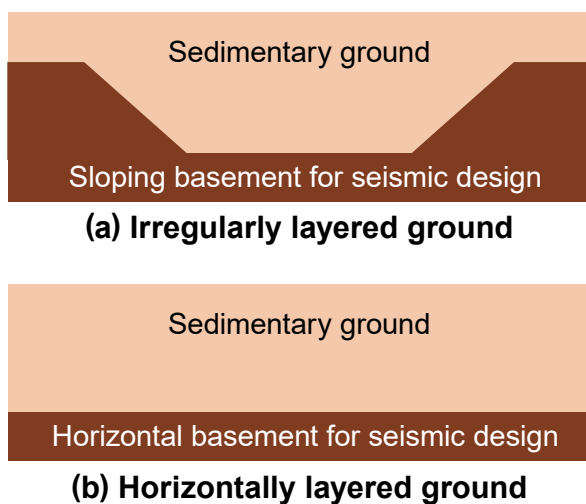


Seismic Stability of Railway Structures on Irregularly Layered Grounds

It is important to accurately understand the seismic behavior of the ground and structures to secure the seismic stability of railway systems. A ground formed on a hard, sloping basement layer is called an irregularly layered ground. On the ground with such a structure, seismic ground motion is likely to be locally amplified and may cause serious damage to railway systems. This paper describes how to accurately and efficiently detect the profile of irregular layered ground to secure the seismic safety of railway structures on an irregularly layered ground.



Mr. Yuki Sugiyama
Researcher,
Structural Dynamics and Response
Control, Center for Railway Earthquake
Engineering Research

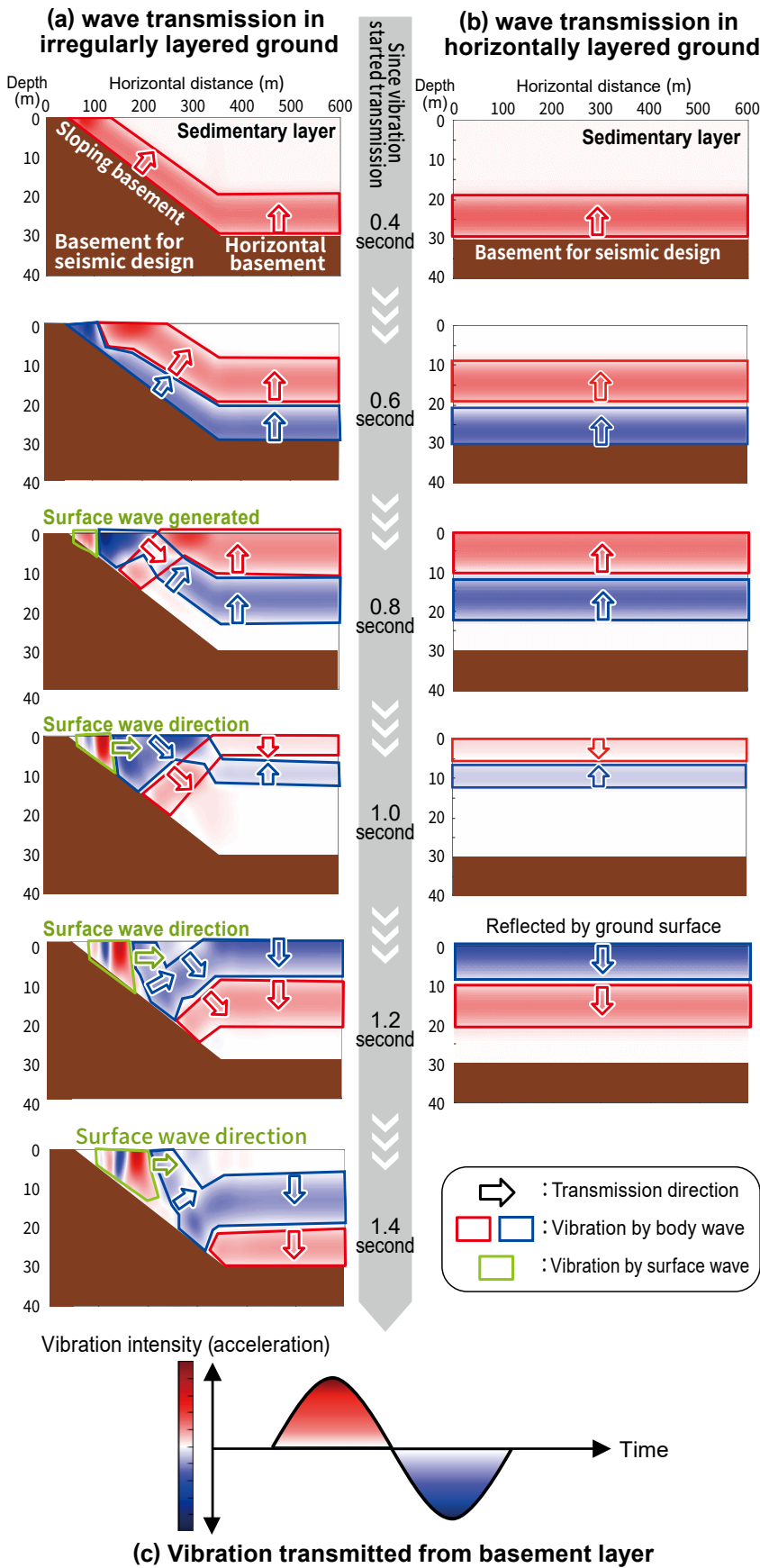


Irregularly layered ground and horizontally layered ground

Introduction

To design railway structures with high seismic stability, it is important to accurately understand seismic ground motion that occurs at construction sites. To achieve this, it is necessary to accurately detect the stratal organization, which significantly affects seismic ground motion.

At the point where the hard-subsurface basement layer (which is used as the basement for seismic design) inclines (*Irregularly layered ground and horizontally layered ground(a)*), ground motion is likely to be intensified, compared to that where the ground is horizontal, as shown in *Irregularly layered ground and horizontally layered ground (b)*. In earthquake engineering, such ground is called an “irregularly layered ground”. Because irregularly layered grounds are found in many areas in mountainous countries, such as Japan, buildings and structures need to be carefully designed for improved earthquake-resistant performance.



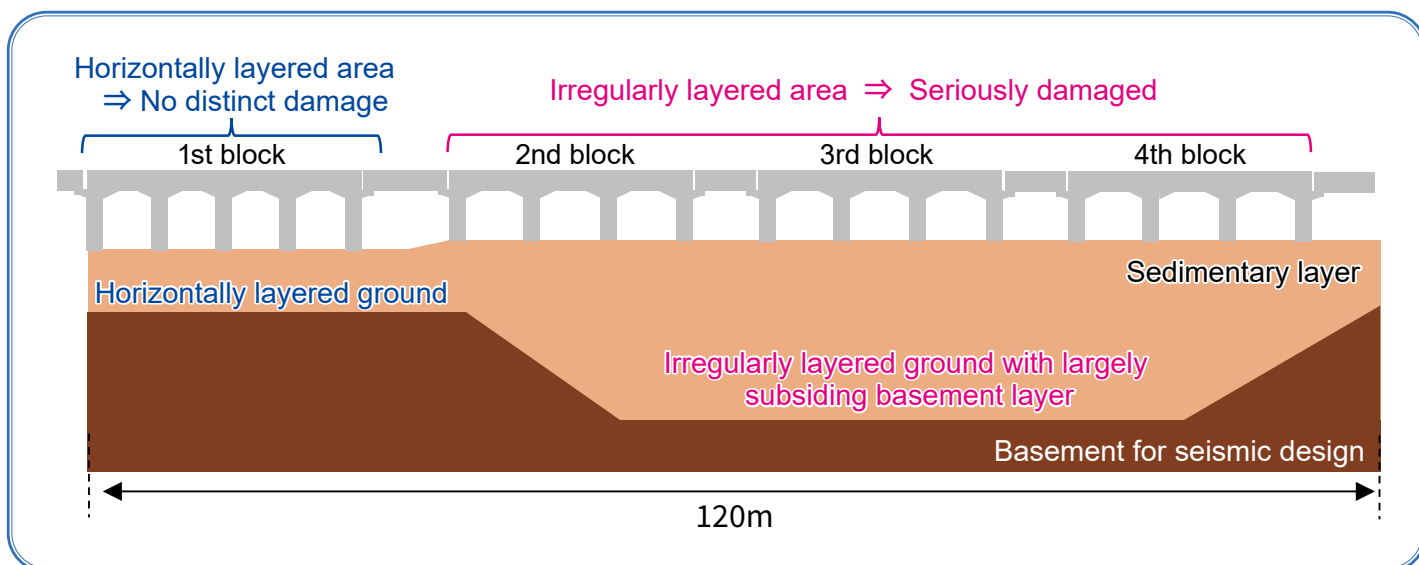
Vibration propagated through irregular subsurface structures

Simulation of wave travelling through irregularly layered ground and horizontally layered (a) and (b) shows how seismic waves travel through irregularly and horizontally layered grounds, respectively. Here, a simple sine wave, as shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (c)*, was applied from the lower part of the basement layer (depth:40 m) and wave propagation was simulated. In *Simulation of wave travelling through irregularly layered ground and horizontally layered (a) and (b)*, the seismic intensity of waves traveling through the ground is indicated by red and blue colors and their gradations.

In the horizontally layered ground shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (b)*, a horizontally stretched red-colored band appears at the lower part of the sedimentary layer, 0.4 s after the transmission started. This indicates that the waves travel through the layer in the upward direction. At this stage, the waves shown in blue were not yet transmitted into the sedimentary layer. At 0.8 s, the figure shows red and blue bands, and this indicates that all the waves shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (c)* are transmitted in the upward direction. Furthermore, at 1.2 s, the figure shows that positions of the red and blue bands were switched. This implies that upward waves are reflected at the ground surface and change their traveling direction downward. Waves that travel through the ground by repeating reflections are called body waves. *Simulation of wave travelling through irregularly layered ground and horizontally layered* shows the body waves represented by the red and blue boxes.

In the irregular subsurface structures shown in *Simulation of wave travelling*

Simulation of wave travelling through irregularly layered ground and horizontally layered



Damage to structures by local seismic amplification on irregularly layered ground

through irregularly layered ground and horizontally layered (a), the body waves travel through the sedimentary layer. However, on the left side of the ground, a slanted red band appeared along the sloping basement layer, and the body waves were transmitted in the upper diagonal direction. Body waves traveling in the diagonal direction were reflected by the ground surface earlier than those on the right-hand side of the horizontal layer ground. The body waves travel through the sedimentary layer in complicated patterns, including both upward and downward transmissions (from 0.8 s).

On the irregularly layered ground, waves are generated in 0.8 s, close to the ground surface, approximately 50–100 m from the left. These waves travel in the horizontal direction near the surface, differently from body waves, and they are called “surface waves”. At the irregularly layered ground, these surface waves are generated at boundary areas between the near-surface basement layer and the sedimentary layer. In *Simulation of wave travelling through irregularly layered ground and horizontally layered (a)*, the surface waves are shown by a green box. Surface waves travel along

the ground surface to horizontally layered sections depending on the angles of the sloping basement.

This simulation assumes that the shaking shown in *Simulation of wave travelling through irregularly layered ground and horizontally layered (c)* travels from the base. However, the shaking caused by actual earthquakes is more complicated, including different patterns of body and surface waves. Consequently, the body and surface waves overlap and sometimes cause intense waves in certain areas.

Damage to railway structures built on irregular subsurface structures

In Japan, earthquake damage to railway structures is caused by irregularly layered ground. In the offshore earthquake that took place near Chiba prefecture in 1987 (magnitude 6.7), the damage to railway structures was located on the irregularly layered ground, where the basement layer largely subsides (*Damage to structures by local seismic amplification on irregularly layered ground*). The damage was particularly serious in the 2nd to 4th blocks, which were located on the irregularly layered ground,

whereas distinct damage was not confirmed in the 1st block located on the horizontally layered ground. As shown in this case, even if they are located in approximately the same area, the extent of damage to structures may differ depending on the slope angles of the basement layer.

Irregularly layered-ground-detection method

The Railway Technical Research Institute (RTRI) has developed methods to calculate the seismic behavior of the ground and structures to improve the seismic stability of railway structures built on irregularly layered grounds. To apply such methods, we should understand the structures of irregular ground in advance. Thus, RTRI proposed the following method to easily and accurately survey irregular ground structures.

Usually, the depth of the basement layer is directly measured by conducting boring investigations. The boring investigation is normally conducted at 100–200-meter intervals as shown in *Ground survey method using microtremor measurements instead of boring exploration (b)*, but it does not determine the depths of the layers

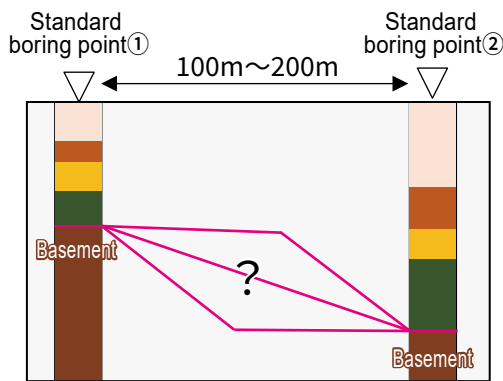
in between. If the results of the boring investigation indicate that the sediment structures of the area might be irregular, additional investigations should be conducted to understand the contour of the layer more accurately. Because additional boring investigations require considerable labor and cost, there are limits to conducting these additional investigations.

For this reason, RTRI developed a survey method using a small-sized portable device for microtremor measurements. The depth of the basement layer directly beneath

the device can be estimated by placing this device on the ground surface for approximately 30 min and measuring the microtremor, as shown in *Ground survey method using microtremor measurements instead of boring exploration (d)*.

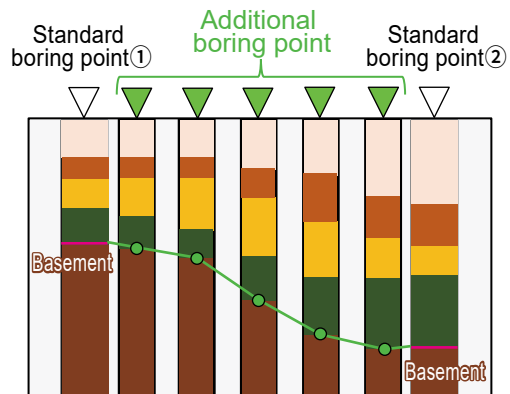
As shown in *Survey of basement profile with microtremor measurements (a)*, microtremors include waves with various periods and amplitudes. By analyzing the microtremor through spectrum analysis, the relationships between the amplitudes and periods were obtained. As indicated

in *Survey of basement profile with microtremor measurements (b)*, the results of the spectral analysis at two different points on irregularly layered ground show different peak periods that depend on the depth of the basement layer. RTRI conducted microtremor measurements and numerical simulations in many areas on an irregularly layered ground and determined the relationship between the basement depth difference and the peak period difference of two points (*Survey of basement profile with microtremor*



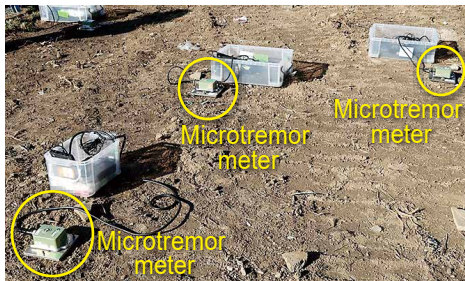
Possibility of sloping basement layer

(a) Standard boring



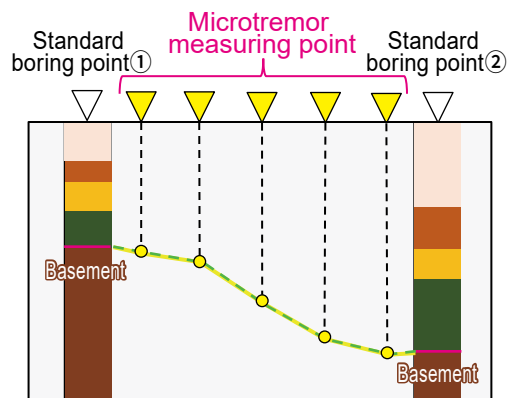
High-density additional boring desirable

(b) Survey of possible irregularly layered ground



Microtremor is measured at ground surface

(c) Microtremor measurements with microtremor meter



Basement depth can be measured without boring

(d) Survey of basement profile with microtremor measurements

Ground survey method using microtremor measurements instead of boring exploration

measurements(c)). Applying this relationship to survey data, the profiles of irregularly layered ground can be accurately understood by measuring microtremors at several points between boring points.

Conclusion

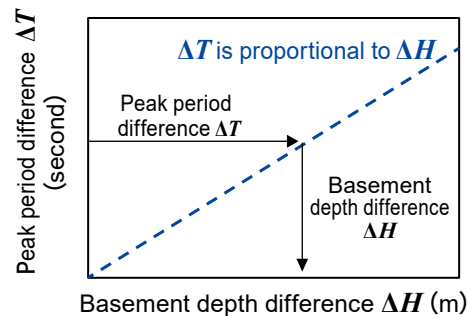
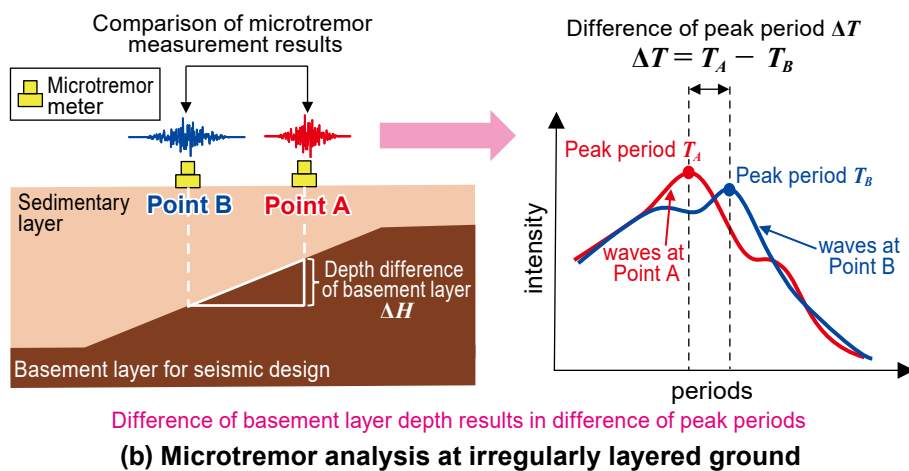
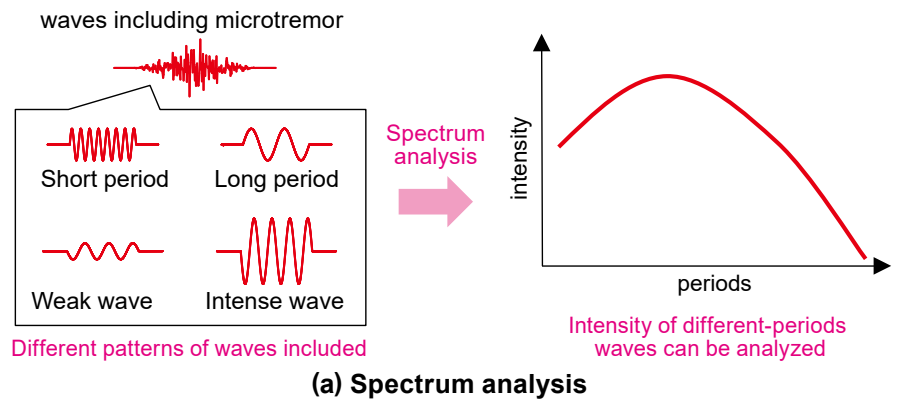
This paper describes seismic ground motion on irregularly layered grounds and the profiles of such irregular grounds, which is one of RTRI's research projects conducted to secure the seismic stability of railway structures. Through this method, the intensity of shaking on irregular grounds can be calculated more easily and accurately, and safer structural designs are possible.

Boring investigation

A survey method was used to measure the ground structure conditions and depth of the basement layers used for seismic design. The data, including soil strength, were obtained from soil samples collected at a depth of 1 m in holes that were vertically drilled at the survey points.

Microtremor

Microwaves are caused by a variety of movements, such as natural phenomena including ocean waves, winds, and human activities, including automobile running. In contrast to earthquakes, microtremors can be measured at any time.



Survey of basement profile with microtremor measurements

References

- 1) Takashi Kikuri, Yoshitaka Murono, Shinji Nagatsuma, Akihiko Nishimura: "The Impact of Local Geographical Conditions on the Damage to Railway Structure", Proceedings of the 24th Earthquake Engineering Research Seminar, 1997
- 2) Railway Technical Research Institute: "Design Standards for Railway Structures and their Details, Seismic Design", Maruzen Publishing Co., Ltd., 2012
- 3) Taro Ishikawa, Kimitoshi Sakai, Yoshitaka Murono, Takahiko Nishi, Daisuke Soga, Hiroki Aoyagi: "Correction of Nonlinear Response Spectra Based on Random Vibration Theory at Geologically Irregular Soil Ground", Proceedings of Railway Engineering Symposium, Vol.23, pp.171-178, 2019
- 4) Kohei Tanaka, Kimitoshi Sakai, Kahori Iiyama, Hitoshi Morikawa: "Estimation Method for The Shape of Engineering Bedrock Using The Vertical Fourier Spectrum by Microtremor Observations", Proceedings of the Japan Society of Civil Engineers A1, Vol.77, No.1, pp.219-228, 2021