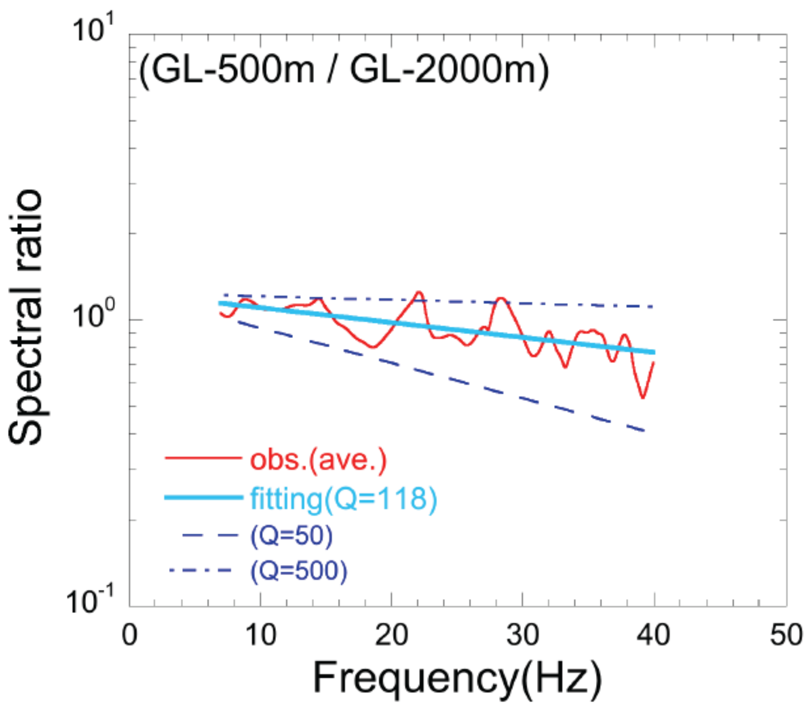


Figure 6. Fitting result of the normalized auto-correlation function (ACF)

Reproduced from Sato(2015)

- Ikata Nuclear Power Plant, Shikoku Electric Power Co., locates on very hard rock (2.2~3.5 km/s) site except surface; then amplifications of horizontal motions inside rock is very small as theoretically understandable.
- Sato et al. (2015) obtained Q (as left figure) with less frequency dependency. It is very interesting that Q in the homogenous hard rock site differ frequency dependency from many results of Q in sedimentary layers.

Contribution from deep borehole sites of the KiK-Net

- Contribution of KiK-net: Many, Worldwide Use, Mostly shallow site data have been used.

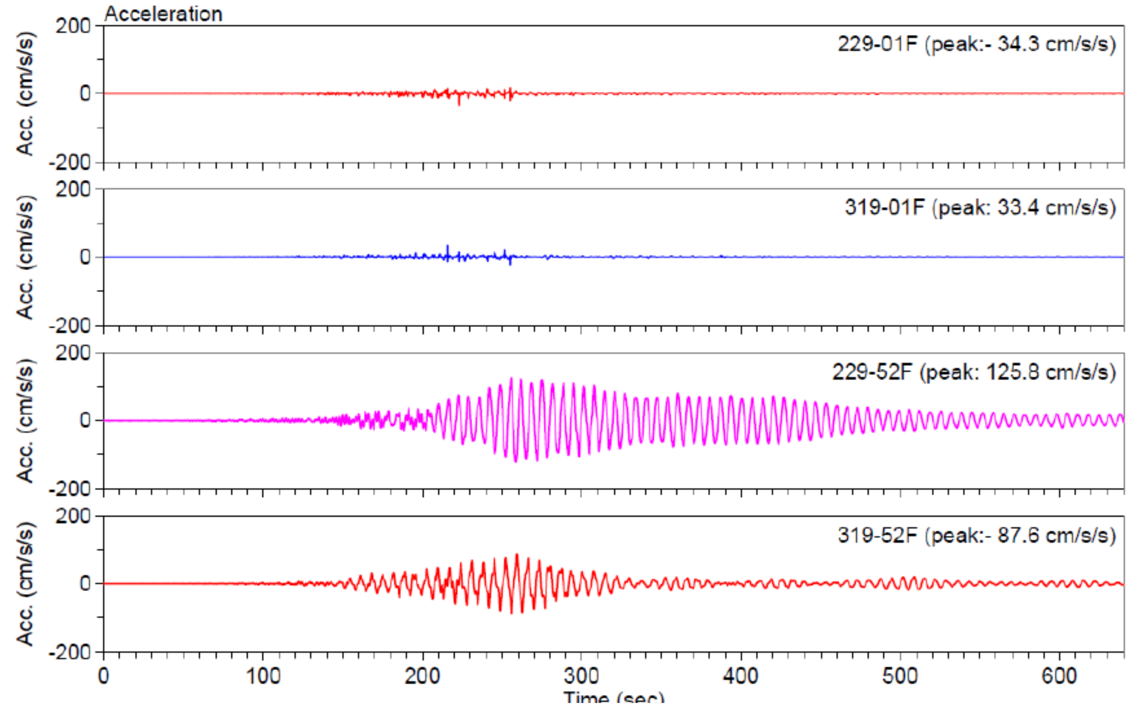
  Detail discussions are found in Kawase (2006): ESG2006

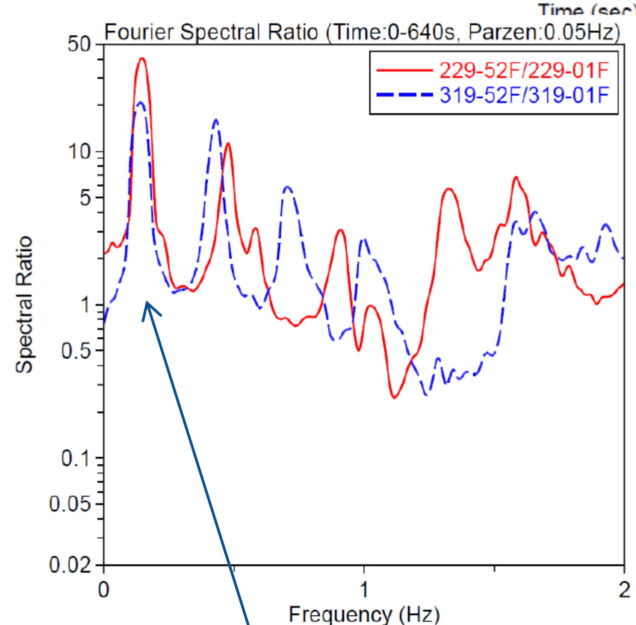
  Deep borehole sites are quite limited except for Kanto basin.

- An Example of the Contribution of the Deep borehole site: OSKH002(Konohana, Osaka) .
  Evidence：a high-rise building (55F) suffered non-structural but considerable damage (e.g. elevator, door, ceiling etc.) from the 2011 Tohoku earthquake. The strong motion records were obtained in the high-rise building (Building Res. Inst. : http://smo.kenken.go.jp/smreport/201103111446)

Osaka Prefectural Government Sakishima Office Building

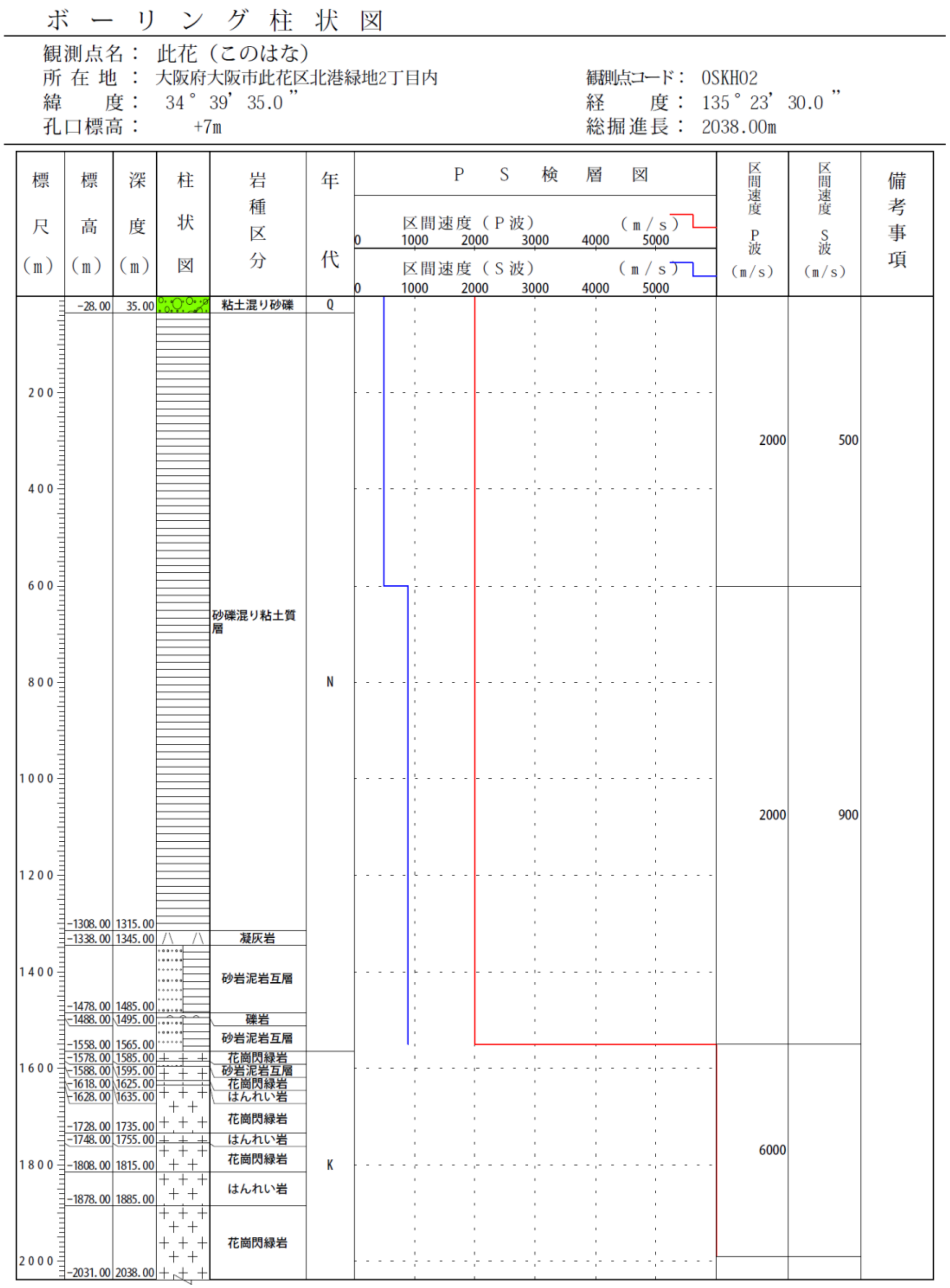
http://f.hatena.com/magnificentscenery/20110801181...

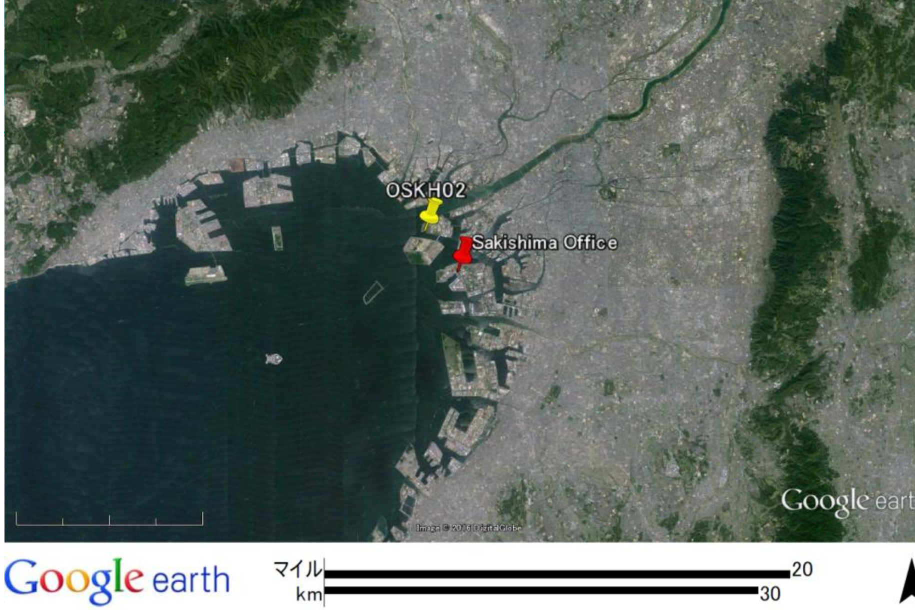




fo~0.15Hz

Reproduced from Iiba et al. (2012): Building Research Data, No.138, BRI

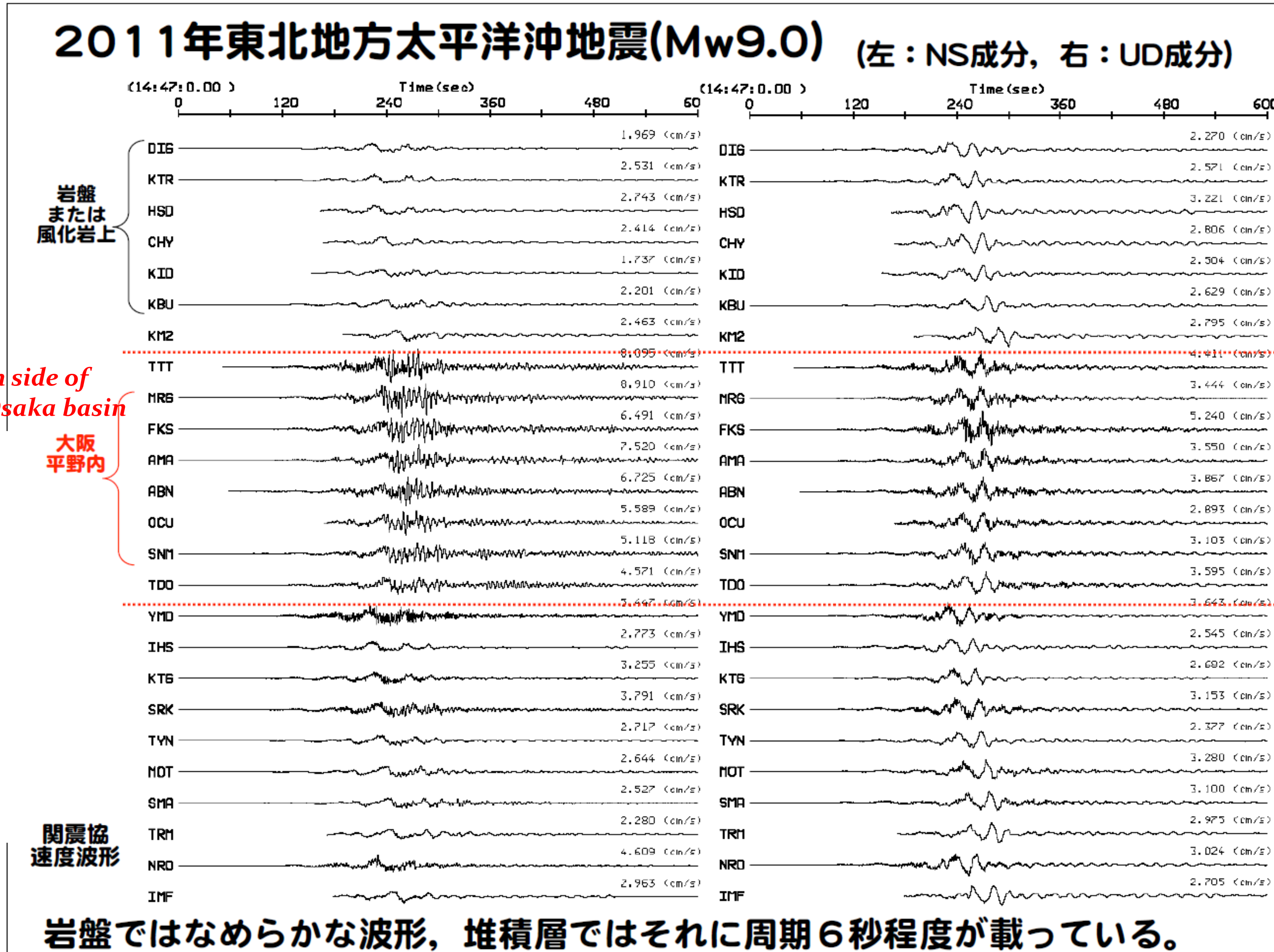




Upper: Location map of Osaka Bay area showing the Sakishima Office (55F) by red mark and the deep borehole site OSKH02 of the KiK-net by yellow mark.

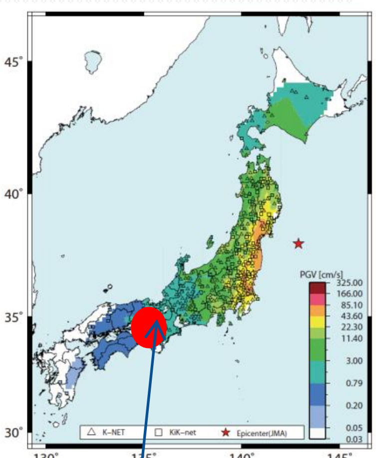
Left: Geotechnical data for OSKH02 provided by NIED. The sensors are installed at the ground surface and −2008 m. Thickness of sediment is 1600m

KiK-net data OSKH02 and the Interpretations by Kagawa(2013)



⊿>６００ｋｍ

In side of Osaka basin

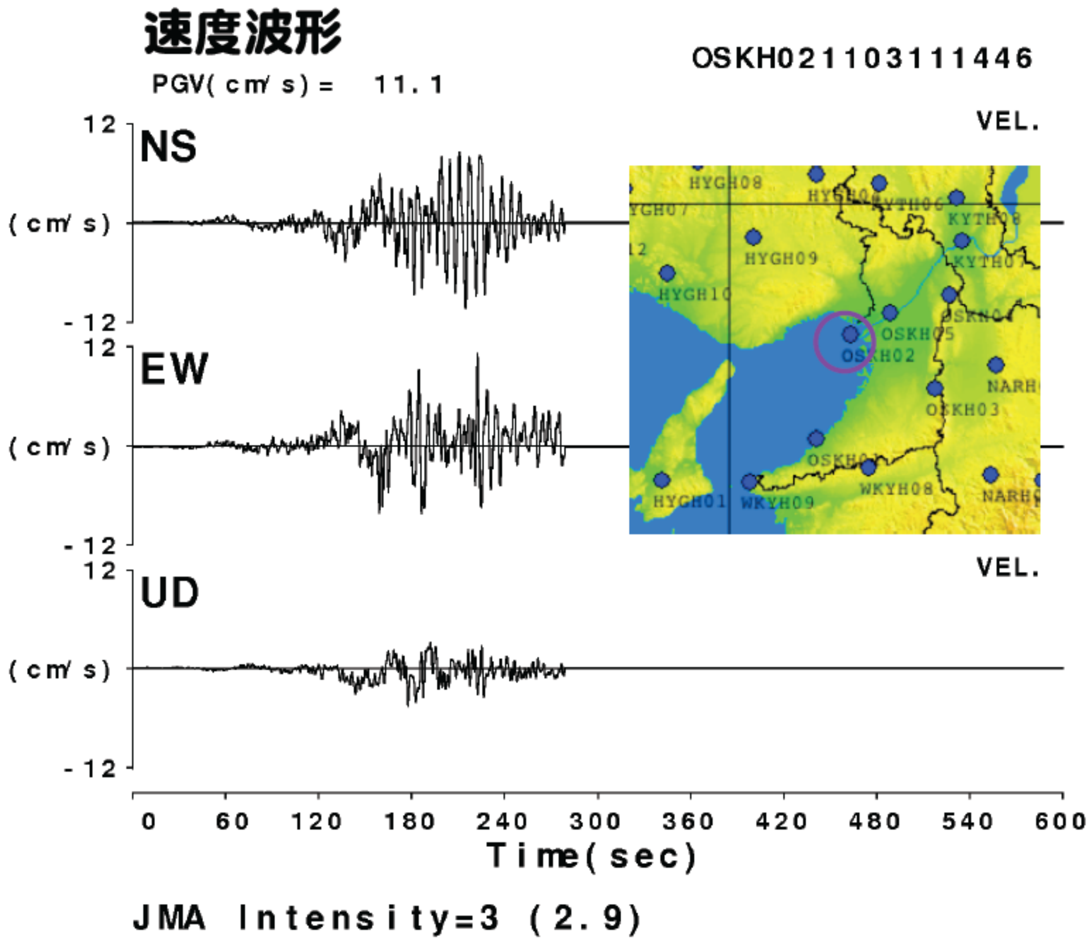


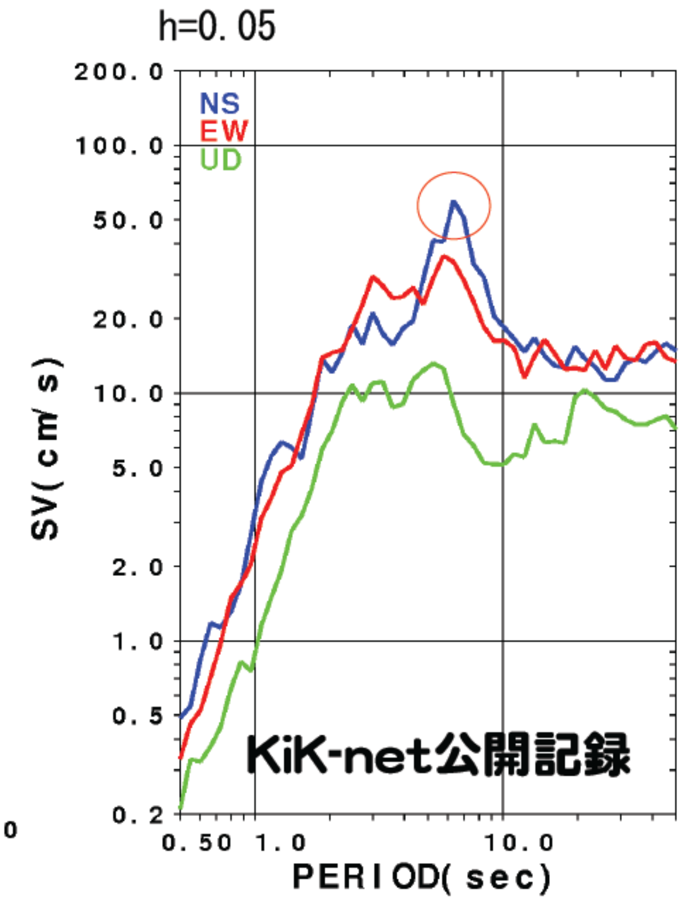
OSKH02

After NIED

Courtesy of Prof. Kagawa

2011年東北地方太平洋沖地震(Mw9.0)



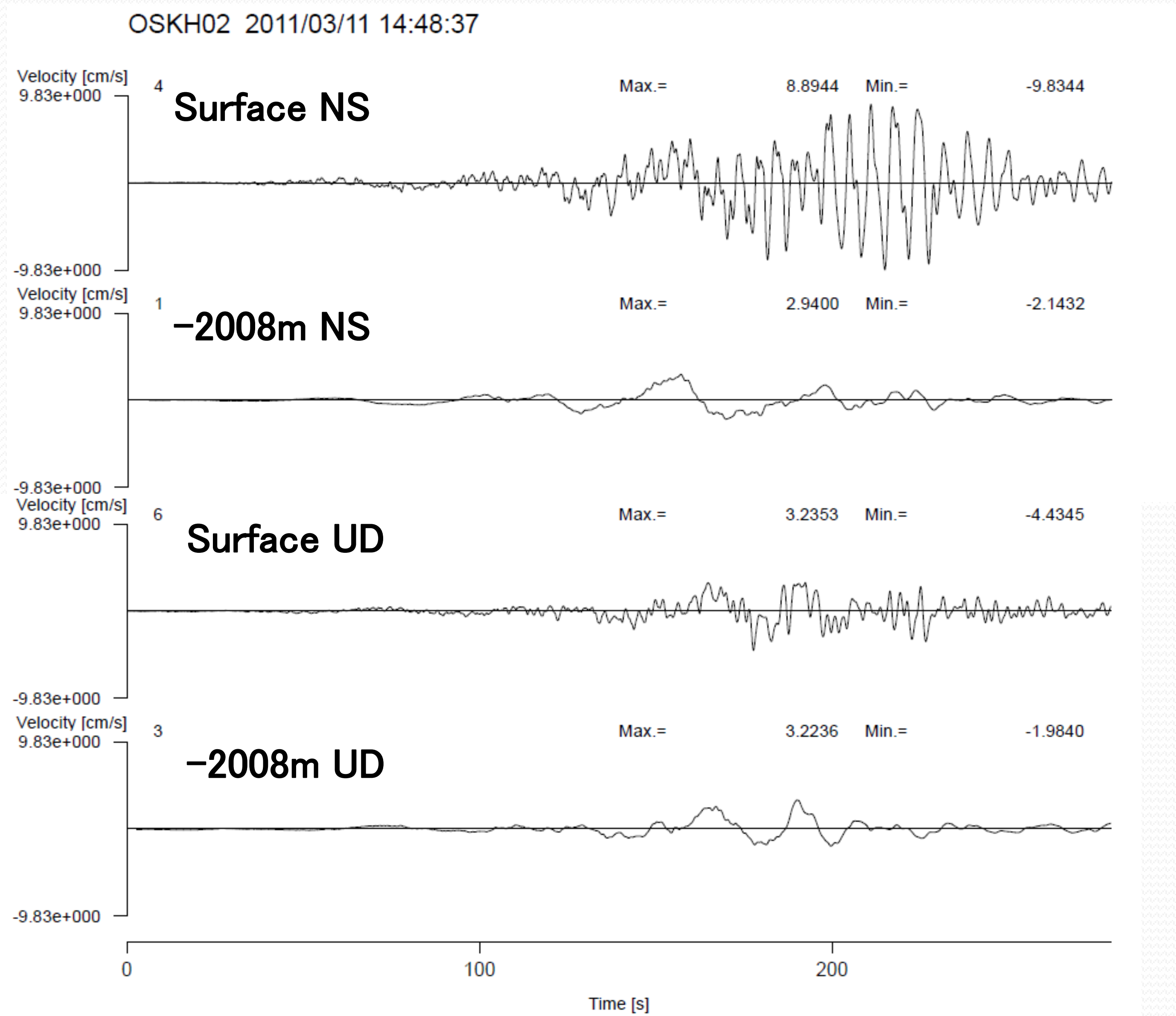


大阪湾岸の此花（OSKH02）における地表記録（速度に積分）

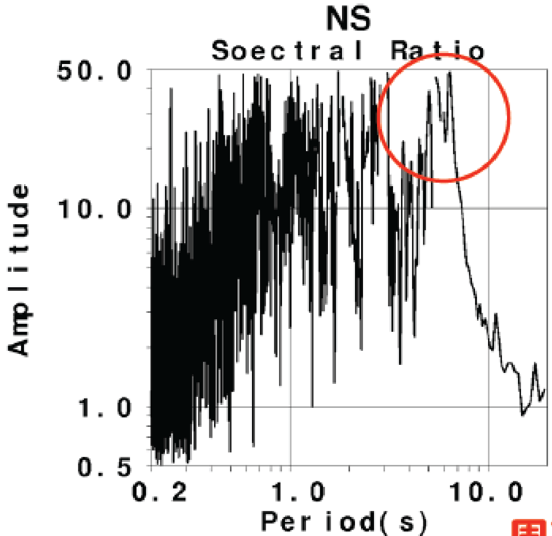
周期約６秒および２～３秒が増幅し，その継続時間も長い。

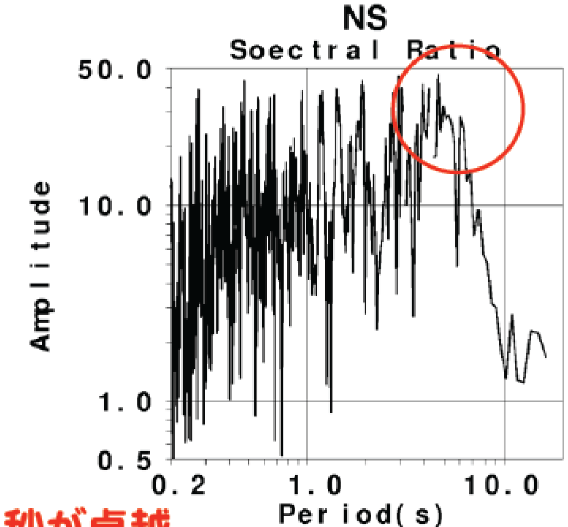
Courtesy of Prof. Kagawa

Comparison between Surface and Deep (-2008m) underground velocity waveforms at OSKH02



KiK-net此花(OSKH02)



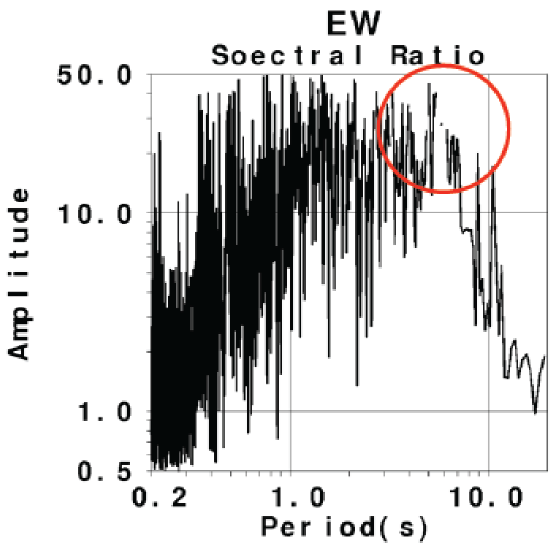


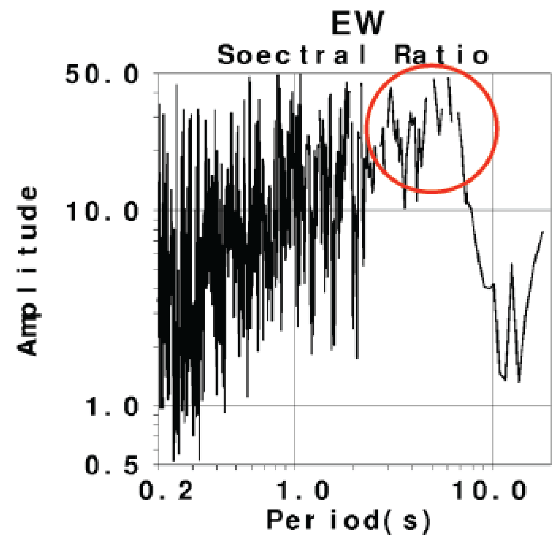
周期６～７秒が卓越

地表記録／地中記録

地表記録／地中記録

地表観測記録と
地中観測記録の
スペクトル比１





長周期が大きい
他の大地震でも
同じような周期
が増幅している

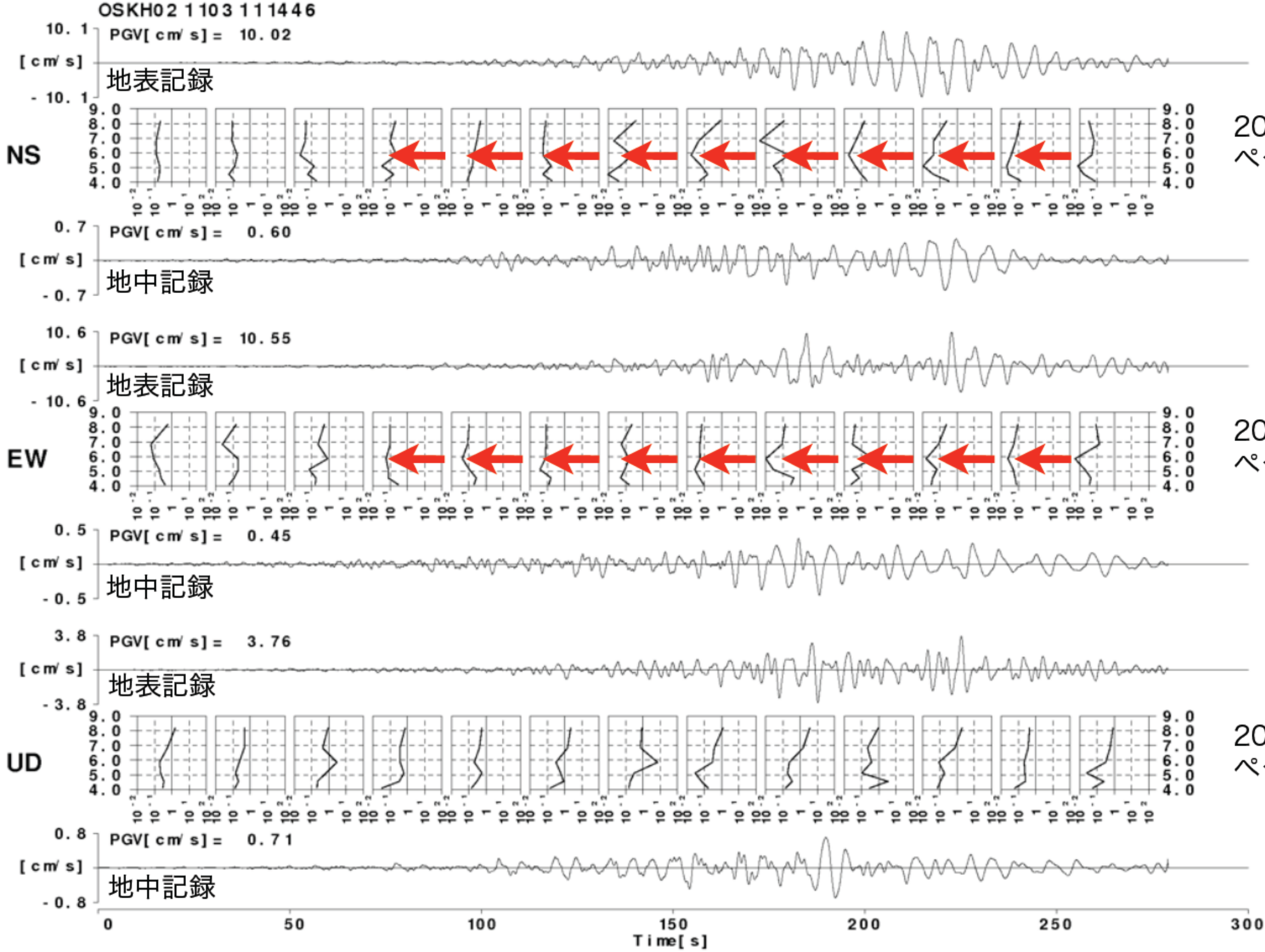
2011年東北地方太平洋沖地震

2000年鳥取県西部地震

Courtesy of Prof. Kagawa

増幅率の時間変化

周期５～７秒のスペクトル比は，観測記録の150秒以降で大きくなる傾向が見られる。



2011年東北地方太平洋沖地震　約40秒の解析区間を約20秒毎に動かす

Courtesy of Prof. Kagawa

Summary on the Ground Motion during the 2011 Tohoku earthquake at Osaka Bay Area

- **Amplification at the Top of the building: 30-40 times due to *Resonance* of the building and 30-40 times from the bedrock motions due to thick sediments in bay area, as a result of roughly 1000 times amplified from bedrock motion at the period of 6-7 seconds.**

- A part of Summary from Kagawa(2013):

Early arrivals of waves are explained as responses of sediments due to vertical incidence of S-waves, but later half arrivals can be interpreted as surface waves. The ground motions with the period of 6-7 sec. dominate for both S-wave and surface waves in Osaka bay area, but amplitude ratio of later arrivals (surface waves) is much larger than the early part.

The revised paper of Kagawa (2013) will be presented at the 16th WCEE.

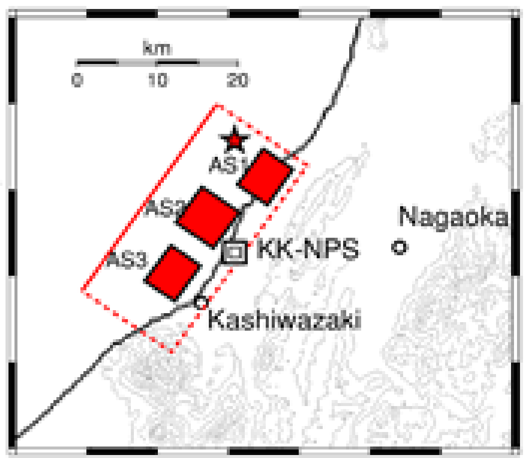
- Our Comments:

OSH02 is very good example to know that the deep bedrock motion is very important for assessing the long period surface ground motion and its long duration. **To confirm the wave types or mechanism of amplification the deep borehole data are inevitable.**

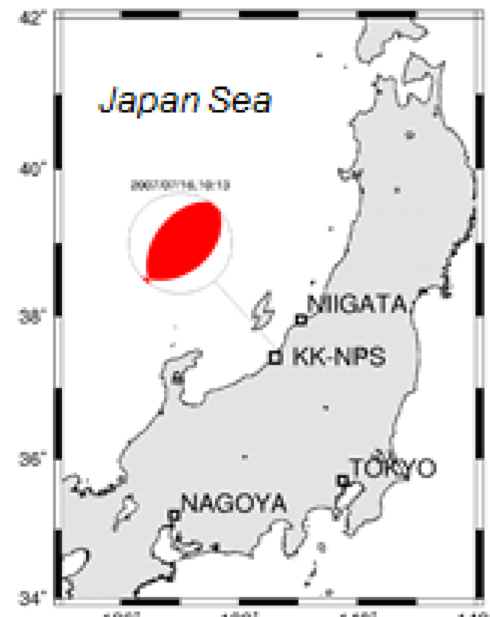
STRONG MOTION ARRAY RECORDS IN THE KASHIWAZAKI/KARIWA NUCLEAR POWER STATIONS FROM THE 2007 NIIGATA-KEN CHUETSU-OKI EARTHQUAKE (M_W6.6)

Location of the site and source model

Origin Time; 2007/07/16, 10:13 (JST) 01:13(UT)
Location; 37.556 N, 138.608 E, Depth; 17 km
Magnitude; M_{JMA}=6.8, Mw=6.7(JMA), 6.6(NIED)
Distance from epicenter ; 16km
from hypocenter; 23 km



Characterized source model by TEPCO(2008)

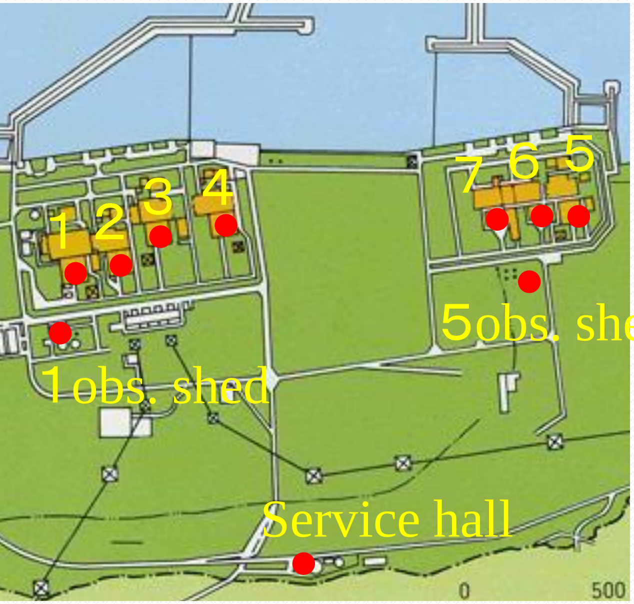


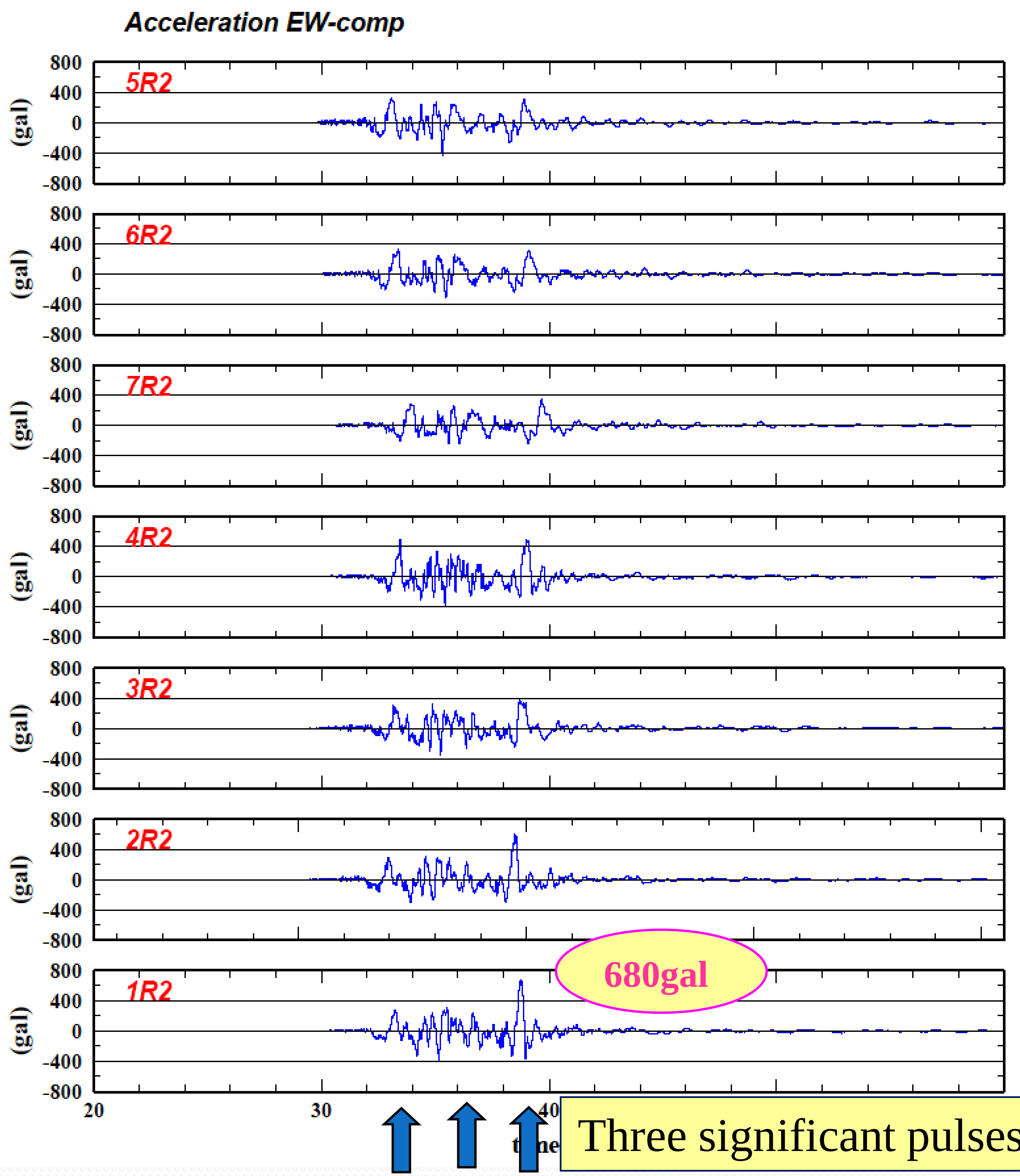
Moment tensor solution by NIED(2007)

Courtesy of Dr. Uetake

TOKYO ELECTRIC POWER COMPANY

Acc. waveforms Base mat of R/B EW-comp.





Three significant pulses

Maximum value was recorded in the third pulse.

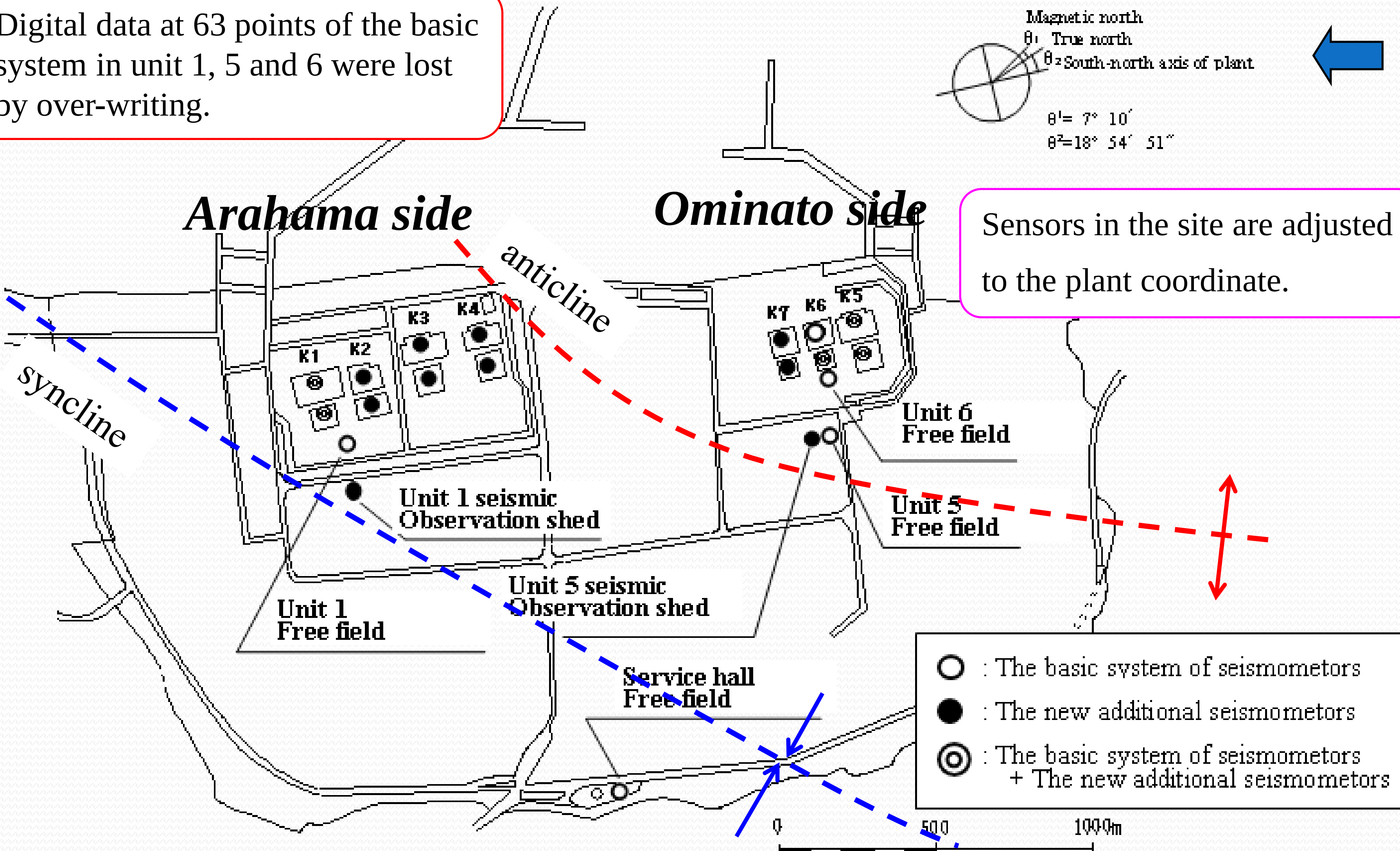
The third pulse in Arahama side was more amplified than that in Ominato side.

Courtesy of Dr. Uetake

Configuration of seismometers

Digital data at 63 points of the basic system in unit 1, 5 and 6 were lost by over-writing.

Sensors in the site are adjusted to the plant coordinate.



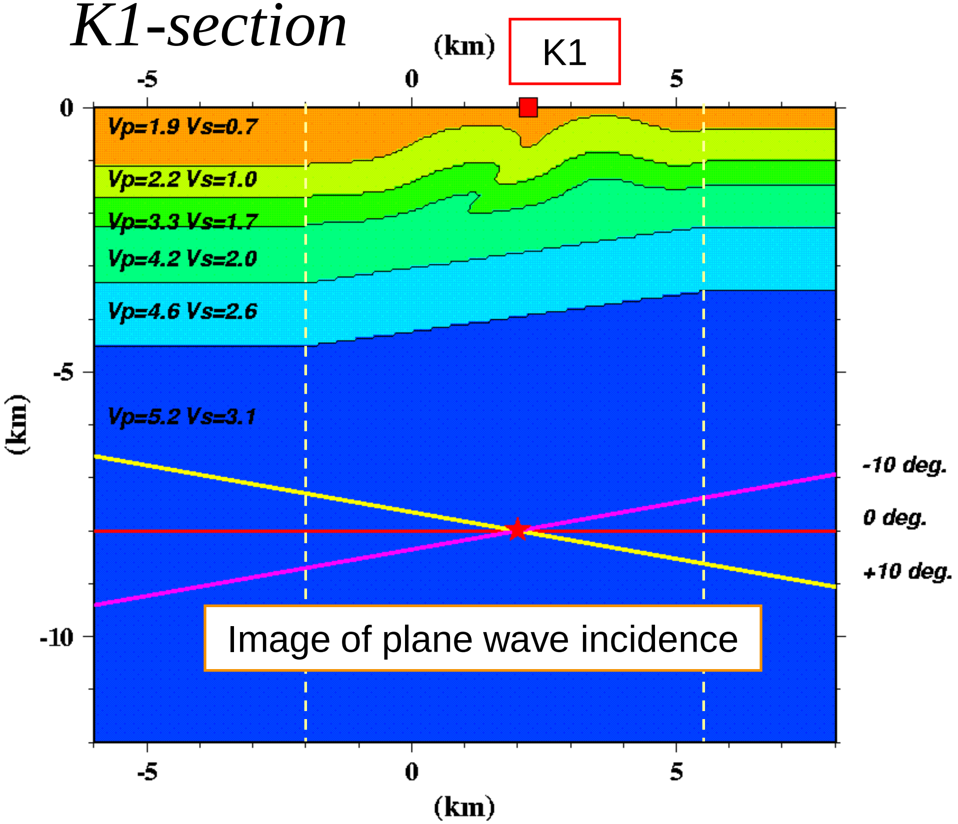
Courtesy of Dr. Uetake

2-D sub-surface structure models

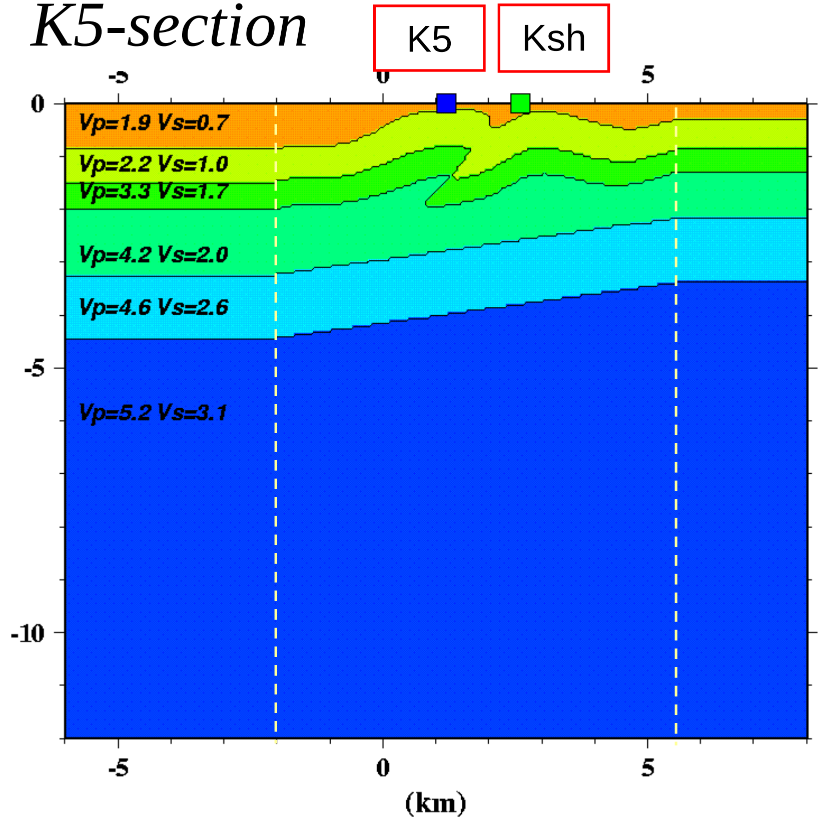
- Asymmetric fold structure
- Depth of Shiiya formation at anticline of K1-section is deeper than that of K5 section.

No.	Vp (km/s)	Vs (km/s)	Dens. (g/cm3)	Q	Formation
1	1.9	0.7	1.7	50	Nishiyama
2	2.2	1.0	2.1	70	Shiiya
3	3.3	1.7	2.3	110	Upper Teradomari
4	4.2	2.0	2.4	130	Lower Teradomari
5	4.6	2.6	2.5	170	Nanatani & Green Tuff
6	5.2	3.1	2.6	210	Bedrock

K1-section



K5-section



Courtesy of Dr. Uetake

Issues are:

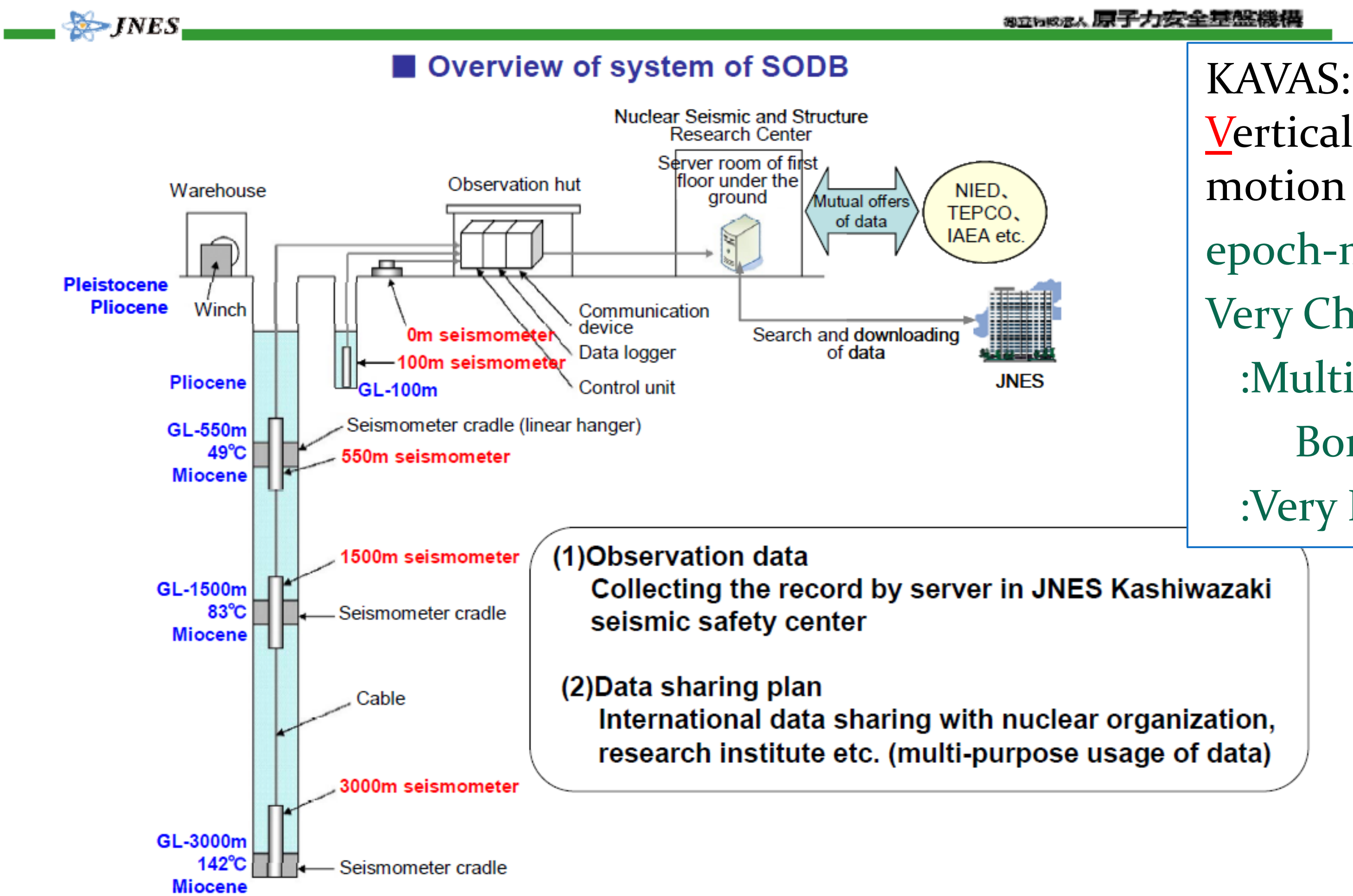
- Observed ground motions were significantly stronger than the level estimated before constructing the Nuclear Power Plant.
- Peak accelerations differ as much as twice at 7 units, nevertheless those are located with in 1~2 km.
- The ground motions are essentially interpreted by three asperities of the fault, but the large variation of ground motions are attributed to focusing/defocusing of waves due to the hold structure at intermediate depth (e.g. Uetake et al., 2010).

If no records existed in the KKNPS, can we identify the complex source?

Japan Nuclear Energy Safety Organization (JNES : now reorganized in the NRA [*Nuclear Regulation Authority, Japan*]) published "Guidance for construction of three-dimensional underground structure model for evaluation of earthquake ground motions"(pp95, Nov. 2013)

: Among many items for determining 3D geotechnical structures, JNES recommended "Geotechnical survey and strong motion observation making deep borehole" to Electric Power Companies, that have nuclear power stations, in Japan. JNES established experiments and observation "KAVAS" project as a model of guidance.

KAVAS project, as a model of Guidance (2013) by JNES



KAVAS: Kashiwazaki Vertical Array seismic motion monitoring System

epoch-making!

Very Challenging

:Multiple Sensors in One Borehole.

:Very High Temperature

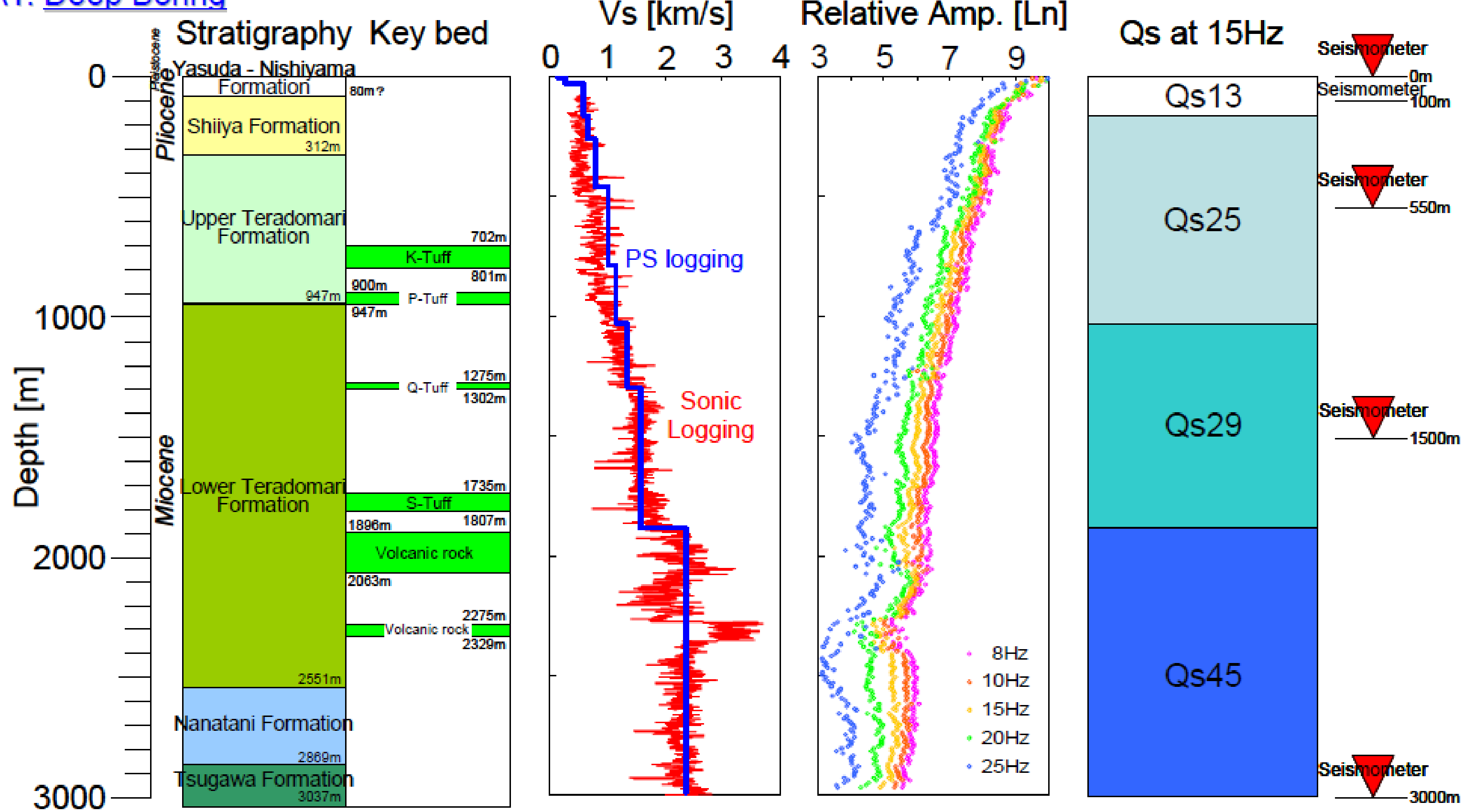
Reproduced from Mamada (2012)

Geotechnical Data

JNES

4. Overview of the Results (2/3)

A1. Deep Boring



【Achievement】 We carried out 3000m deep boring reaching to bedrock equivalent to seismic bedrock, geological investigation, various logging (PS logging, density logging etc.), and obtained verified data to construct site characteristics evaluation method at deep underground.

Reproduced from Kobayashi (2012)

2. Over view of technology for seismic observation in deep borehole

Specification of observation system

(I)Specification of seismometer

I-1 High temp. and press.: 150℃ and 40MPa

I-2-1 3-components (vertical and horizontal 2-comp.)

I-2-2 Freq. response : constant at 1to 50 Hz

resolution:10^{-5}gal（at 1Hz）, S/N :100dB以上、

Max accerelation:±1 000gal

I-3 Specification of cable

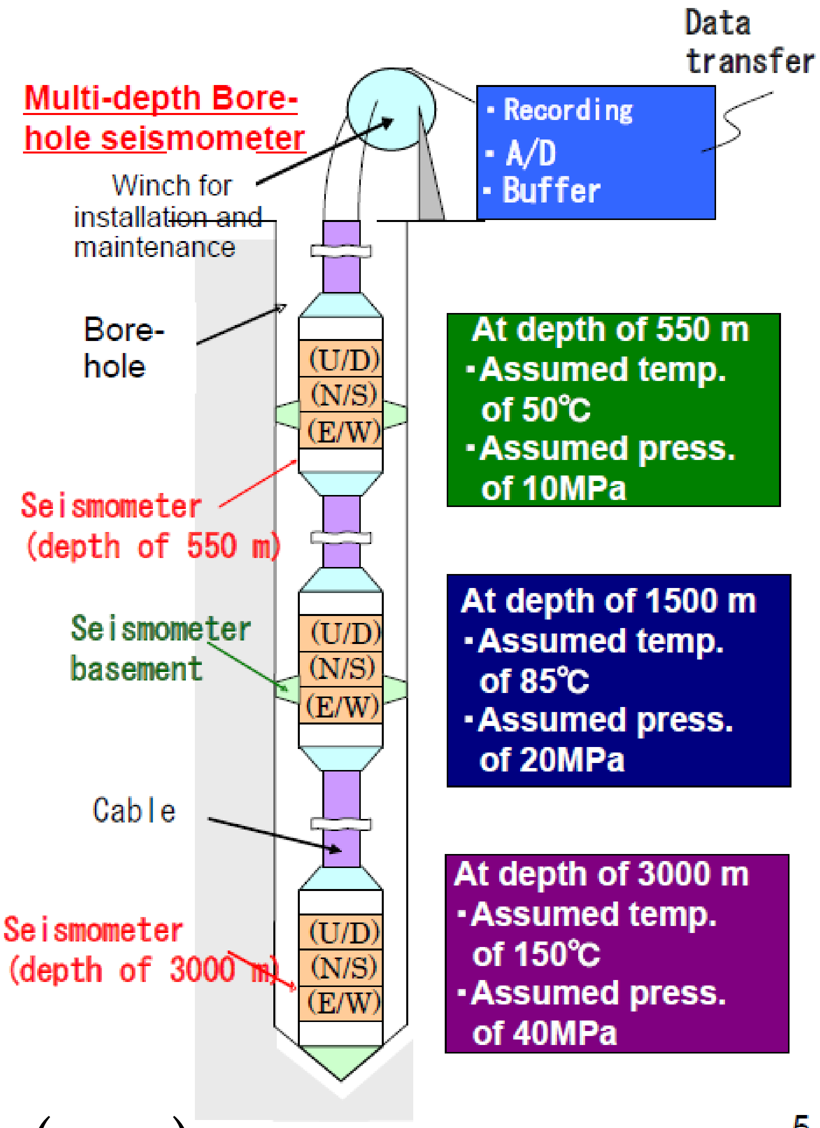
- temp.:150℃、pressure:40MPa
- tensile load:up to 3tf（multi-channel:at least 18 chs.）

(II)Specification of seismometer basement

- Applicable to contacting to borehole at any depths
- Stability of contact（stable up to 20 Hz ）
- Applicable to seismometer maintenance（designed but practically confirmed when maintenance）

(III) Specification of recorder

- Sampling rate: higher than 200 Hz and continuous recording with UPS
- Online real time data transfer system

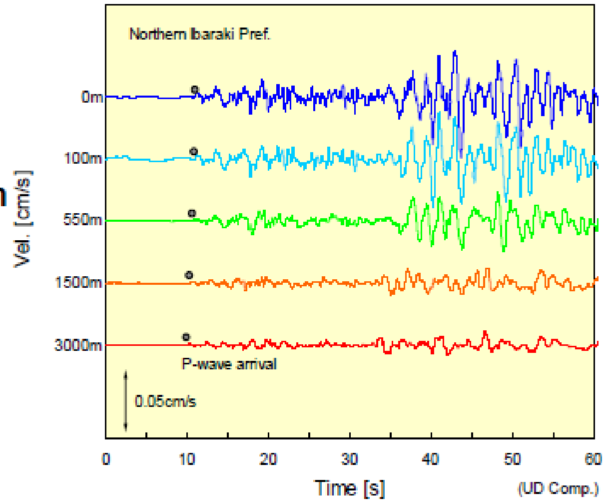


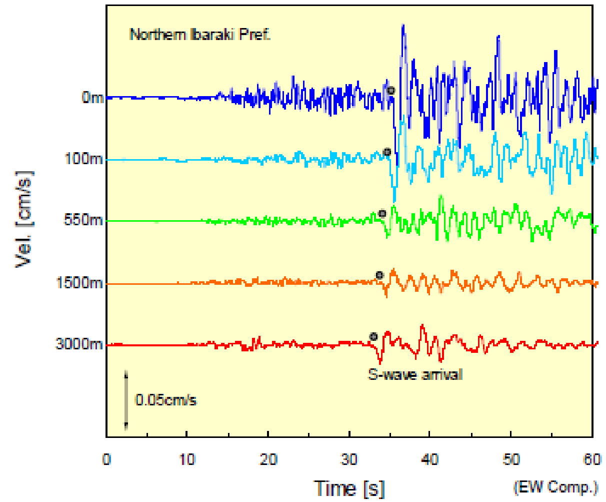
Reproduced from Mamada (2012)

4. Examples of collection data

Event 1 (Northern Ibaraki earthquake)

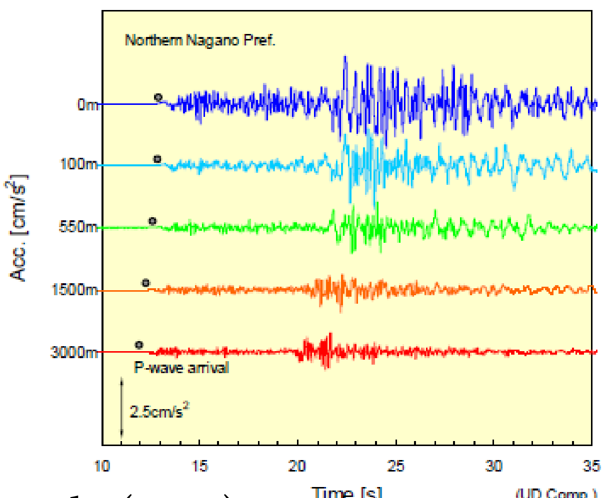
Mj=5.2
Epi. Dist.= 233.2 km
Hypo. Dist.=233.3 km
depth=7.2 km

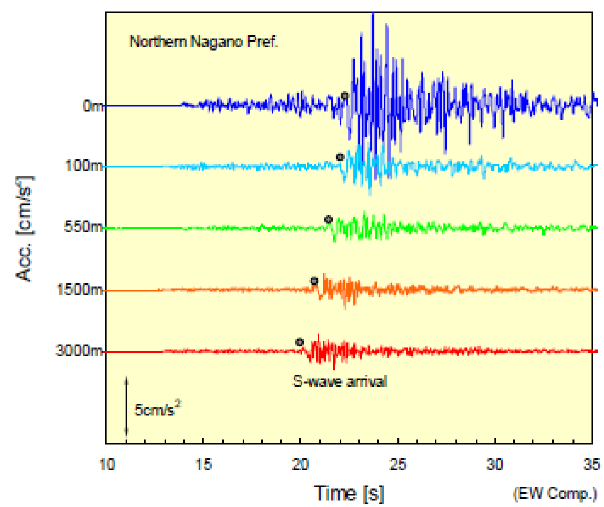




Event 2 (Northern Nagano earthquake)

Mj=5.2
Epi. Dist.= 60.0 km
Hypo. Dist.=60.6 km
depth=8.5km





Reproduced from Mamada (2012)

JNES

5. Achievement Status of Important Items

Status of achievement (FY2012, JNES self-evaluation)

Sign	Large item	Small item	Status of achievement
A1	Deep Boring	Deep Boring	○
		Investigation	○
A2	Construction of Deep Seismic Observation System	Develop High-temperature/High-pressure, High-performance Multi-depth Borehole Seismometer	○
		Construct Seismic Observation System	○
		Deep Vertical Array Seismic Observation	△
A3	Deep Underground Structure Investigation	Geophysical Exploration	○
		Horizontal Array Seismic Observation	△
B	Deep Underground Structure Seismic Ground Motion Evaluation	Consider 3D Underground Structure Model	△
		Propose Site Characteristics Evaluation Method	△
C	Propose Investigation Observation Technology/Analysis Evaluation Method, Simplified Underground Structure Investigation Method	Deploy to Earthquake Countries and Newcomer Countries	△
		Summarize Issues and Improvement	×

【Status of achievement】○ : Good, △ : Slightly good, × : Not good

Reproduced from Kobayashi (2012)

Although no formal announcement from NRA(JNES) , it seems that at least the deepest and at -1500m depth signals have been stopped due provably to high temperature. A plan for renewal is not exist.

We regret to say that the KAVAS project finished(?) so early and the deep borehole array observation itself seems to be finished.

But, KAVAS triggered the deep borehole observations in the nuclear power stations, as next slide,

Deep borehole observations by nuclear power stations in Japan

No	Company	Nuclear Power Station	Depth (m)	Location of sensor	Status	Vs(km/s)	Reference
1	Tokyo Electric Power Company Holdings, Inc.	Kasahiwazaki-Kariwa	1017	GL (x2), -40m, -122m, -400m, -1017m	In Operation	1.2-1.5 (at depth 1-1,3 km)	1)
			1700	-14m, -100m,; GL, -24m, -100m, -180m, -300m, -1500m	Under Construction	1.2 (at depth 1 km) *preparing new results*	
2	Kansai Electric Power Co., Inc.	Mihama	1070	GL, -87m, -203m、-530m	In Operation	-	2)
3		Takahama	1000	GL, -90m, -210m, -400m	Under Construction	-	
4		Ohi	1000	GL, -70m, -120m, -500m	Under Plan	-	
5	Chubu Electric Power Co., Inc.	Hamaoka	1500	-20~25m (x3sites), -100m,(x3sites), -1500m	In Operation	1.6 (at -1.5 km)	3)
6	The Chugoku Electric Power Co., Inc.	Shimane	1500	GL, -19m, -144m, -224m, -500m, -1500m	In Operation	2.7 (at -1.5 km)	4)
7	Shikoku Electric Power Co., Inc.	Ikata	2000	-5m, -160m, -2000m	In Operation	3.3 (at -2 km)	5)
8	The Japan Atmoic Power Co., Inc.	Tokai No2	1000	EL8m, -17m, -192m, -372m, -992m	In Operation	2.97(at 1 km)	6)

Ref 1) http://www.tepco.co.jp/kk-np/safety/earthquake/pdf/13102501.pdf
2) https://www.nsr.go.jp/data/000113821.pdf
3) https://www.nsr.go.jp/data/000036123.pdf; https://www.nsr.go.jp/data/000085796.pdf; Narita et al.,(2016), In this proceedings
4)http://www.nsr.go.jp/data/000120136.pdf; http://www.energia.co.jp/anzen_taisaku/taisaku/pdf/h27_09.pdf
5)http://www.ensc.jp/pc/user/HOUDOU/h25/o260320/genshiryou1-1-1.pdf; https://www.nsr.go.jp/data/000034340.pdf
6)https://www.nsr.go.jp/data/000050685.pdf; Nobuoka et al.,(2012), Butsuri-Tansa, 65, 79-90

- Following two Posters are presented related to the previous table, please visit them.
- P204E Masatoshi Fujioka et al. ; DEEP VERTICAL ARRAY OBSERVATION IN KASHIWAZAKI-KARIWA NUCLEAR POWER STATION
- P209H Masahiro Sawairi et al. ; A STUDY ON THE LOCAL AMPLIFICATION MECHANISMS AT HAMAOKA NUCLEAR POWER STATION IN 2009 SURUGA BAY EARTHQUAKE

Concluding Remarks

First we have to apologize that we could not include many excellent papers /reports, especially concerned with California, in this discussion due to limitation of time and our ability.

- We have quickly looked the pioneers' works (80-120 years ago) of borehole seismic observation and results mostly in Japan. The foresight and efforts of pioneers are very impressive.
- The deep borehole records will be essential for confirming adequacy of the ground responses at a site in wide period range and modelling by geotechnical data (velocity structure and Q model), especially for long period ground motion.
- In addition, as the borehole records at bedrock will provide almost direct information on earthquake source, so that they are very valuable for engineering seismology as well as earthquake seismology.

Concluding Remarks -(2)-

Difficulties

- The most significant difficulty or issue of deep borehole observation is cost or finance. In addition technical issues have not yet solved as “KAVAS” face to the difficulty of long-term maintenance under high temperature and pressure.

Needs of corroboration to other objectives?

- Make multiplex purposes; e.g., Earthquake Early Warning project

Concluding Remarks –(3)-

- We could understand the strong spatial variations of ground motion at the KKNPS and the Hamaoka Nuclear Power Station, because both nuclear stations had installed dense strong instruments at the reactor buildings.
- Significant numbers of nuclear power stations has carried out various geotechnical/geophysical surveys for site characterizations. The deep borehole observations at nuclear stations just began or are going to operate and long-term efforts would be required to maintain.
- We hope that the electric power companies will find a method to distribute or release the borehole earthquake data and share the idea of strong motion evaluation with research communities.

Acknowledgements

I am very grateful to Prof. Wen and the Organizing Committee of ESG5 for giving me this opportunity.

Prof. Kagawa kindly permit me to use his read (2013) but unpublished slides.

KiK-net data by NIED were used.

Than you for listening!