A new attenuation relation for Japan applicable up to Mw9

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Background

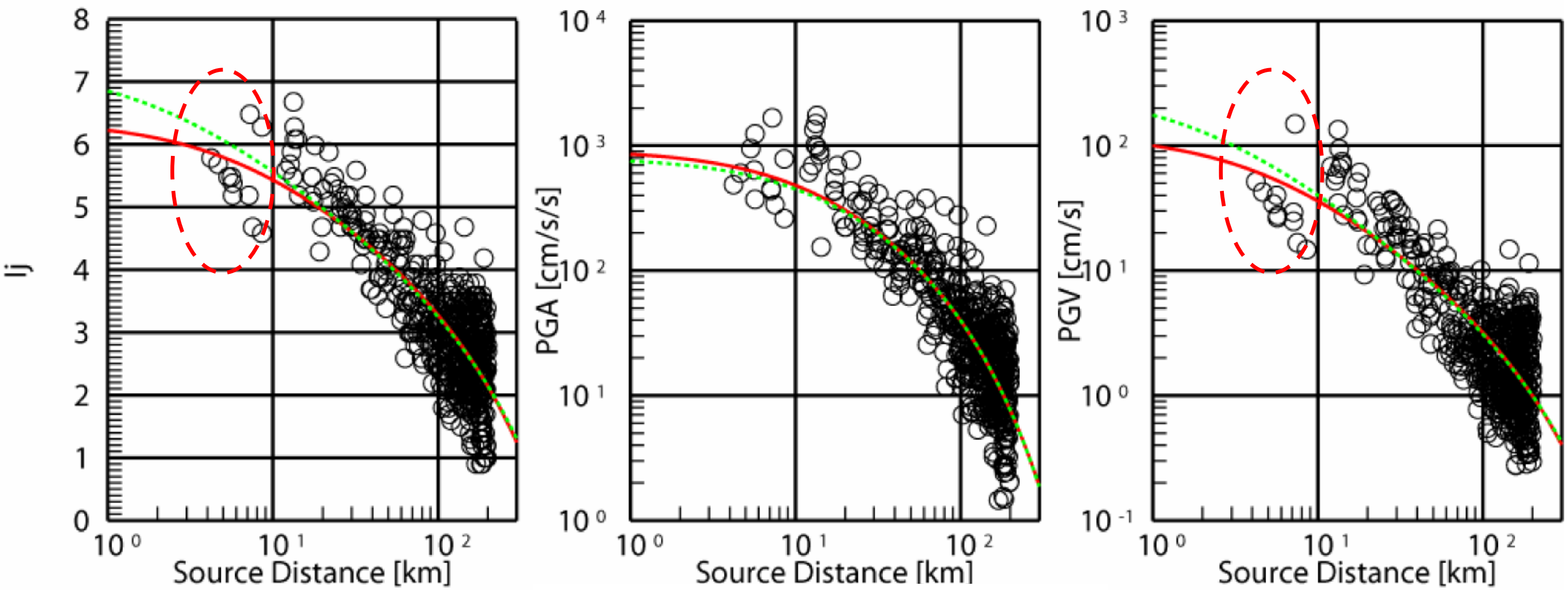
- We have constructed a database of strong-motion records and have obtained a new attenuation relation for Japan. (Kanno et al., 2006; BSSA)
- The 2011 Tohoku-oki mega-earthquake (Mw=9.0) on is the largest event which many strong-motion records were obtained. (over 2,000 records in Japan)
- We must consider Mw9-class mega-earthquakes (e.g. Nankai trough earthquake) in our seismic hazard assessment.

A new attenuation relation directly applicable up to Mw=9 earthquakes is required for the “Next Generation National Seismic Hazard Maps for Japan”.

Background ②

We have suggested a new attenuation relation based on the strong-motion records of the 2011 Tohoku-oki earthquake (Morikawa et al., 2012). However, the new attenuation relation have a tendency that overestimates the amplitude at near source region. Therefore we examine to improve it.

The 2004 Chuetsu earthquake (Mw=6.5)



Model-1 Model-2

Strong-motion data

- Update the strong-motion database of Kanno et al. (2006) by adding recent (after the 2003 Tokachi-oki EQ) records.
  - Up to end of 2011 (including the 2011 Tohoku EQ)
  - NIED (K-NET and KiK-net), JMA, PARI

- Target strong-motion parameters:
  - JMA seismic intensity (I)
  - Peak ground acceleration (PGA)
  - Peak ground velocity (PGV)
  - 5% damped acceleration response spectra (SA; 0.05-10s)

- Data used in the regression analysis
  - Earthquake: *Mw*>=5.5 & number of records>=5
  - Station: X<=200 km & installed on the ground surface

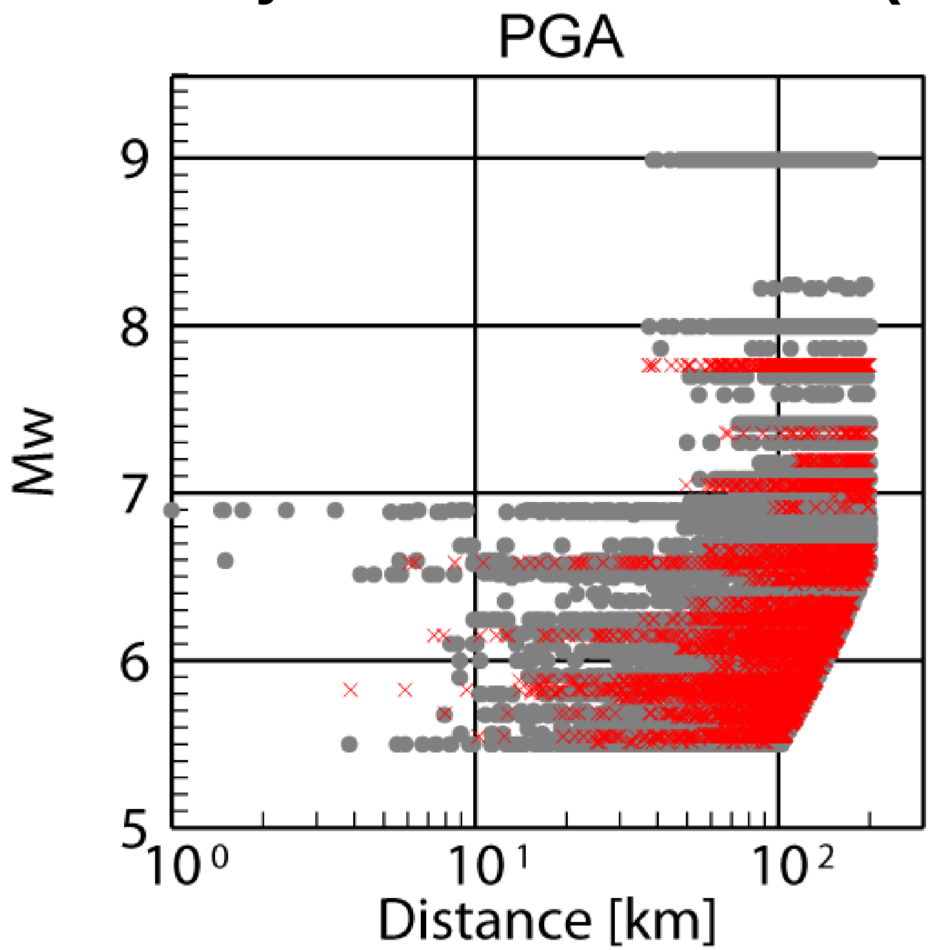
    X: closest distance to the source fault

Add strong-motion records

Morikawa et al. (2012):

End of 2009 (1967～) + Main shock of the 2011 Tohoku EQ

This study: End of 2011 (1967 ～)



※ records near source region are not added

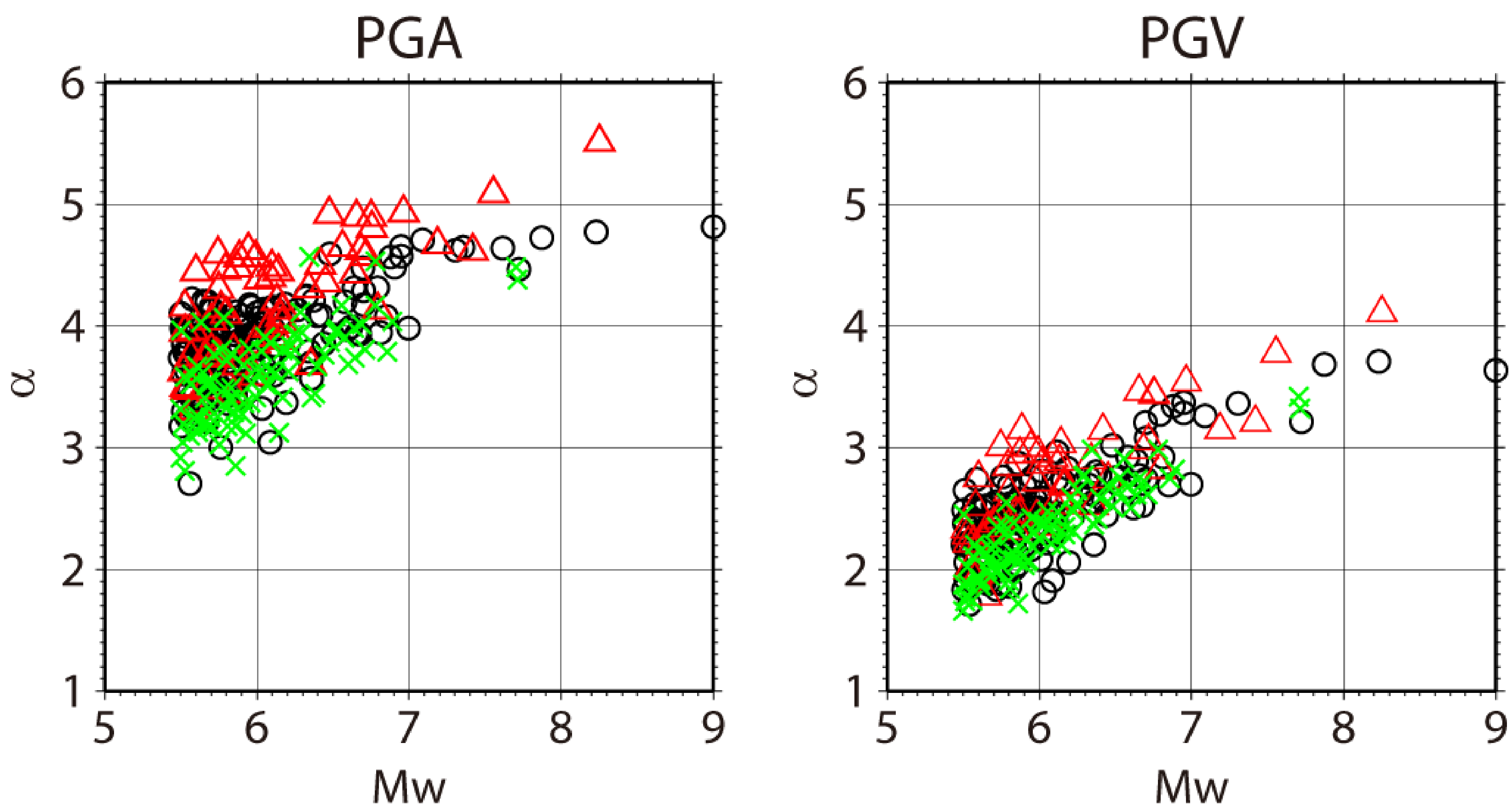
● Morikawa et al. (2012)

× This study

Examination of magnitude-term

First step of the regression analysis: $\log A = \sum_i \alpha_i + b \cdot X - \log(X)$

***α_i* can be obtained for each event "i"**



× **Crustal (shallow) earthquakes**

○ **Subduction-zone plate-boundary earthquakes**

△ **Subduction-zone intra-plate earthquakes**

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Revision of magnitude term for model-1

○ Model-1: Quadratic Mw model

Morikawa et al. (2012)

$$\log A = a_1 \cdot (Mw - Mw_1)^2 + b_1 \cdot X - \log (X + d_1 \cdot 10^{e_1 \cdot Mw}) + c_1$$

Introduce amplitude saturation at “Mw_{01}”

$$\log A = a_1 \cdot (Mw_{in1} - Mw_1)^2 + b_1 \cdot X - \log (X + d_1 \cdot 10^{e_1 \cdot Mw_{in1}}) + c_1$$

$$Mw_{in1} = \min (Mw, Mw_{01})$$

○ Model-2: Linear Mw model (usual model in Japan)

Amplitude saturation has been already introduced in Morikawa et al. (2012)

$$\log A = a_2 \cdot Mw_{in2} + b_2 \cdot X - \log (X + d_2 \cdot 10^{e_2 \cdot Mw_{in2}}) + c_2$$

$$Mw_{in2} = \min (Mw, Mw_{02})$$

Re-categorization of earthquakes

Morikawa et al. (2012) ･･･ 2 types

① Crustal (shallow) earthquakes

(including earthquakes on active faults)

② Subduction-zone earthquakes

(including plate-boundary and intra-plate earthquakes)

This study ･･･ 3 types

① Crustal (shallow) earthquakes

(including earthquakes on active faults)

② Subduction-zone plate-boundary earthquakes

③ Subduction-zone intra-plate earthquakes

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Change weight in the regression analysis

Morikawa et al. (2012)

[after Kanno et al. (2006)]

$$\begin{cases} 6.0 & X \le 25\text{km} \\ 3.0 & 25\text{km} < X \le 50\text{km} \\ 1.5 & 50\text{km} < X \le 75\text{km} \\ 1.0 & 75\text{km} < X \end{cases}$$

This study

$$\begin{cases} 8.0 & X \le 10\text{km} \\ 4.0 & 10\text{km} < X \le 20\text{km} \\ 2.0 & 20\text{km} < X \le 40\text{km} \\ 1.0 & 40\text{km} < X \end{cases}$$

Although the number of strong-motion records at near source have been increased, the ratio with the records at far sites have been smaller.

We set much larger weight for records at near source sites.

Regression procedure

In the regression analysis, we apply below assumptions because the number of earthquakes larger than Mw8 is quite few.

1. We assume that "Mw_0", "Mw_1" and "e" take a constant value independent from type of earthquake and strong-motion parameters.

At first, we fix $e_1=e_2=0.5$ referring past studies

2. We also assume "*a*" and "*d*" are independent of type of earthquake.

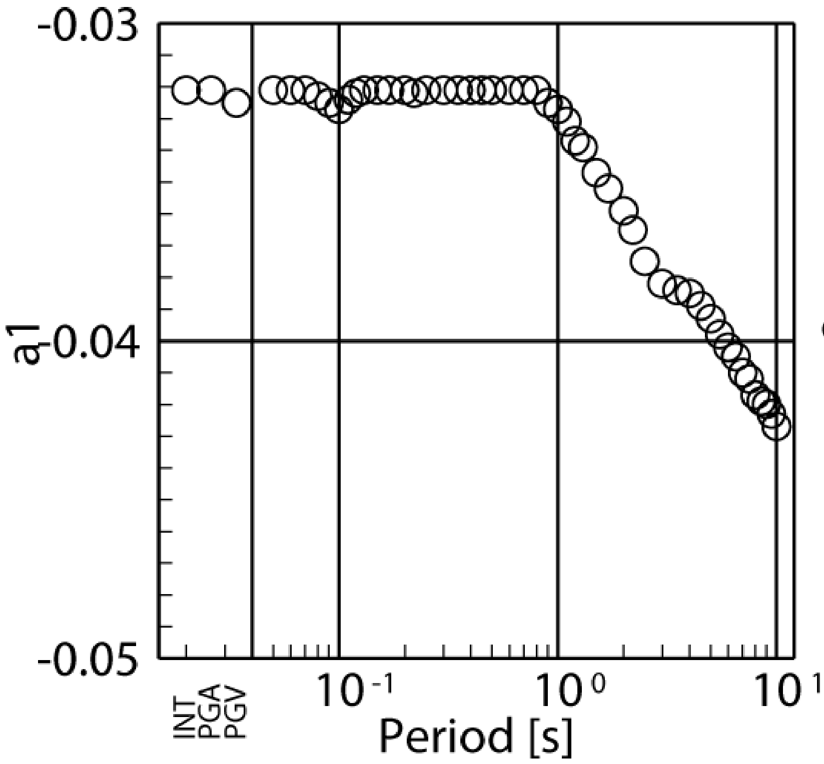
3. "Mw_0" and "Mw_1" determined after a trial-and-error approach by changing 0.1 and 1, respectively.

⇒ Model-1: $Mw_{01}=8.2$、$Mw_1=16.0$

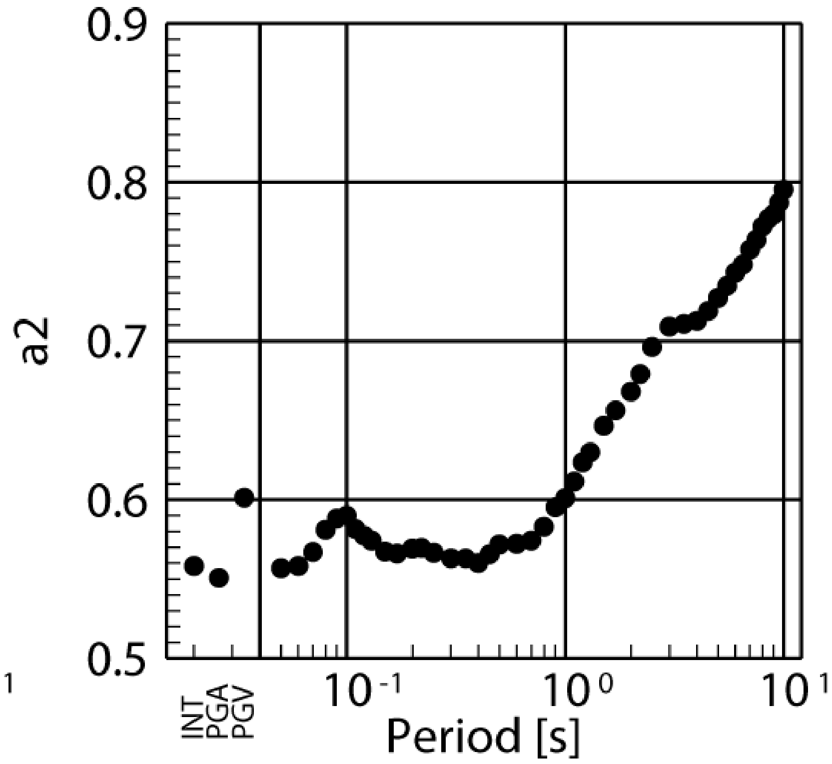
Model-2: $Mw_{02}=8.1$

Result (*a*: Magnitude term)

Model-1 (Quad. Mw)



Model-2 (Linear Mw)



Absolute value of "a" is larger when the period is longer

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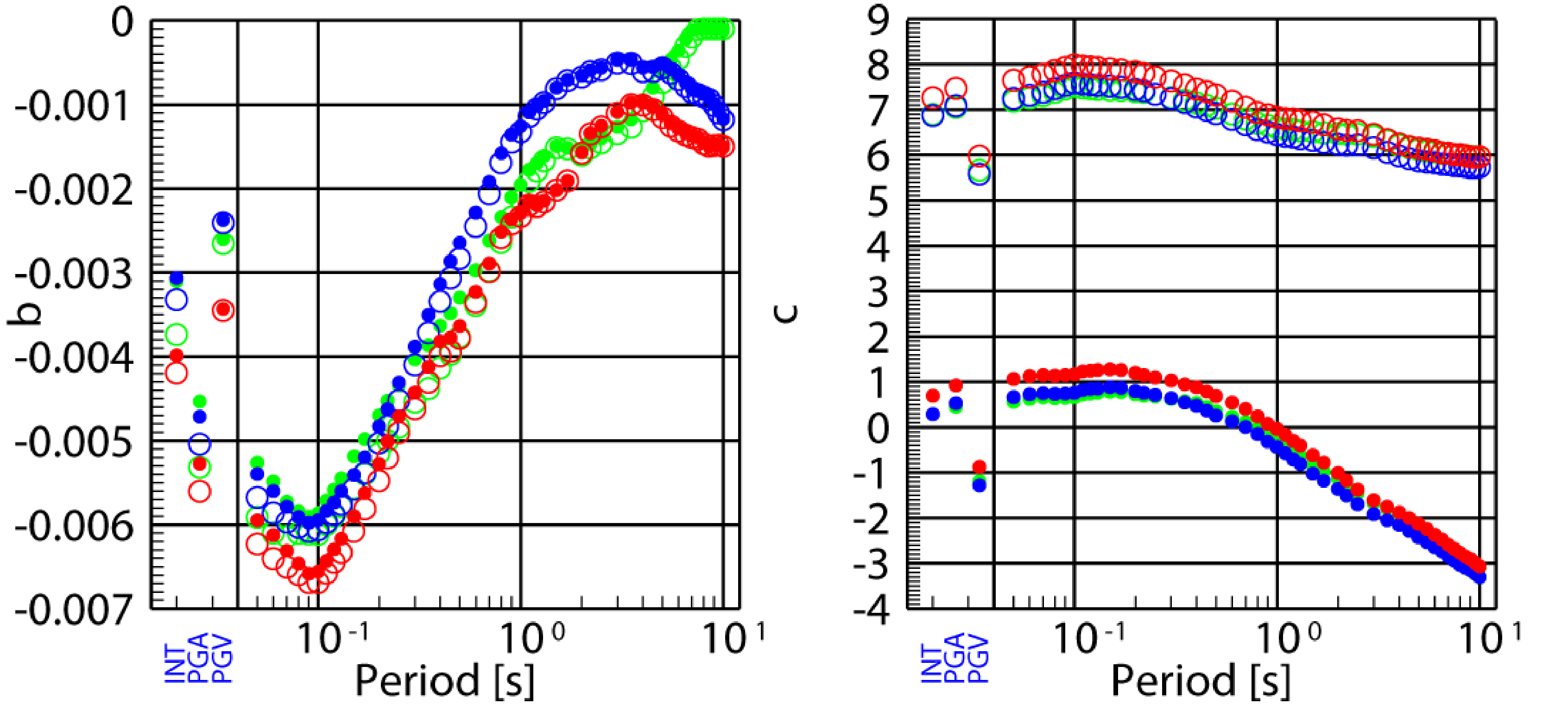
Result (*b*: Distance term, *c*: Constant term)

Crustal **Subduction Plate-boundary** **Subduction Intra-plate**

○Model-1 (Quad. Mw) **●Model-2 (Linear Mw)**

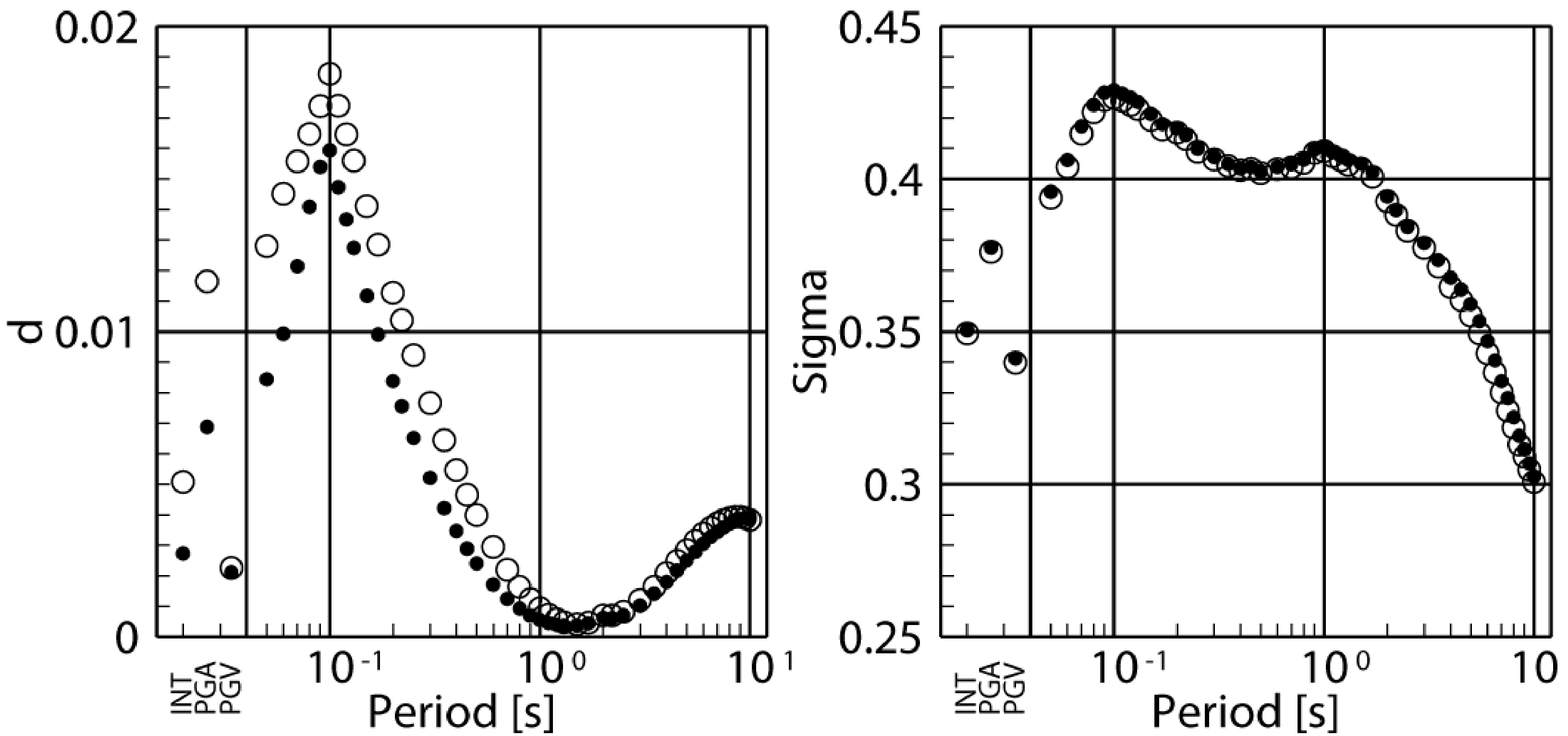


"c" for intra-plate EQs is larger than other type EQs (The tendency is remarkable at short period range)

The ground motion from intra-plate EQs becomes larger

Result (*d*: Distance saturation, σ: Standard deviation)

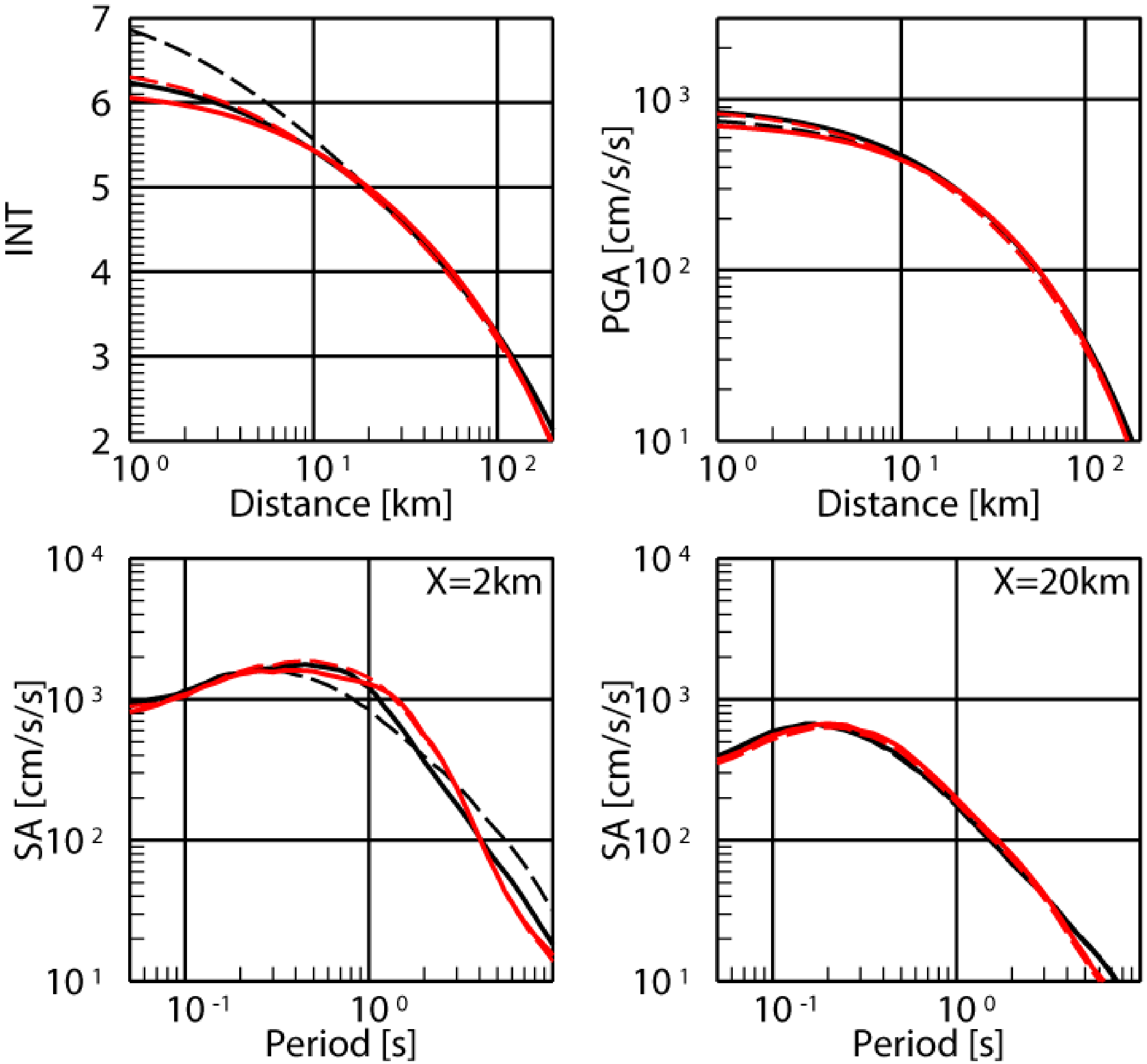
○ **Model-1 (Quad. Mw)** ● **Model-2 (Linear Mw)**



"σ" of model-1 is slightly smaller than that of model-2

Comparison of result ①

Crustal earthquakes (Mw = 6.5)



Morikawa et al. (2012)

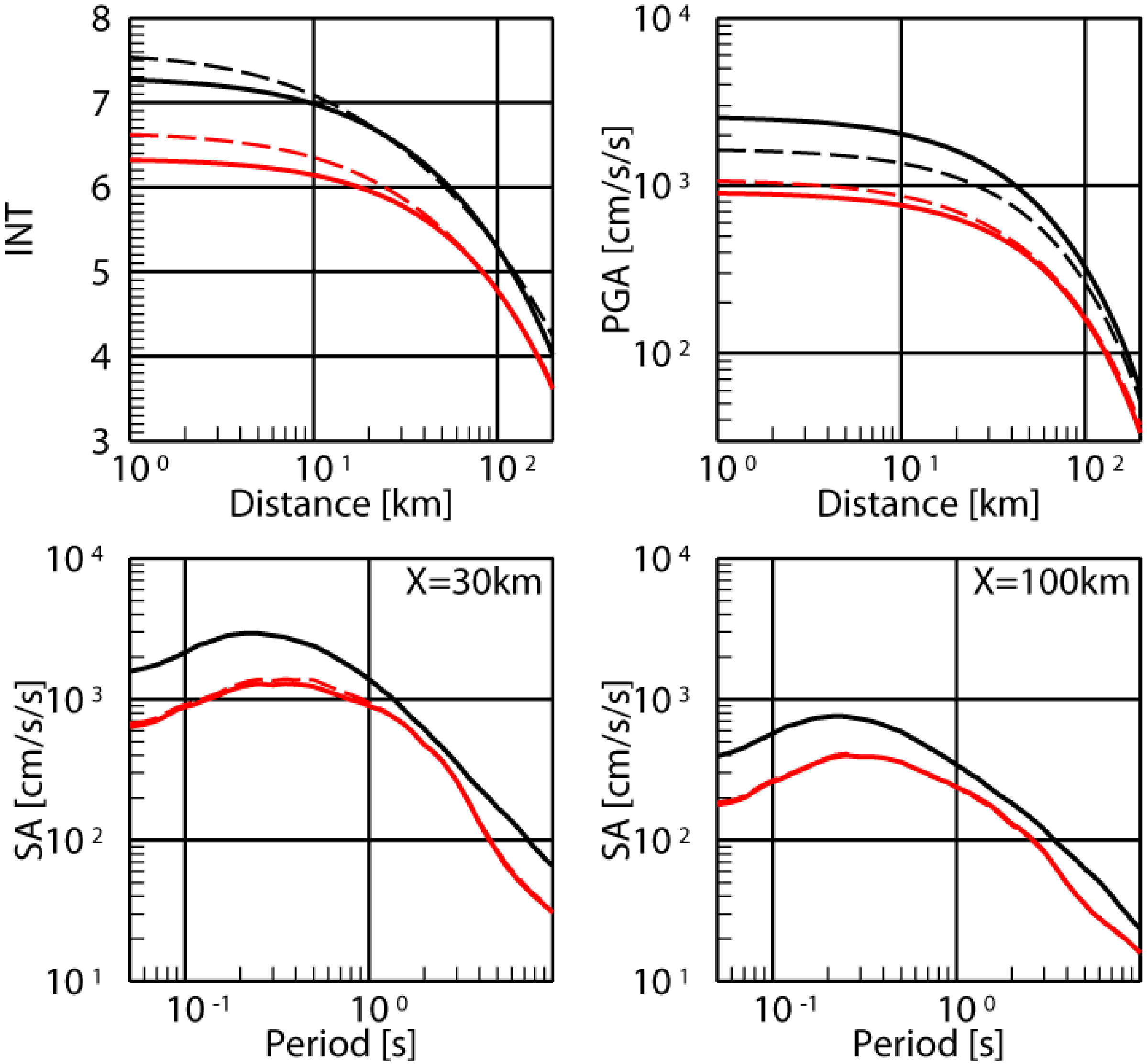
This study

Thick lines: Model-1

Dashed lines: Model-2

Comparison of result ②

Subduction-zone earthquake (Mw = 9.0)



Morikawa et al. (2012)

This study (pb event)

Thick lines: Model-1

Dashed lines: Model-2

Additional correction terms

We have suggest additional correction terms as follows

○ Amplification by deep sediment layers:

$$G_{deep} = \begin{cases} p_d \cdot \log(D_{l0}) + q_d & D_l \leq D_{l0} \\ p_d \cdot \log(D_l) + q_d & D_l > D_{l0} \end{cases}$$

D_l : Depth of the layer with Vs=l (m/s) at the site [in m]

○ Amplification by shallow soft soils:

$$G_{shallow} = \begin{cases} p_s \cdot \log(Vs30) + q_s & Vs30 \leq Vs30_0 \\ p_s \cdot \log(Vs30_0) + q_s & Vs30 > Vs30_0 \end{cases}$$

Vs30: Average S-wave velocity up to 30m depth [in m/s]

○ Anomalous seismic intensity distribution:

$$AI = \gamma \times X_{vf} \times (H - 30)$$

X_{vf}: Distance from volcanic front to the site [in km]

H: Focal depth of the earthquake [in km]

Conclusions

- **We suggest a new attenuation relation applicable up to Mw9 by using the strong-motion records during the 2011 Tohoku-oki earthquake.**
- **The quadratic magnitude model is slightly better than linear magnitude model.**
- **The weight for near source records enlarged in this study. As the result, the value “d” becomes large and predicted amplitude at near source region becomes smaller than the last study.**
- **Large amplitude is observed during the subduction-zone intra-plate earthquakes. Therefore, it is effective to divide inter-plate and intra-plate earthquake beforehand in regression analysis.**

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Further problems

- **Examination of the uncertainty for applying to seismic hazard evaluation.**
- **Since strong-motion records for large earthquakes (Mw>7.5) at short distances (X<30km) are not included in this study. Therefore it is not constrained such region. The validation of predicted amplitude for large (Mw>7.5) earthquake at short distance (X<30km) is required by using the foreign records.**
- **The relation of duration of strong-motion is also required for mega-earthquake.**
- **The nonlinear site response should be considered in the future.**

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Acknowledgements

We use strong-motion records by NIED （K-NET, KiK-net）, JMA, PARI, 土技術政策総合研究所, Central Research Institute for Electric Power Industry, Committee for Earthquake Resaeach Kansai Area, JR Group, NTT、Tokyo Electric Power Company, Kansai Electric Power Company, Osaka Gus, 、滋賀県、神戸市、大林組、鴻池組、前田組、松村組、京都大学、滋賀県立大学、阪神高速道路公団（当時）、本州四国連絡橋公団（当時）、の各機関によりご提供いただいた強震動記録を使用しました。

補正項①　深部地盤による増幅

◎使用データ

「基本式」の導出に用いた強震動記録のうち

・ 深さ 30km 以浅の地震による記録

（異常震域の影響を除くため）

・ 最大加速度の観測値が 100 cm/s/s 以下の記録

（地盤の非線形応答による影響を除くため）

観測値（*obs*）と基本式による予測値（*pre*）との残差（*residual*）

$residual = \log[obs] - \log[pre]$ （ $= \log[obs/pre]$ ）

（※ただし、震度の場合は $residual = [obs - pre]/2$ ）

をもとに検討する。

注）本検討では、pre は「頭打ちモデル」によるものを用いた

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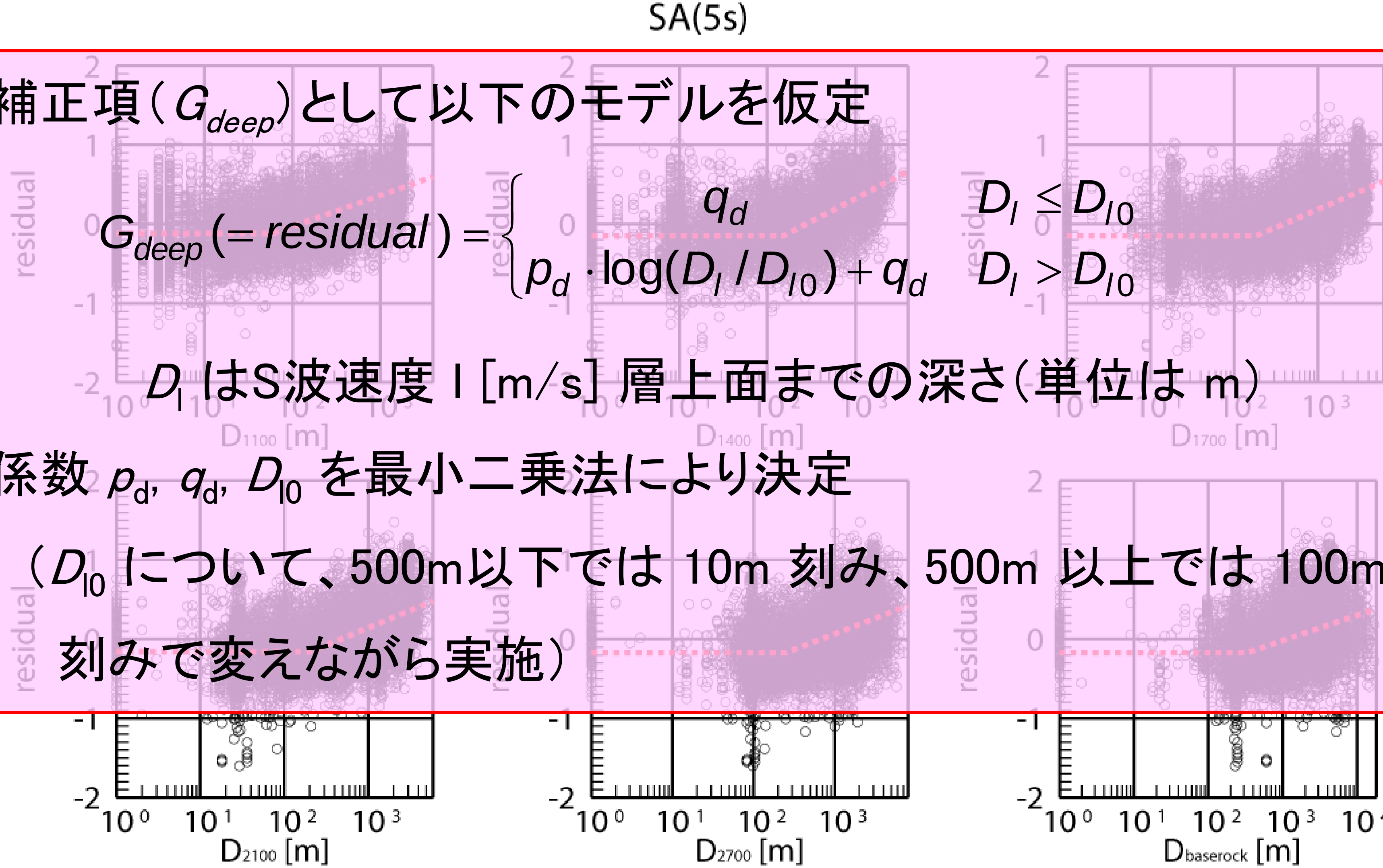
補正項①　深部地盤による増幅

藤原・他(2009)による全国深部地盤モデル(地震基盤～工学的基盤)

における6つの層の上面深さと「residual」との関係の例



補正項(G_{deep})として以下のモデルを仮定

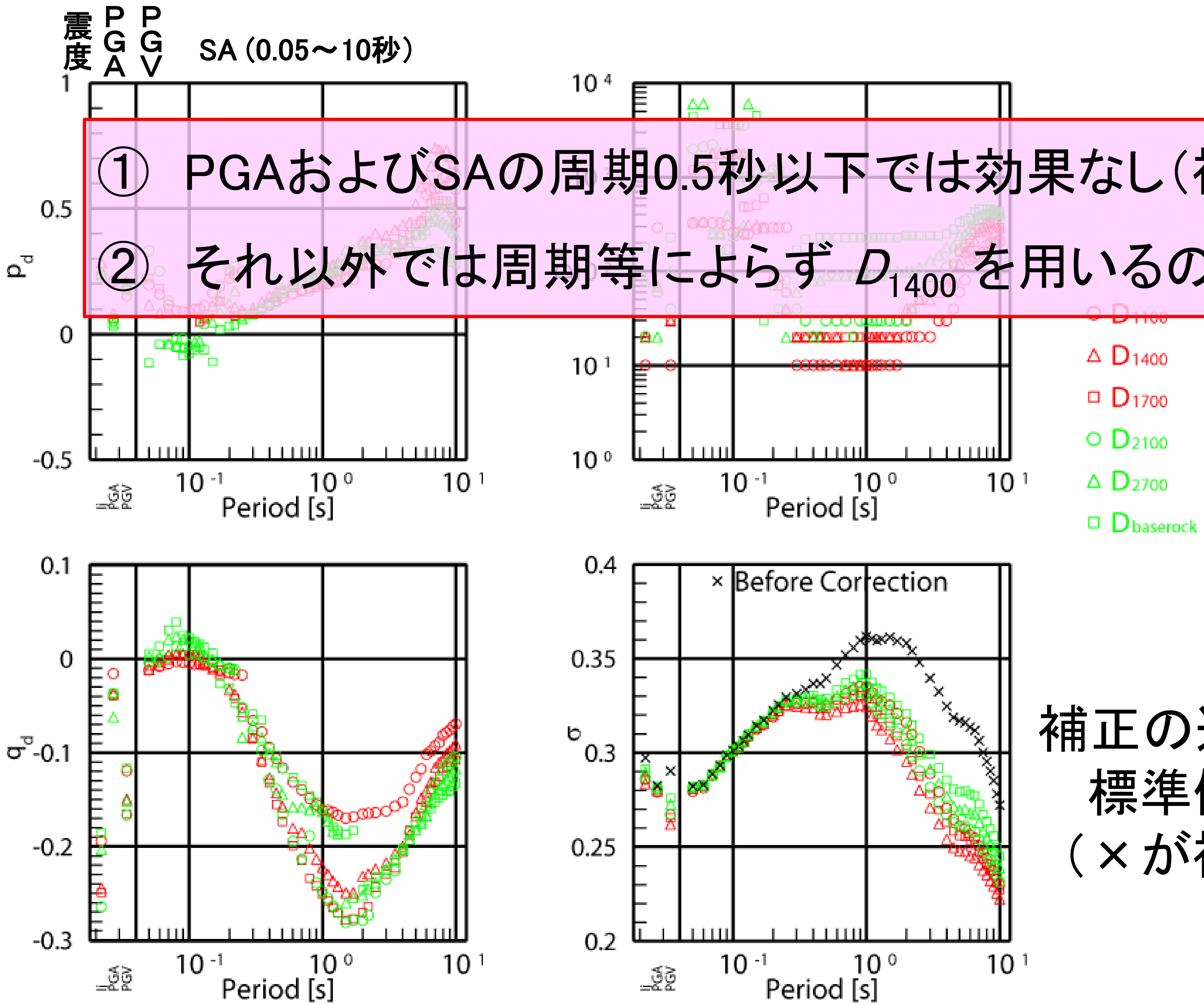
$$G_{deep}(=residual)=\begin{cases} q_d & D_l \le D_{l0} \\ p_d \cdot \log(D_l/D_{l0})+q_d & D_l > D_{l0} \end{cases}$$

D_l はS波速度 l [m/s] 層上面までの深さ(単位は m)

係数 p_d, q_d, D_{l0} を最小二乗法により決定

（D_{l0} について、500m以下では 10m 刻み、500m 以上では 100m 刻みで変えながら実施）

補正項①　深部地盤による増幅



① PGAおよびSAの周期0.5秒以下では効果なし(補正不要)

② それ以外では周期等によらず D_{1400} を用いるのが良い

補正の適用前後での標準偏差の比較（×が補正適用前）

補正項②　浅部地盤による増幅

◎使用データ

「基本式」の導出に用いた強震動記録のうち

・深さ 30km 以浅の地震による記録

・最大加速度の観測値が 100 cm/s/s 以下の記録

・深さ 20m 以深の S波速度構造が得られている観測点の記録

（→　K-NET, KiK-net, 港湾地域強震観測網の観測点）

※ Kanno et al. (2006) による Vs20⇔Vs30 の関係式を利用

観測値（*obs*）と基本式による予測値（*pre*）および深部地盤による増幅の補正（G_{deep}）との残差（*residual*）

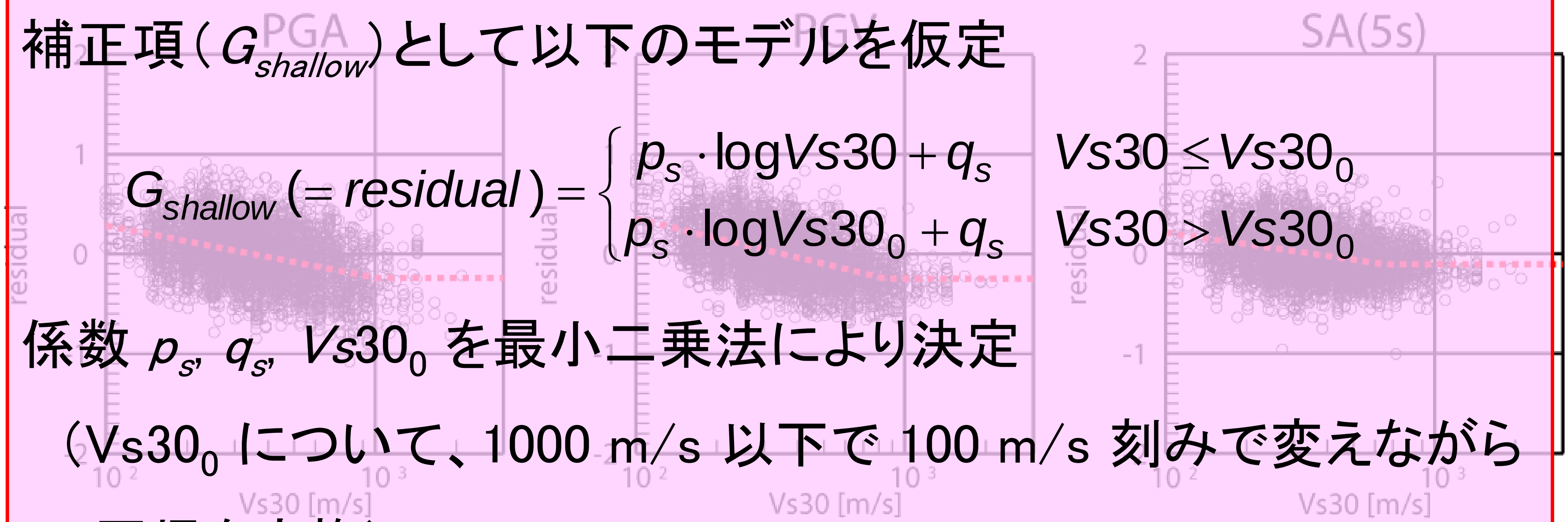
$$residual = \log[obs] - (\log[pre] + G_{deep})$$

（※ただし、震度の場合は $residual = obs - (pre + G_{deep})$ ）

をもとに検討する。

補正項②　浅部地盤による増幅

深さ 30m までの平均S波速度（$Vs30$）と「*residual*」との関係の例



補正項（$G_{shallow}$）として以下のモデルを仮定

$$G_{shallow}(=residual)=\begin{cases} p_s\cdot\log Vs30+q_s & Vs30\le Vs30_0\\ p_s\cdot\log Vs30_0+q_s & Vs30>Vs30_0\end{cases}$$

係数 p_s, q_s, $Vs30_0$ を最小二乗法により決定

（$Vs30_0$ について、1000 m/s 以下で 100 m/s 刻みで変えながら回帰を実施）

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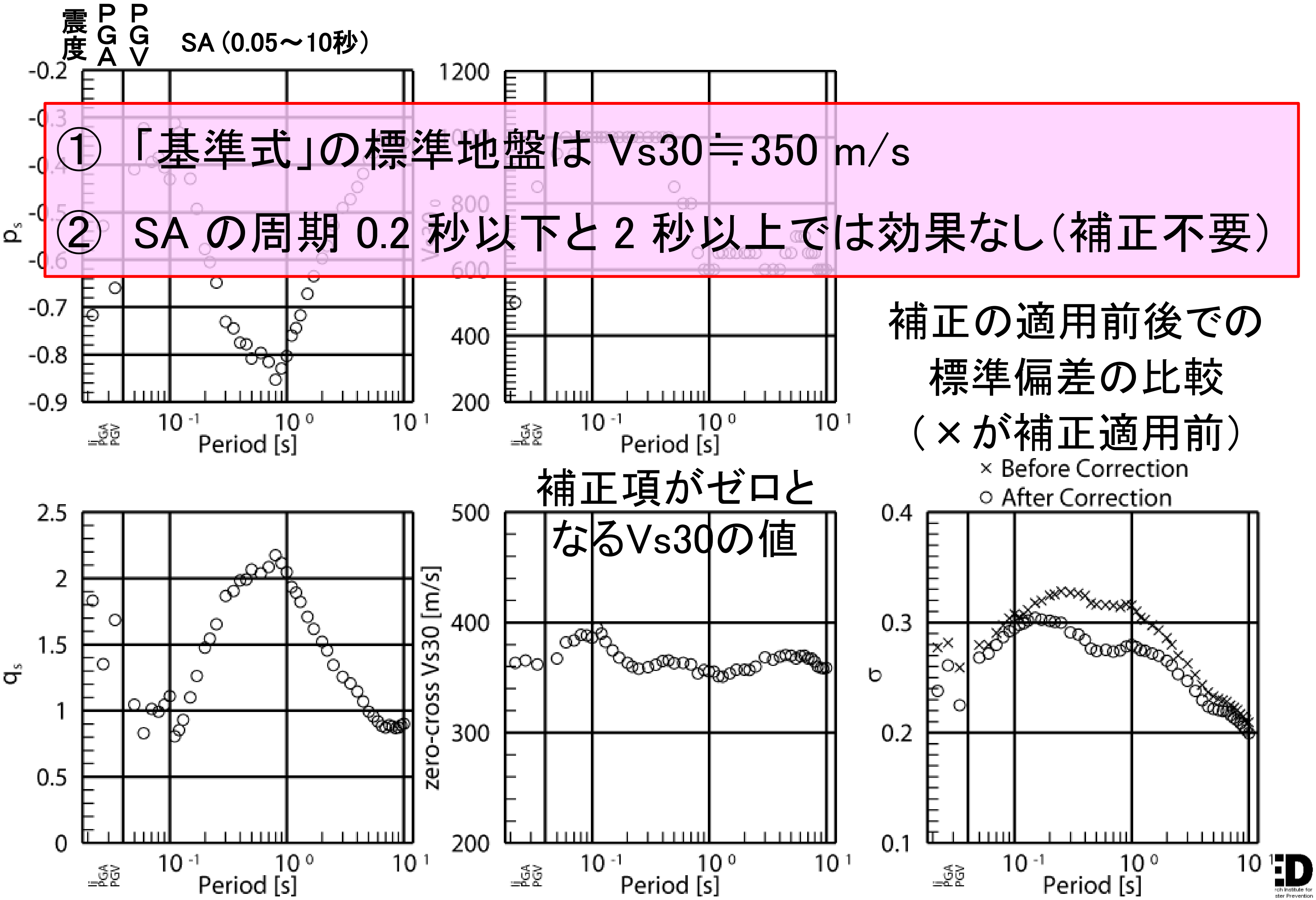
補正項② 浅部地盤による増幅

① 「基準式」の標準地盤は Vs30≒350 m/s

② SA の周期 0.2 秒以下と 2 秒以上では効果なし(補正不要)



補正項③　異常震域

◎使用データ

「基本式」の導出に用いた強震動記録のうち

・深さ 30km 以深の地震による記録

・最大加速度の観測値が 100 cm/s/s 以下の記録

観測値（*obs*）と基本式による予測値（*pre*）および深部地盤、浅部地盤による増幅の補正（G_{deep} と $G_{shallow}$）との残差（*residual*）

$$residual = \log[obs] - (\log[pre] + G_{deep} + G_{shallow})$$

（※震度の場合は $residual = obs - (pre + G_{deep} + G_{shallow})$ ）

をもとに検討する。

（→ K-NET, KiK-net, 港湾地域強震観測網の観測点）

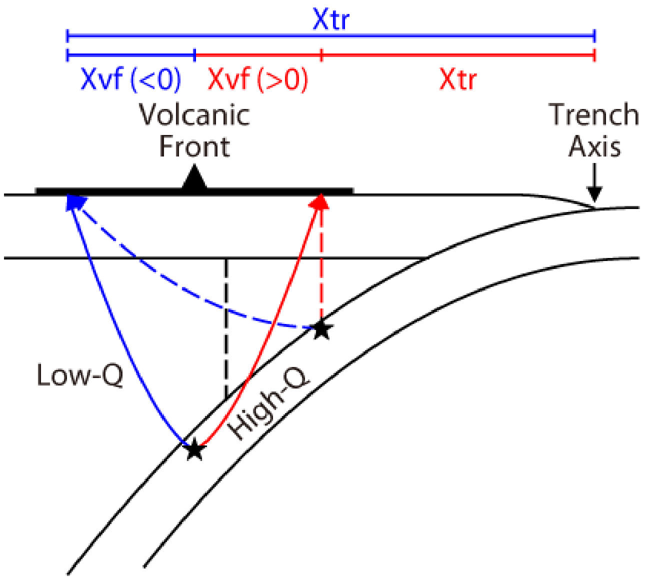
補正項③　異常震域

ここでは、森川・他(2006)による火山フロントから観測点までの距離(Xvf)を用いた補正項(*AI*)

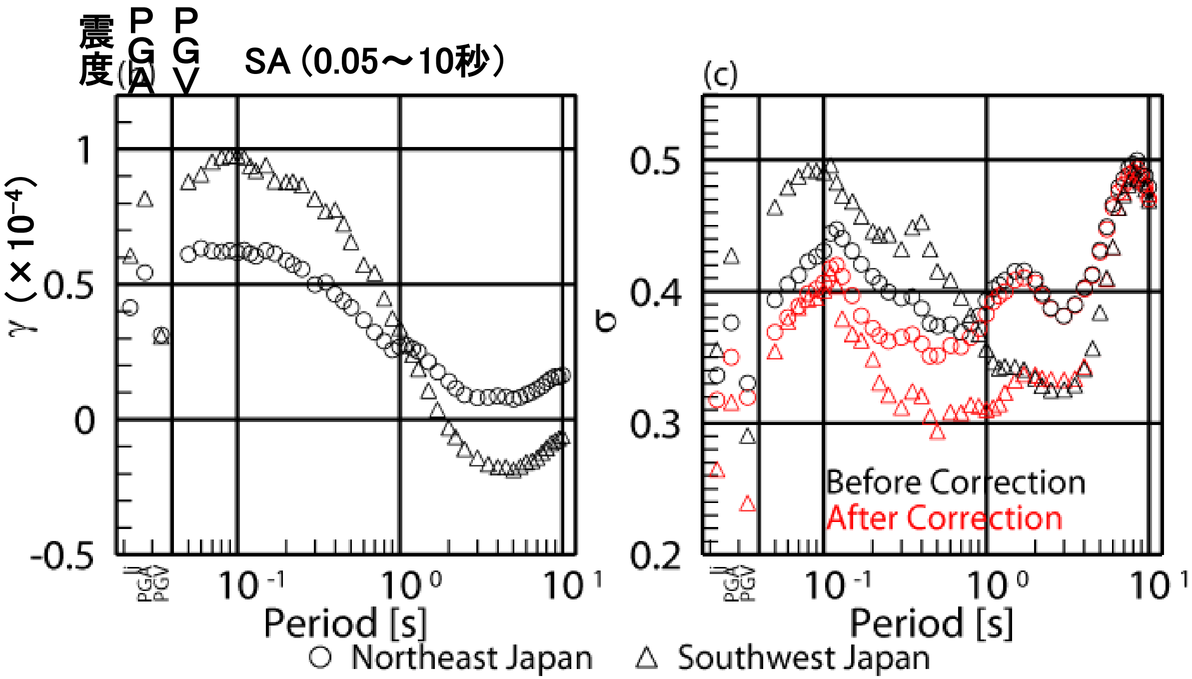
$$AI(=residual) = \gamma \times X_{vf} \times (H-30)$$

H:震源の深さ [km]

を仮定して係数 γ を東北日本(太平洋プレートの地震)、西南日本(フィリピン海プレートの地震)それぞれについて最小二乗法により求める。



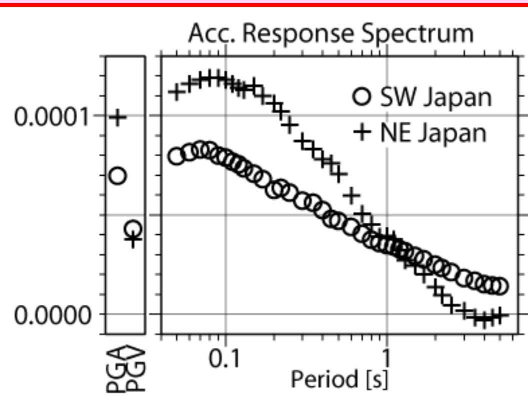
補正項③　異常震域



補正の適用前後での標準偏差の比較（黒が補正適用前）

① 西南日本の方が異常震域が顕著？（現時点で原因は不明）

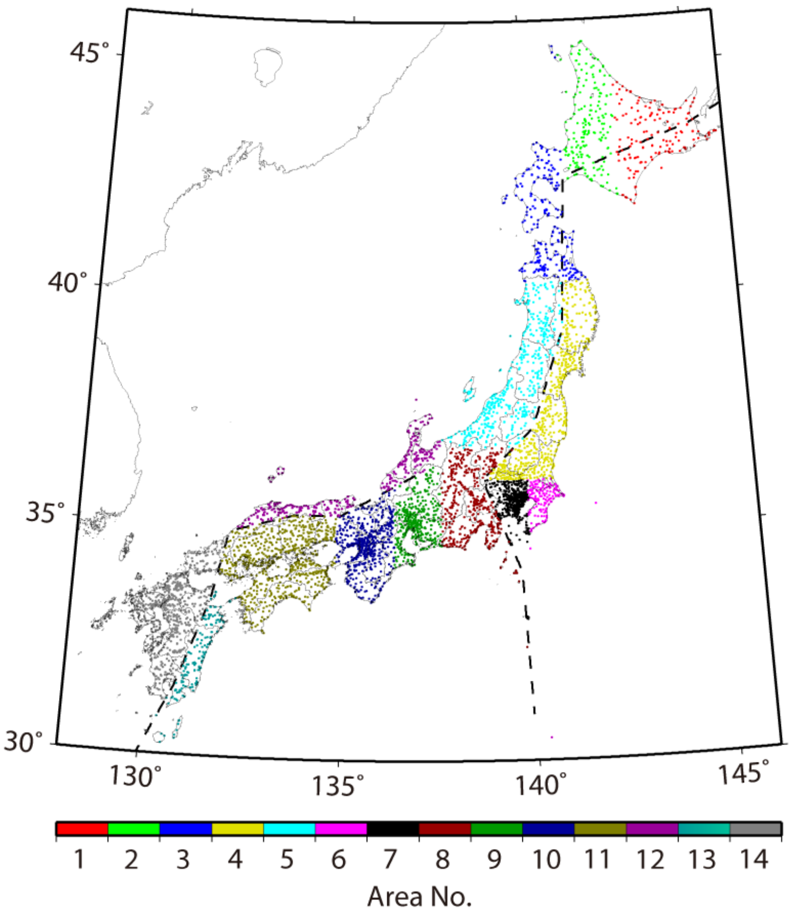
② SA の周期 1.5 秒以上では効果なし（補正不要）

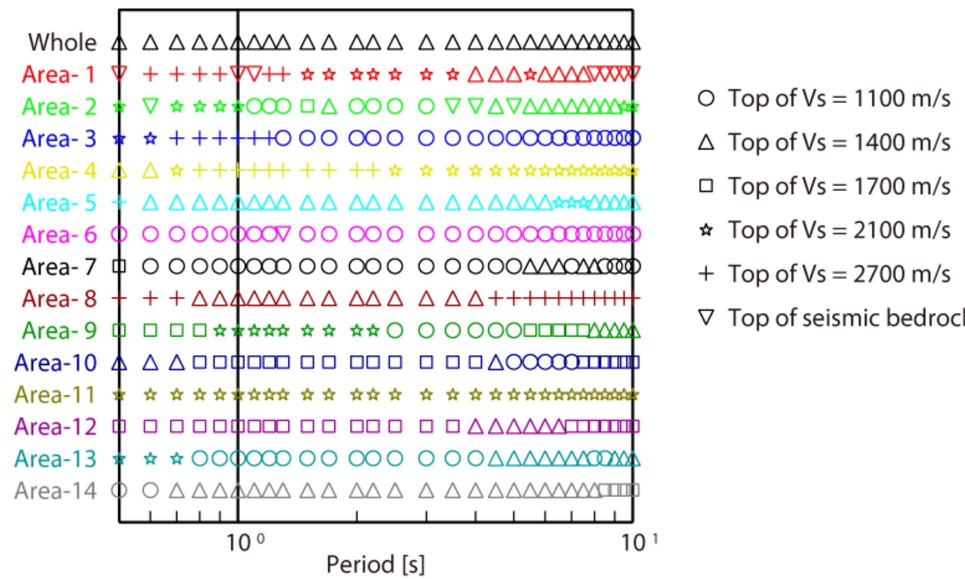


【参照】 森川・他（2006）の結果

東北日本（＋）の方が顕著（係数が大）

（深部地盤補正の）地域性





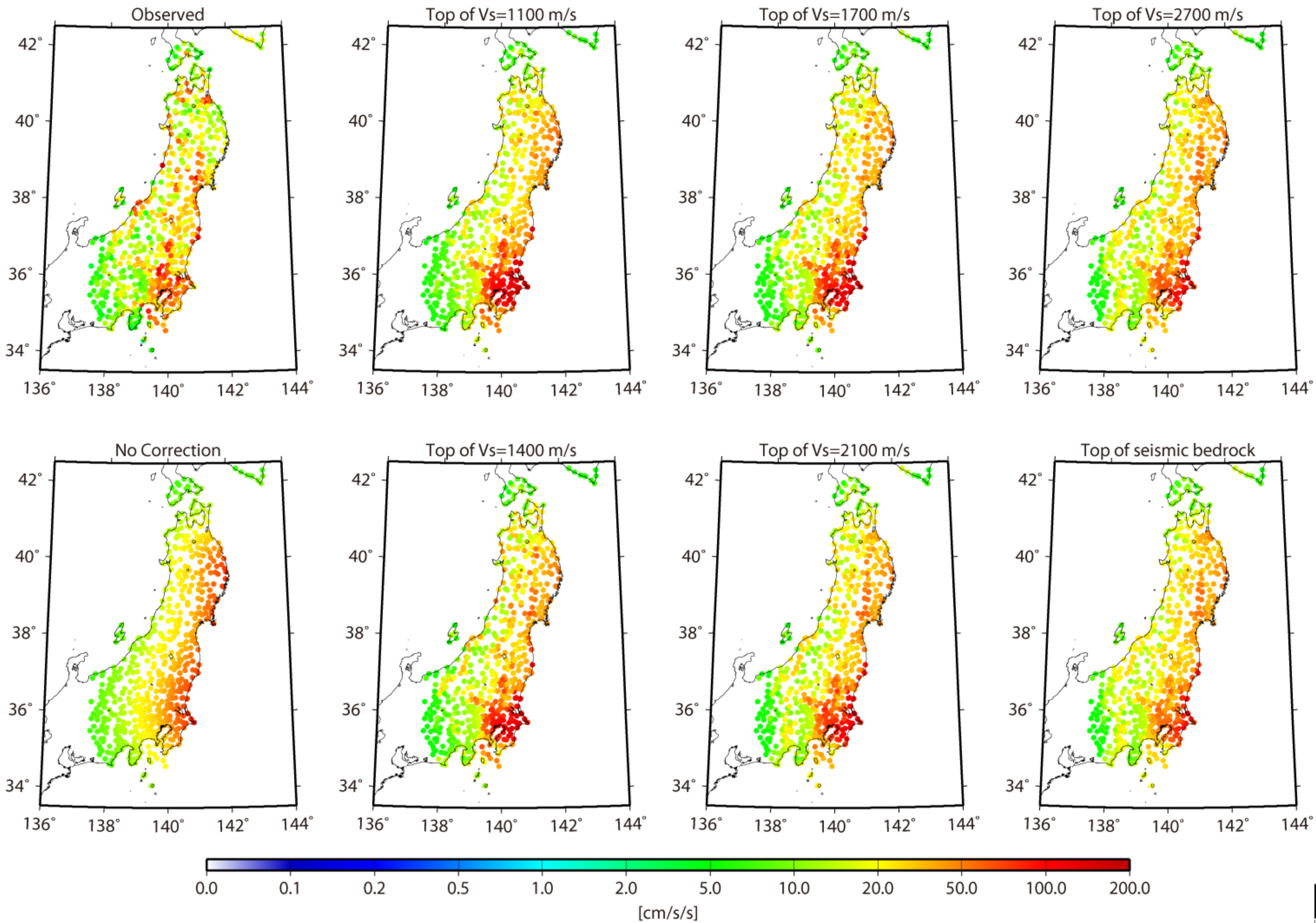
関東（Area-6, 7）:　　1100 m/s 層上面
中国・四国（Area-11）:2100 m/s 層上面

⇩

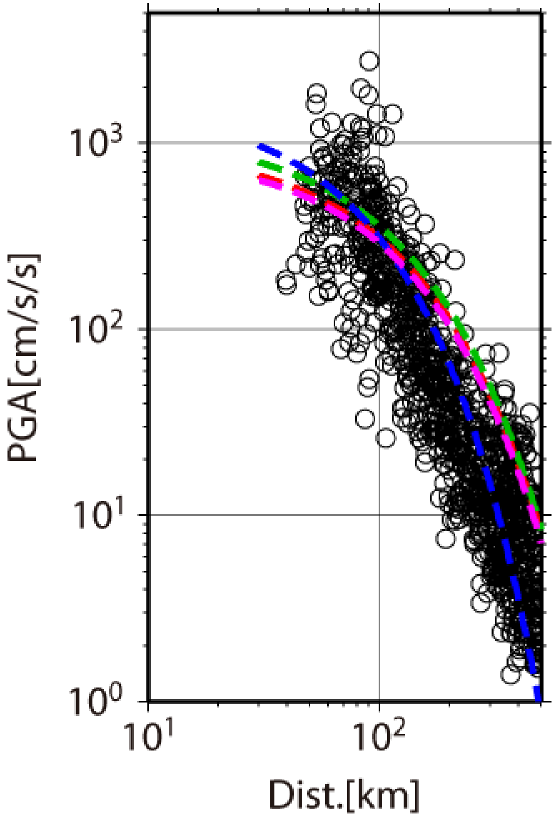
地域性は有るようだ

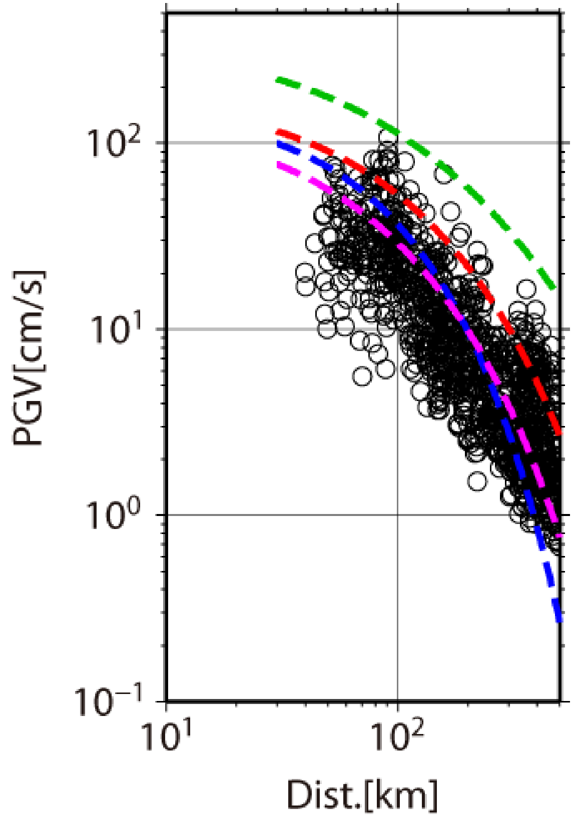
（深部地盤補正の）適用例

2011/03/11 14:46 SA（周期5秒）

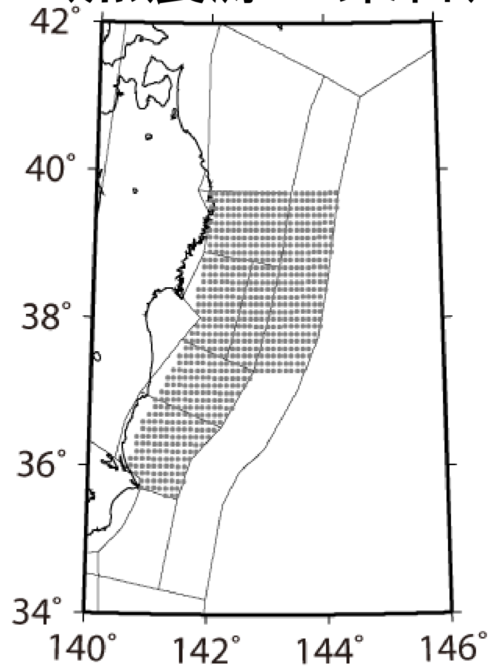


既往の距離減衰式とM9地震の記録との比較





設定した断層面
（点震源の集合）



○　観測記録： 0.1-10Hz バンドパス、地表

------ 司・翠川（1999）：プレート間地震、PGVはAVS30=300m/s上に変換

------ 片岡・他（2006）：海溝性地震（Mw, X, D）をパラメータ、全観測点平均

------ Kanno et al. (2006)：浅い（深さ30km以浅の）地震、地表

------ 佐藤（2010）：太平洋プレートのプレート間地震、地表

※ 各式は Mw=9.0 まで外挿

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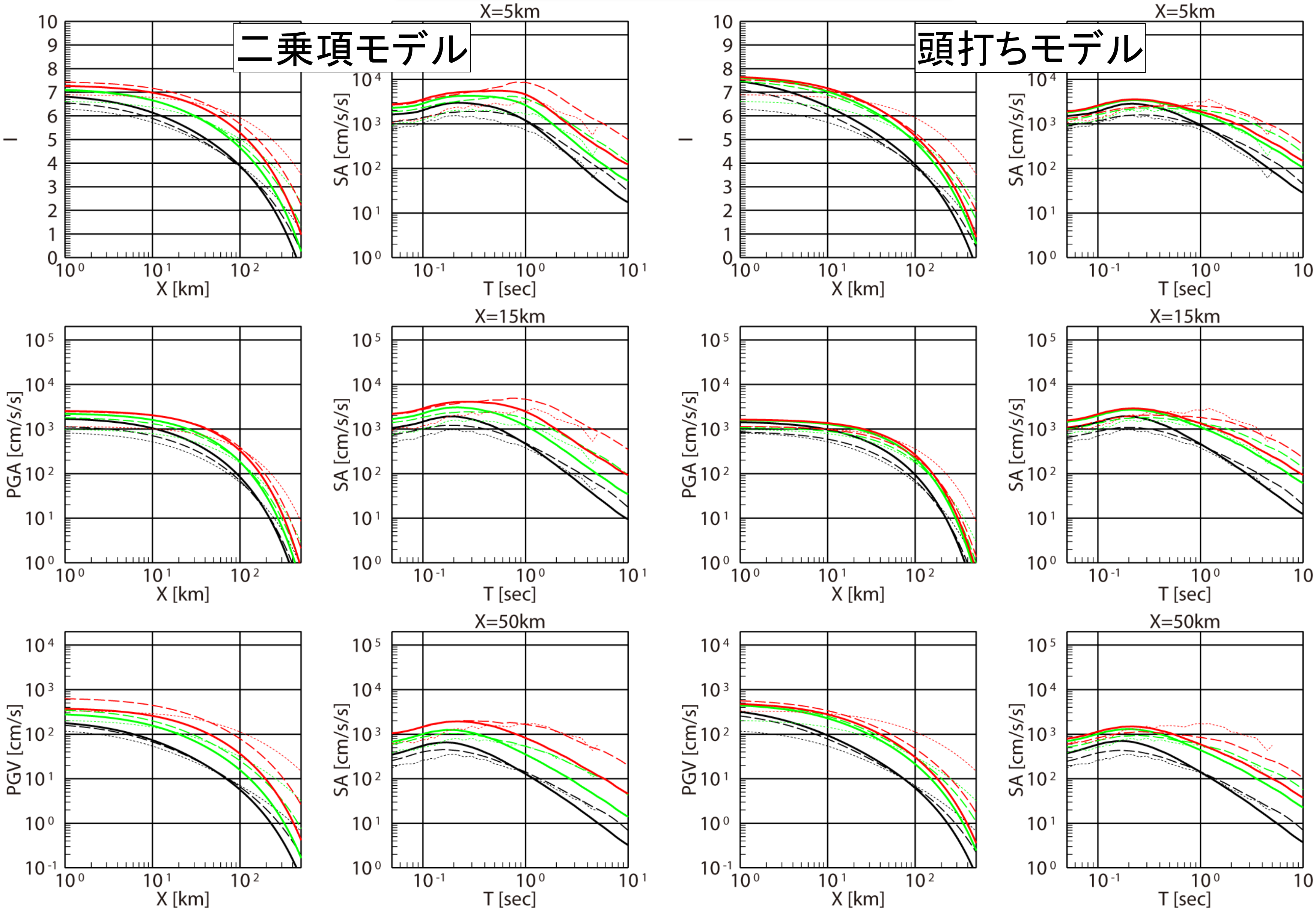
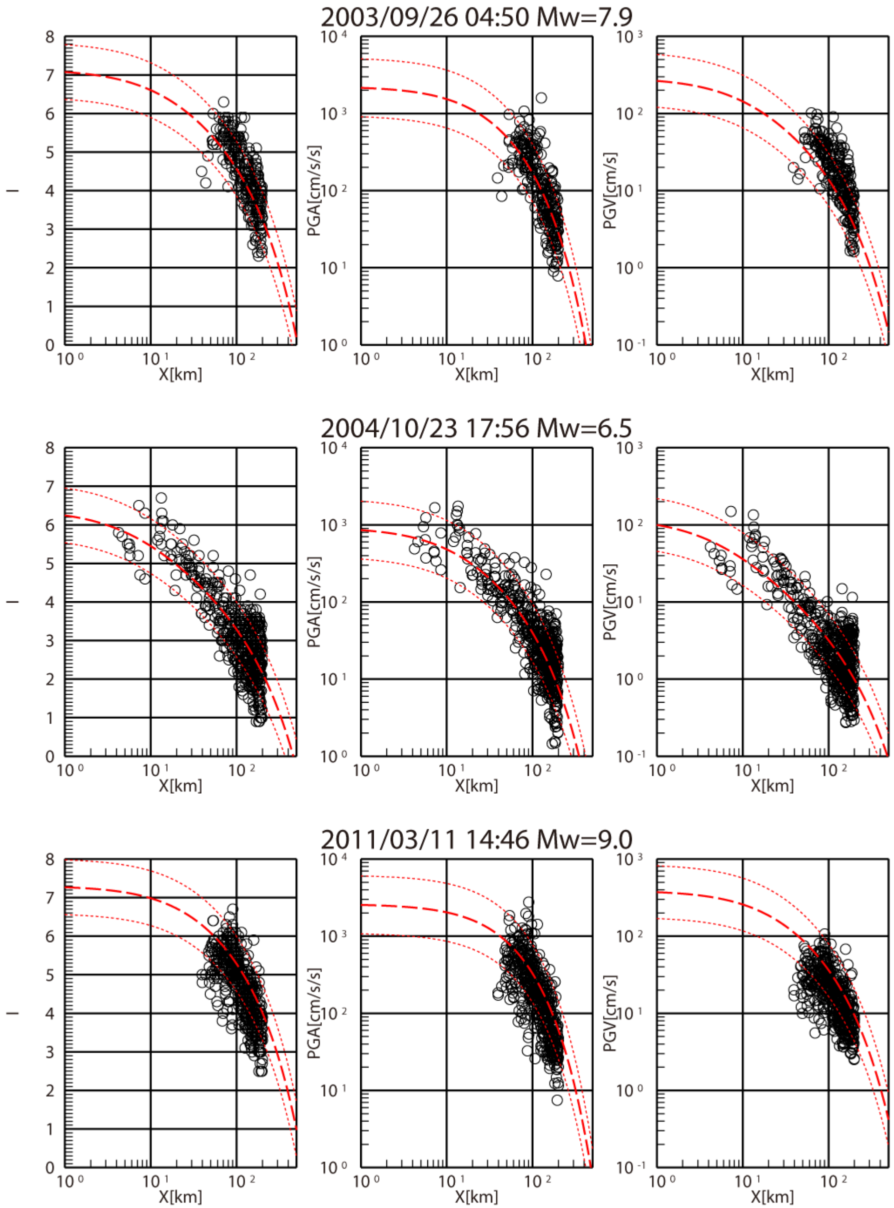
求められた基本式



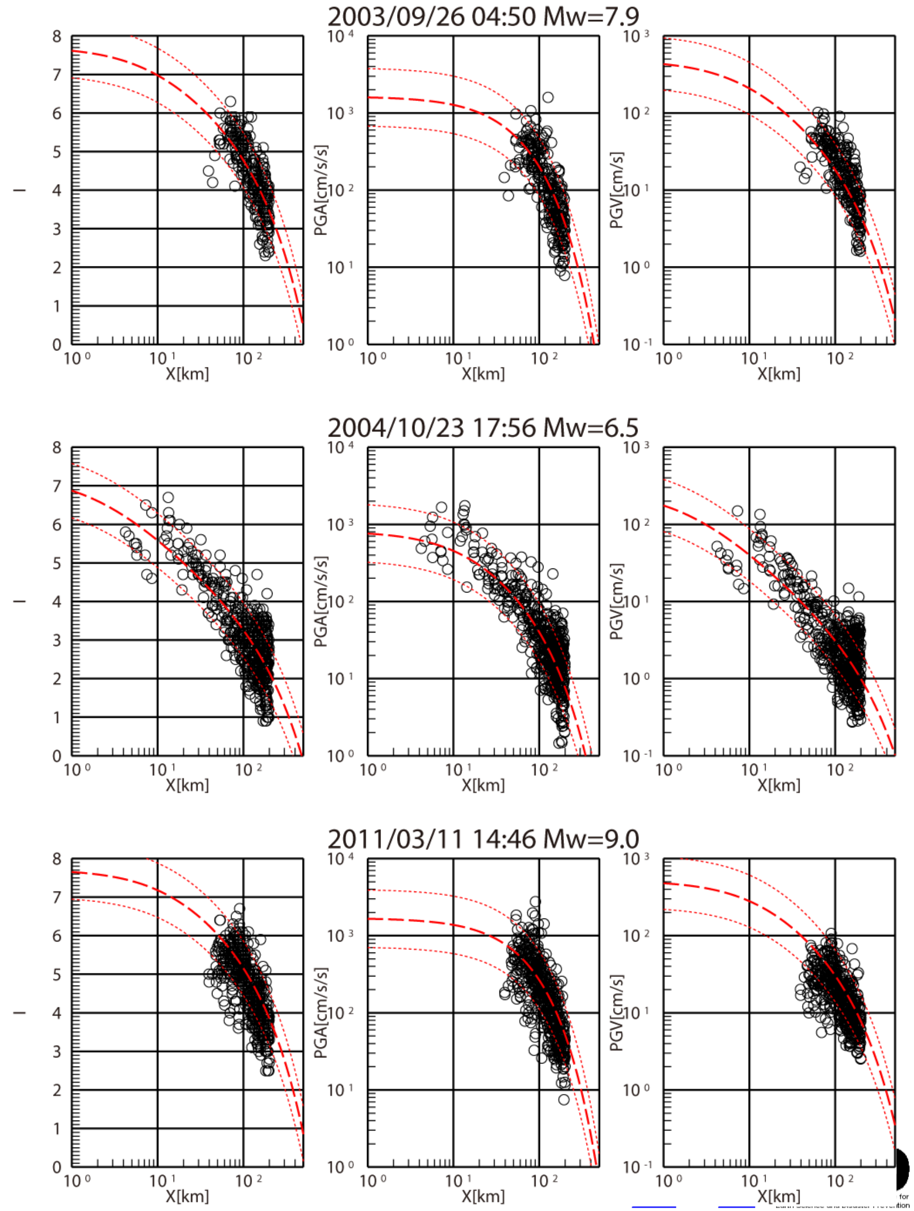
赤：Mw=9.0、緑：Mw=8.0、黒：Mw=7.0　　実線：カテゴリーⅠ＆Ⅱ、破線：カテゴリーⅢ

観測記録との比較の例

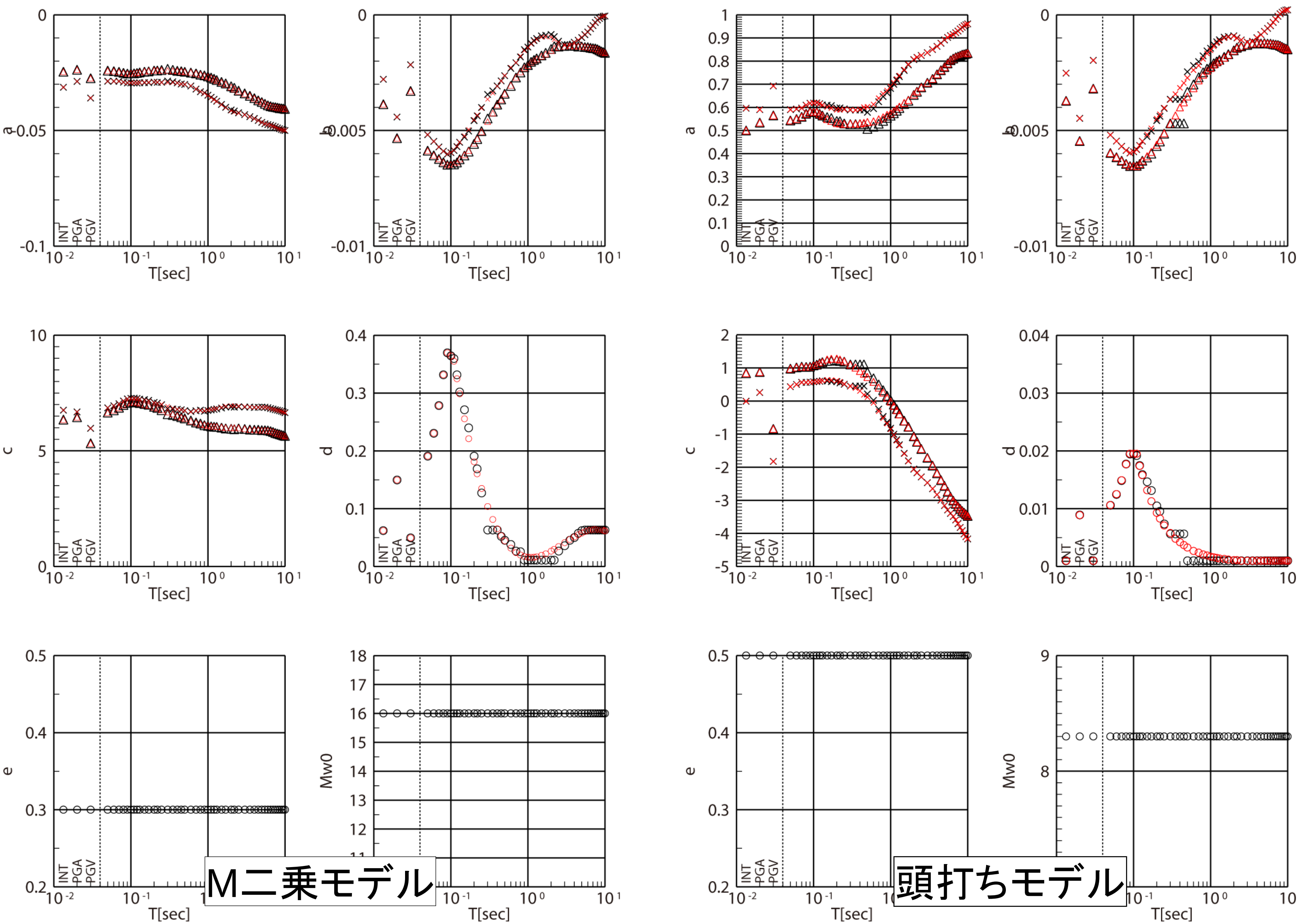
二乗項モデル



頭打ちモデル



求められた回帰係数



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