Estimation of three-dimensional basin structure based on waveform modeling: a case study in the Osaka sedimentary basin

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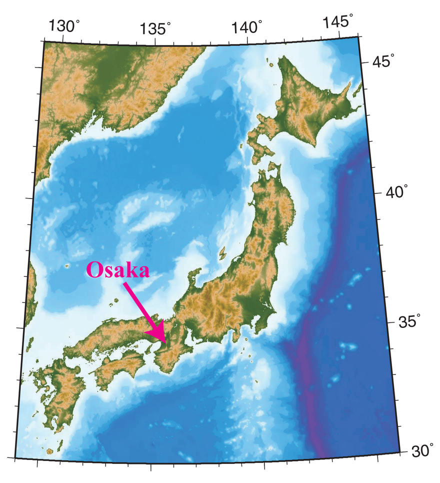
Abstract

Three-dimensional (3D) sedimentary basins often cause long-period ground motion with large amplitude and long duration because of the amplification due to soft sediment with low seismic velocity and generation of surface waves due to 2- or 3-dimensional laterally heterogeneous velocity structure. Therefore modeling of 3D sedimentary basin structure is necessary for quantitative evaluation of ground motions observed in sedimentary basins. In this study, we present a method to estimate the 3D boundary shape of a sedimentary basin by inversion of time series of seismic waveforms. We apply it to the real seismic data observed in the Osaka sedimentary basin, Japan, aiming to construct a 3D basin velocity structure model that can reproduce the observed wavefield in the period range between 3 – 10 s.

Osaka basin velocity structure model

The Osaka sedimentary basin, located in western Japan, includes the megacities Osaka and Kobe. We refer to the 3D basin velocity structure model presented by Iwata *et al.* (2008), which is the updated version of the model by Kagawa *et al.* (2004), as the initial model of our inversion.



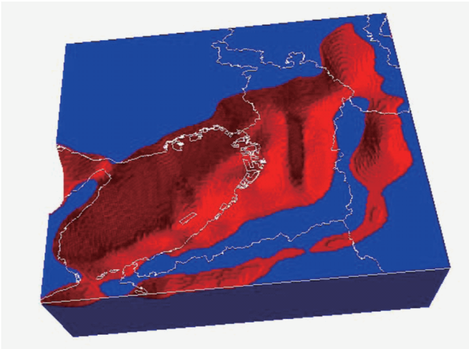


Fig 1. Map of Japan (left) and the 3D Osaka sedimentary basin velocity structure model by Iwata et al. (2008) showing the bedrock geomtry (right).

Table 1. Model parameters of the velocity structure model used in this study.

	V_P (km/s)	V_S (km/s)	ρ (kg/m^3)	Q_0	Depth (km)
Sedimentary layer 1	1.60	0.35	1700	175	0.0
Sedimentary layer 2	1.80	0.55	1800	275	r_1z
Sedimentary layer 3	2.50	1.00	2100	500	r_2z
Seismic bedrock	5.50	3.20	2700	500	z
Upper crust	6.00	3.45	2800	1000	3.1
Lower crust	6.70	3.90	2900	500	15.0

Note: The rightmost column shows the depth of the top surface of each layer. The spatial distribution of depth z corresponds to the bedrock geometry. r_1 and r_2 are constant values.

Waveform inversion

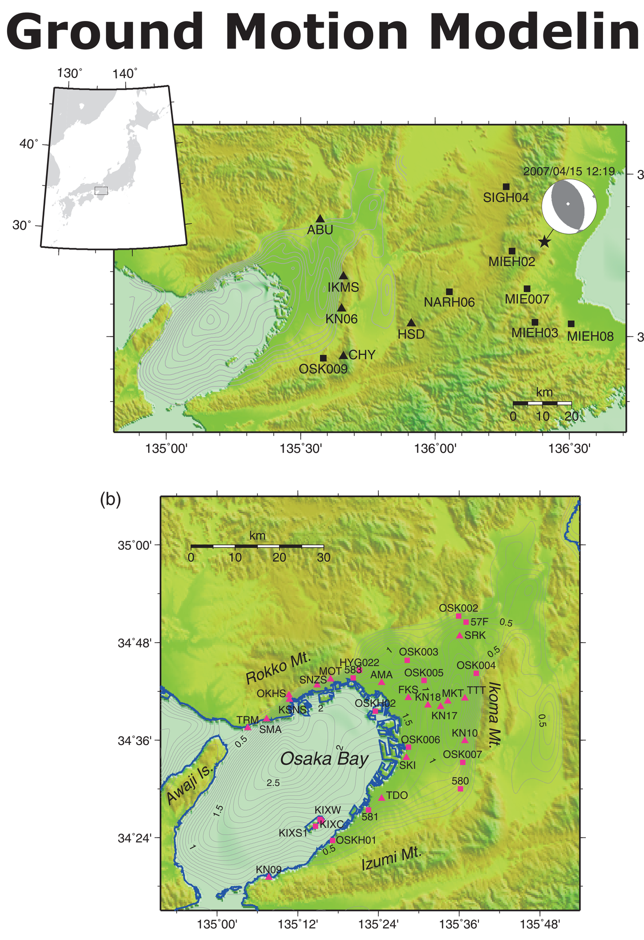
The observation equation to be solved is $\boldsymbol{u}(\boldsymbol{m}) \sim \boldsymbol{u}^{obs}$ where $\boldsymbol{m}$ is set of model parameters which discribe the geometry of the basin boundary. The bedrock geometry is described by a cubid B-spline function with 19 x 17 nodes with 4.5 ~ 9.0 variable intervals (see Fig. 6). We treat the spline coefficients at the nodes as the model parameters. We solve the linearized equation iteratively following the idea presented by Aoi (2002) until the waveform residual converges.

$$u_i(\boldsymbol{m}^l) + \sum_{k=1}^{K} \left.\frac{\partial u_i}{\partial m_k}\right|_{m=m^l} \delta m_k^l \simeq u_i^{obs} \quad (i = 1, 2, ..., N).$$

$$A_{ik} \equiv \partial u_i / \partial m_k^l = \left[u_i(\boldsymbol{m}^l + \Delta \boldsymbol{m}_k^l) - u_i(\boldsymbol{m}^l) \right] / \Delta m$$

$$\boldsymbol{m}^{l+1} = \boldsymbol{m}^l + \delta \boldsymbol{m}^l \qquad \text{residual} = \frac{1}{N} \sum_{i=1}^{N} \left[u_i^{obs} - u_i(\boldsymbol{m}) \right]^2$$

Ground Motion Modeling of Target Event



2007/04/15 M_w=5.0 depth~10km

The target event we chose is a moderate sized earthquake that occurred in Mie Prefecture, approximately 80-90 km to the east from the city of Osaka.

We model the ground motion by a 3D finite- difference method (Pitarka, 1999) in the period range 3 s and longer.

Velocity structure model : 3D basin model combined with a 1D crust model.

Source model : A point source is assumed. The depth, mechanism and source duration are estimated by fitting waveforms at the near-source rock stations.

Fig 2. (a) Map of the study area. Triangles (▲) indicate the location of rock stations used to constrain the source parameters. (b) Map of Osaka basin showing the stations inside the Osaka basin (▲). The contour lines denote the bedrock depth distribution of the initial model.

Waveforms at near-basin rock stations

The synthetic waveforms at the rock stations (outside the basin) show good fit with the observed waveforms.

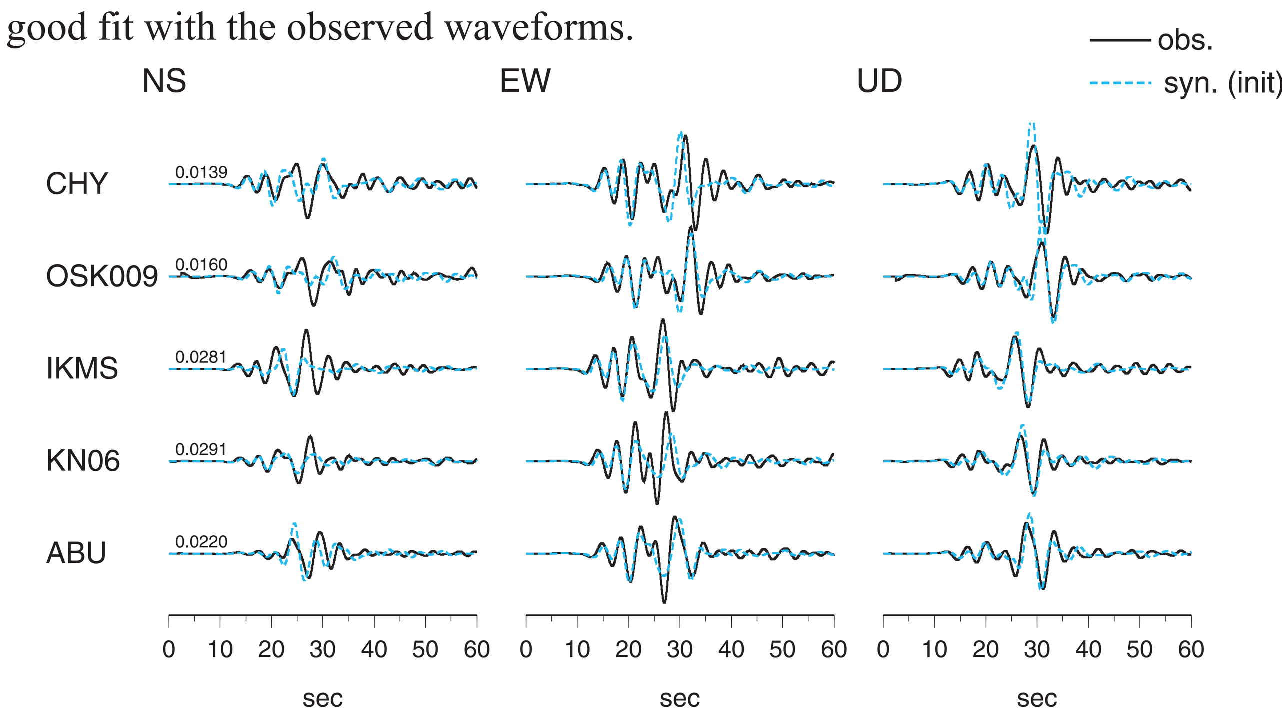


Fig 3. Comparison of **observed** and synthetic velocity waveforms at near-basin rock stations, All waveforms are bandpass filtered between 3 - 10 s.

Synthetic Tests

Validation of the method

Waveforms computed from a target model are treated as *"observed"* waveforms.

Waveform inversion was performed to see if we could recover the target model from the initial model. We used velocity waveforms (BPF 3-10 s) with time window from 12 s before to 25 s after S-wave onset. All synthetic waveforms are computed by a 3D finite-difference method by Pitarka (1999).

Results

Target model was almost perfectly recovered after 6 iterations (Fig.4).

The synthetic waveforms computed from the updated model after 6 iterations show good agreement with the target (or "observed") waveforms.

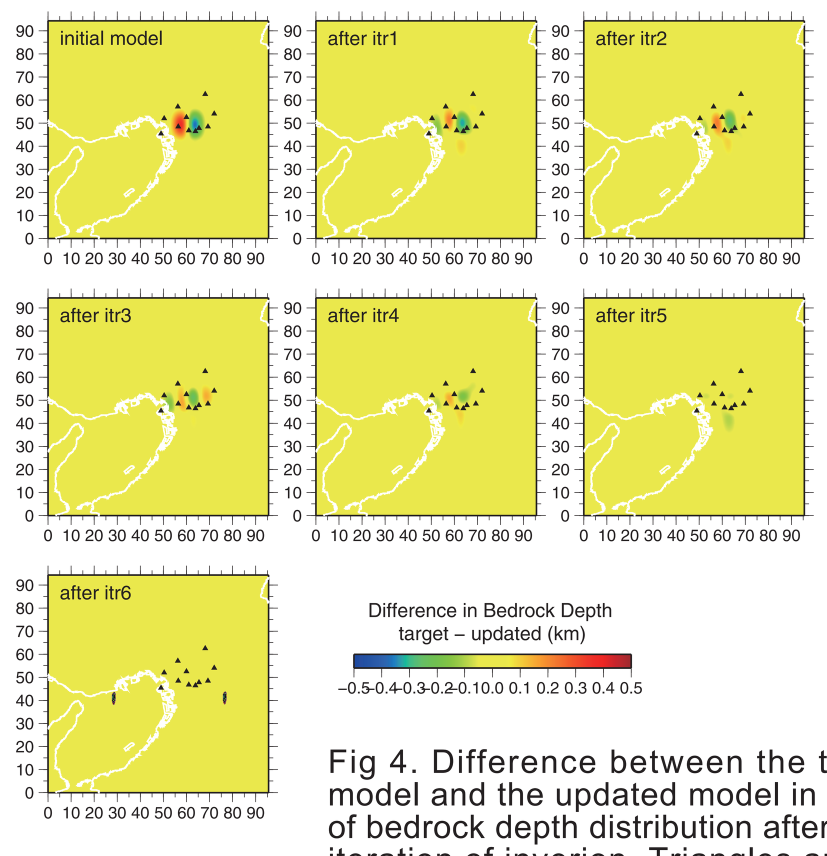


Fig 4. Difference between the target model and the updated model in terms of bedrock depth distribution after each iteration of inverion. Triangles are the stations used in the synthetic tests.

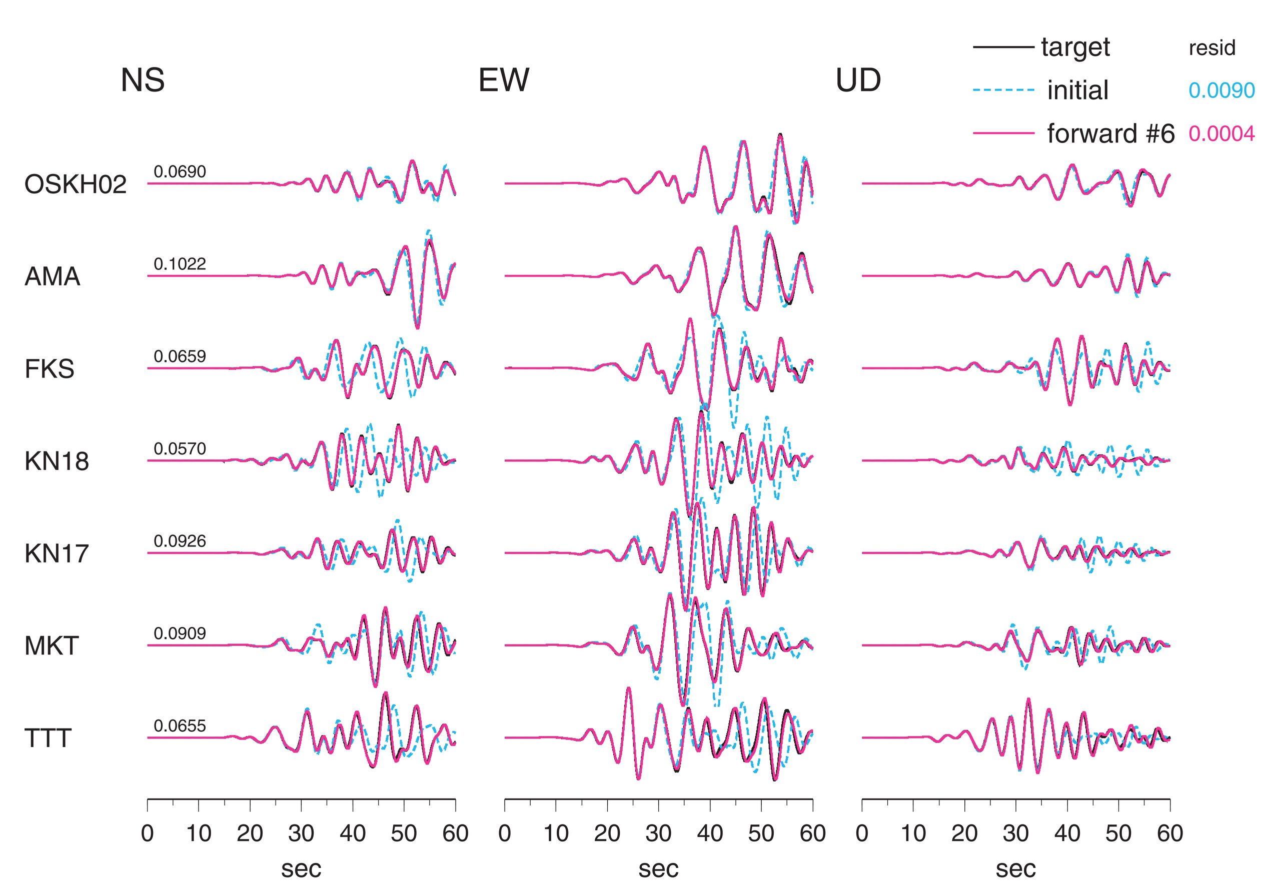


Fig 5. Comparison of the **target** waveforms and the synthetic velocity waveforms computed from the initial and updated models. The **target** and updated waveforms show good agreement.

Application to Real Data

Data: Velocity waveforms recorded at 23 stations inside the basin (Fig. 2b).

12 s before ~ 25 s after S-onset

BPF 3-10 s

Computation: 3D FDM (Pitarka, 1999)

minimum vertical grid spacing = 62.5m

Model parameters: Spline coefficients at 50 selected nodes that cover the main portion of the basin (Fig. 6).

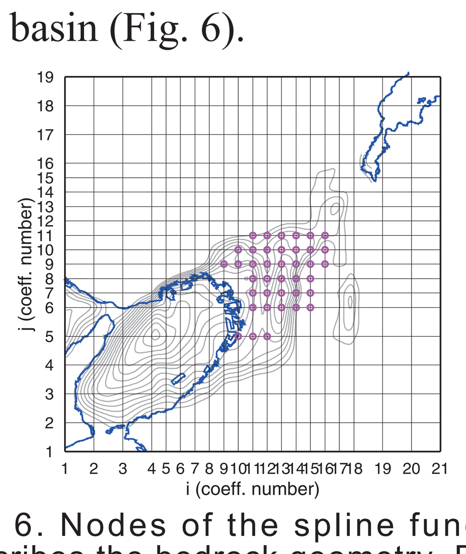


Fig 6. Nodes of the spline function that discribes the bedrock geometry. Red circles indicate the nodes used in the inversion.

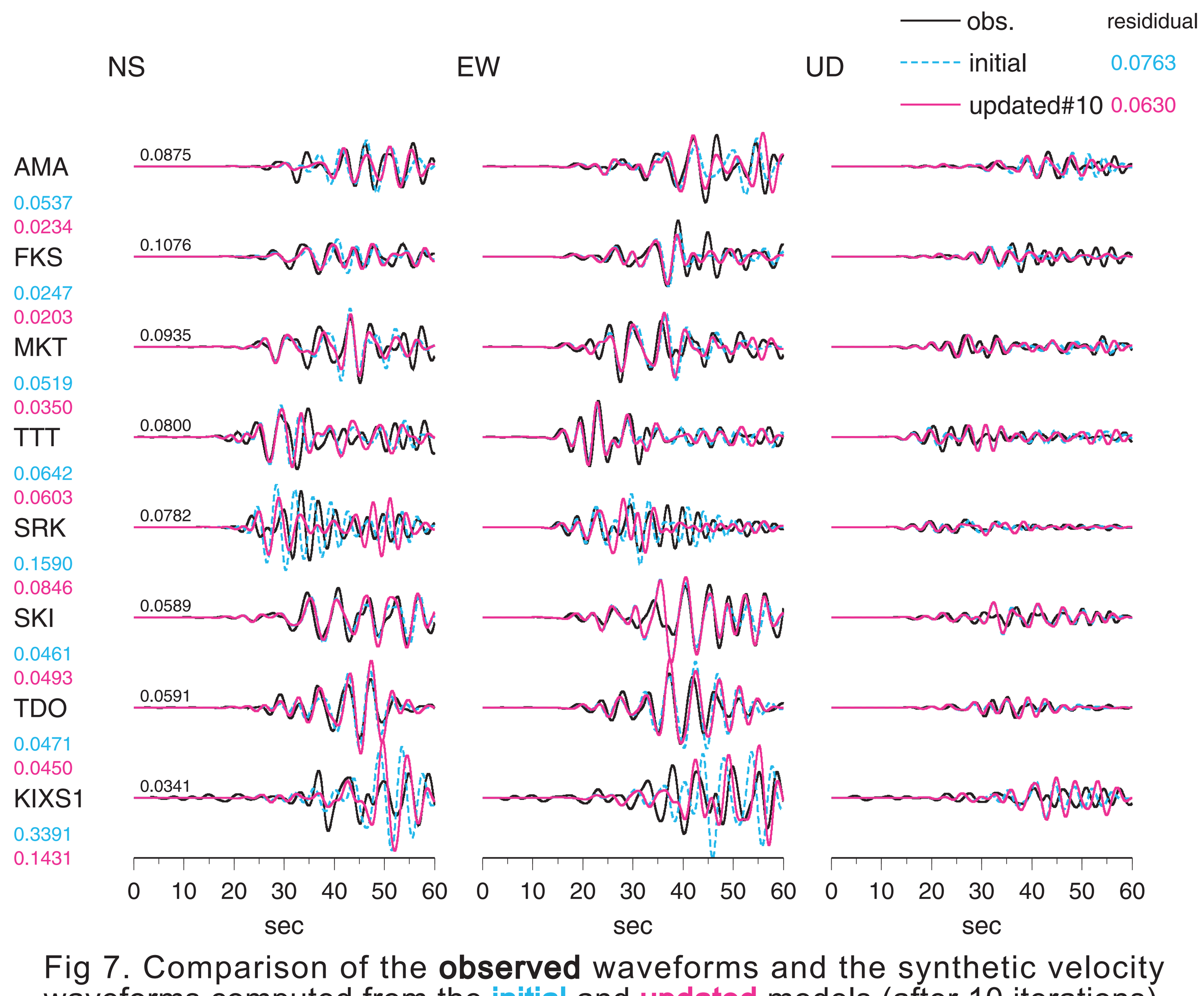


Fig 7. Comparison of the **observed** waveforms and the synthetic velocity waveforms computed from the initial and updated models (after 10 iterations). The numbers below the station names indicate the waveform residual.

Comparison with Deep Borehole Data

Inside the Osaka basin, there are a number of deep boreholes that reach to the bedrock (~1500m). The estimated model in our inversion are more consistent with the bedrock depth of the boreholes compared with the initial model.

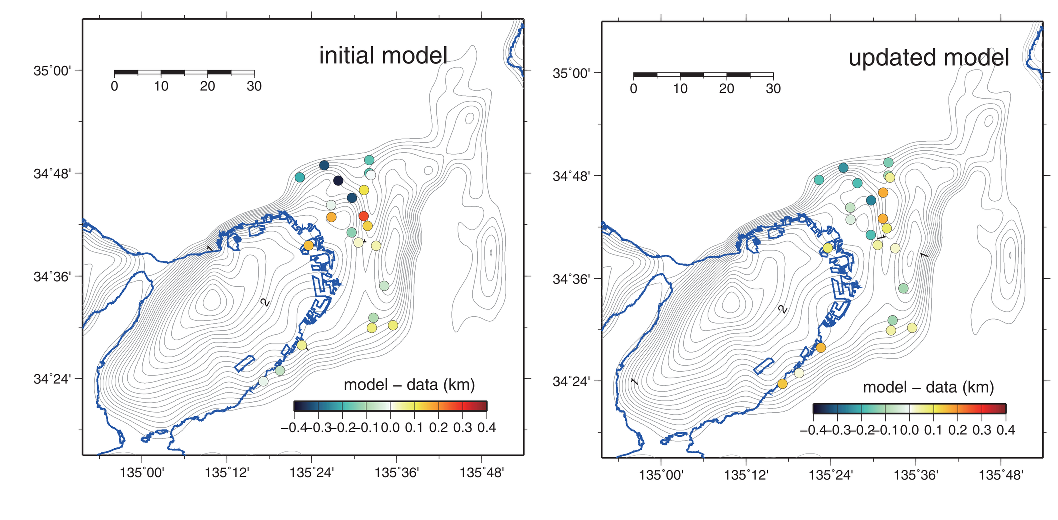


Fig 8. Comparison of the bedrock depth data at deep boring-digging points with that of the initial and updated models (after 10 iterations). Red color means the model is deeper than the data.

Conclusions

- We propose a method to estimate the boundary shape of a sedimentary basin by waveform inversion at the Osaka sedimentary basin as a test field.
- B-spline function is adopted as the basis function to discretize the bedrock geometry.
- The method is applied to real seismic data observed by dense strong motion observation networks in the basin during a M_w5.0 local earthquake.
- The estimated model is more consistent with the deep borehole data than the initial model in terms of bedrock depth at the boring points.

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References

Aoi, S. (2002). *Bull. Seism. Soc. Am.*, **92**, 2410-2418.

Iwata, T. *et al.* (2008). *J. Seismlogy*, **12**, 223-234.

Kagawa, T. *et al.* (2004). *Bull. Seism. Soc. Am.*, **94**, 1353-1368.

Pitarka, A. (1999). *Bull. Seism. Soc. Am.*, **89**, 54-68.