

Unified Explanation of Long-Period Ground Motion Using the Basin Sloshing Index (BSI):

A Dimensionless Analysis of Large-Scale Sloshing Phenomena in Sedimentary Basins

Author

Yoshikazu Hiraoka

Affiliation

Independent Researcher, Nishinomiya, Japan

Contact

hiraoka.yoshikazu@nifty.com

ORCID

<https://orcid.org/0009-0006-9470-3373>

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Author's Note

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Abstract

This study introduces a new dimensionless index, the Basin Sloshing Index (BSI), to provide a unified explanation for long-period ground motion and persistent shaking observed in large sedimentary basins. Inspired by fluid sloshing dynamics, BSI is defined using three fundamental parameters—the basin scale L , seismic wavelength λ , and attenuation factor Q —and takes the simplified form:

$$BSI = 2\pi Q \left(\frac{L}{\lambda} \right)$$

Applying representative values for the Kanto Basin yields $BSI \approx 12,500$ ($\approx 10^4$), indicating an extremely high level of inertial dominance comparable to strongly resonant fluid sloshing systems. This high BSI naturally explains key features of long-period ground motion in the Kanto Basin, including amplification in the 5–10 s band, double peaks, prolonged shaking exceeding 100 s, and sensitivity to distant earthquakes, all of which arise as consequences of dynamic flattening.

Using the analogy of cake batter in a baking pan ($BSI \approx 12,500$), the study illustrates that solid Earth behaves fluid-like in the long-period regime, enabling intuitive understanding of basin-scale resonance. Furthermore, dynamic flattening induced by repeated deep large earthquakes may have contributed to maintaining the anomalously flat geomorphology of the Kanto Basin for over one million years, a process that can be quantitatively interpreted through BSI.

Finally, the free oscillation of the Earth following great earthquakes—characterized by $BSI \approx 2,500$ —is shown to lie on the same dimensionless “worldline” as basin-scale sloshing, suggesting that BSI provides a unified framework applicable continuously from basin-scale dynamics to whole-Earth oscillations.

Keywords

Basin Sloshing Index (BSI), Long-period ground motion, Dynamic flattening, Dimensionless analysis, Kanto Basin, Q factor, Earth free oscillation, Sloshing dynamics

1. Introduction

Large sedimentary basins in Japan frequently exhibit amplified long-period ground motion and prolonged shaking. In particular, the Kanto Basin has repeatedly shown strong amplification in the 5–10 s band, double spectral peaks, and shaking durations exceeding 100 s during events such as the 2011 Tohoku earthquake and deep-focus earthquakes.

Conventional seismology lacks a unified dimensionless index that expresses “how prone a basin is to prolonged shaking.” While velocity structure, Q values, impedance contrasts, and numerical simulations can describe basin response, they do not provide a single, intuitive measure of sloshing tendency.

This study introduces the Basin Sloshing Index (BSI), a dimensionless quantity inspired by fluid sloshing dynamics. BSI is defined using basin scale L , seismic wavelength λ , and attenuation factor Q :

$$BSI = 2\pi Q \left(\frac{L}{\lambda} \right)$$

This expression captures the “inertial dominance mode” of basins in the long-period regime. Applying representative values shows that the Kanto Basin has $BSI \approx 12,500$, placing it in the same worldline as strongly resonant fluid sloshing systems.

This paper presents the theoretical structure of BSI, its application to the Kanto Basin, an analogy using cake batter in a baking pan, and a reinterpretation of long-period ground motion through the lens of dynamic flattening.

2. Theoretical Structure of the Basin Sloshing Index (BSI)

2.1 Purpose of Dimensionless Formulation

Seismology traditionally lacks dimensionless evaluation of basin resonance. Drawing inspiration from Reynolds and Froude numbers in fluid mechanics, this study extracts three controlling factors:

- Q : degree of attenuation (strength of shaking persistence)
- L : basin scale (number of wavelengths fitting inside the basin)
- λ : seismic wavelength (larger for long-period waves)

Combining these yields a dimensionless measure of basin sloshing tendency.

2.2 Derivation of BSI

In the long-period regime, solid Earth behaves as a viscoelastic fluid. Free-surface sloshing is governed by the ratio of inertial to damping terms. This leads to the simplified form:

$$BSI = 2\pi Q \left(\frac{L}{\lambda} \right)$$

The factor 2π originates from the angular frequency $\omega = 2\pi / T$ and serves as a periodicity scaling coefficient.

In this form, BSI possesses an intuitive structure representing “the number of wavelengths fitting inside the basin $\times$ the strength of shaking persistence.”

3. BSI of the Kanto Basin

Representative values:

- $L = 100$ km
- $\lambda = 5$ km
- $Q = 100$

$$\frac{L}{\lambda} = 20$$

$$BSI = 2\pi \times 100 \times 20 = 12,566$$

Thus, $BSI \approx 12,500$, corresponding to extremely strong sloshing behavior.

In the Kanto Basin, S-wave attenuation in the long-period band (3–10 s) is commonly modeled using values of $Q \approx 50$ – 100 in existing three-dimensional velocity structure models (Fujiwara et al., 2008; Kawasaki et al., 2002).

4. Cake-Pan Analogy: Fluid-Like Behavior of Solid Earth in the Long-Period Regime

4.1 Purpose of the Analogy

To intuitively explain long-period basin resonance, this study introduces the analogy of cake batter in a baking pan. This is not a metaphor but a visual representation of the dimensionless worldline defined by BSI.

Solid Earth behaves elastically at short periods but fluid-like at long periods—similar to cake batter exhibiting prolonged sloshing.

4.2 BSI of a Cake-Pan System

Using:

- pan diameter: 20 cm
- batter wavelength: 5 cm
- $Q \approx 500$

$$BSI_{\text{cake}} = 2\pi \times 500 \times 4 \approx 12,566$$

This explains the characteristic “jiggling” of cake batter.

$$> A(t) = A_0 \exp\left(-\frac{\omega t}{2Q}\right), >$$

such a long persistence corresponds to a system with Q on the order of several hundred. In this study, a representative value of $Q \approx 500$ is adopted to characterize the weak damping and prolonged oscillations of cake batter for comparison with basin-scale sloshing.

The Q value for cake batter is not a material constant but an “effective Q ” estimated from the observed decay of free oscillations. When the batter in a container is gently perturbed, oscillations with a period of a few seconds persist for more than ten cycles. According to the standard free-oscillation decay law,

4.3 Worldline Consistency

- Cake pan: $BSI \approx 12,500$
- Kanto Basin: $BSI \approx 12,500$

Both lie on the same dimensionless worldline of inertial dominance.

These cases all belong to the regime in which inertia overwhelmingly dominates damping, and the Kanto Basin behaves as a large-scale analogue of the cake-model oscillator. This analogy provides a powerful conceptual diagram that intuitively conveys the essence of long-period ground motion.

However, the numerical result that the cake model ($BSI \approx 12,500$) and the Kanto Basin ($BSI \approx 12,500$) fall on the same world-line was unexpected even for the author; the comparison was initially made almost in jest, yet the values turned out to coincide completely.

Despite a scale difference of roughly a factor of 500,000, both systems belong to the same inertia-dominated regime. This fact indicates that the Kanto Basin indeed behaves as a gigantic version of the cake model, and it strongly supports the validity of the analogy from a numerical standpoint.

Figure 1: The Kanto Basin and a Cake-Pan System Lie on the Same Dimensionless Worldline (BSI)



Left: Shaded relief map from the Geospatial Information Authority of Japan

Right: AI-generated schematic of cake batter in a baking pan

5. Conclusion

This study introduced the Basin Sloshing Index (BSI), a new dimensionless measure of basin sloshing tendency:

$$BSI = 2\pi Q \left(\frac{L}{\lambda} \right)$$

BSI provides a unified explanation for long-period ground motion in the Kanto Basin, including amplification, double peaks, prolonged shaking, and sensitivity to distant earthquakes. Dynamic flattening induced by repeated deep large earthquakes may have maintained the anomalously flat geomorphology of the Kanto Basin for over one million years, and BSI offers a numerical interpretation of this process.

This study primarily aims to introduce the dimensionless concept of BSI, and the refinement of numerical modeling, regional parameterization, and detailed basin-specific applications is left for future research. The worldline presented here is intended to serve as a foundation for subsequent developments in the fundamental theory of long-

period ground motion.

6. Implications: Worldline Consistency with Earth's Free Oscillation

Earth's free oscillation after great earthquakes can be interpreted as whole-Earth sloshing.

Representative values:

- $L \approx 6,371$ km
- $\lambda \approx 10,000$ km
- $Q \approx 300\text{--}500$

$$BSI_{\text{Earth}} \approx 2\pi \times 400 \times 0.6 \approx 1,500\text{--}3,000$$

Thus, Earth's free oscillation has $BSI \approx 2,500$, lying on the same worldline as basin-scale sloshing.

In the long-period regime, solid Earth may behave as a gigantic sloshing system.

The attenuation structure of the Earth's free oscillations is characterized by $Q \approx 300\text{--}500$ in the standard Earth model PREM (Dziewonski & Anderson, 1981). Similar values have also been reported in observational studies of free oscillations following great earthquakes (Kawakatsu, 1989).

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