Geotechnical, Geological and Earthquake Engineering

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Preface

Earthquake resistant design is an important consideration for designing structures in seismic prone areas including Japan. Recently, following the developments in seismology and earthquake engineering, design earthquake motion is defined at the engineering seismic base layer (engineering bedrock) or the seismic bedrock regardless of the structural type and the ground type. Therefore, in order to get the design earthquake motion at the ground surface or at the foundation of a structure, engineers need to make a seismic ground response analysis.

I graduated from the Department of Architecture and Architectural Engineering, Kyoto University (Japan), and my thesis for doctor of engineering was cyclic behavior of steel braces subjected to earthquake loading. Several years after my post-doctoral life in the university, I joined Sato Kogyo, a general contractor firm, and I engaged in the design of the RCWS (reactor cooling water system) of a nuclear power plant. There, I faced a problem on how to consider the liquefaction of the crushed rock that was used to fill the excavated area during construction just neighboring the grit chamber. I visited Prof. Ishihara, University of Tokyo, to get an idea. He introduced a computer program YUSAYUSA and I engaged to improve it with him, which is now open for public from my website (Yoshida and Towhata 1991), and it was my first technical paper in this field. Soon after, Prof. Ishihara introduced me to Prof. Finn, University of British Columbia, Canada, and I got a chance to stay with him for 1 year. I engaged to develop the computer code TARA-3 (Finn et al. 1986). After coming back to Japan, I decided to change my research topic from structure to geotechnics, especially earthquake geotechnical engineering.

There were many differences between the structure and the soil as engineering materials and I was sometimes overwhelmed by these differences. Why, for example, stress-strain curve is expressed by, so-called, G-γ and h-γ relationships, and why just an approximated method is called an equivalent linear method, etc. Modeling the stress-strain behaviour was not a big issue in structural engineering, but it was a big issue in the new field. The error of the analysis was very large compared with the one in my former field. Things that are believed to be common sense looked curious to me. So, it was a new world for me and I believed that I could contribute something in this field, which is the reason why I decided to move to the earthquake geotechnical engineering.

I started as an academician in the university several years ago quitting my second practical engineering job in Oyo Corporation, a consulting company. I was surprised that there is no time to teach the seismic ground response analysis in the syllabus. There are many topics that should be taught in the university, but time is limited. Seismic ground response analysis is a difficult issue because all other issues taught are necessary in order to understand the behavior during an earthquake.

On the other hand, seismic ground response analysis is an essential tool for the practical engineers. Then I had a question how they study this subject. Just that time, I was asked a lecture titled "seismic ground response analysis for practical use" from Prof. Wakamatsu, Kanto Gakuin University, who was a board member of the Japan Association for Earthquake Engineering (JAEE). Fortunately, the lecture was successful such that the JAEE turned away many people as the room became full. Then I understood that practical knowledge is desired from the practical engineer.

I published a book in Japanese in 2010 (Yoshida 2010) on the seismic ground response analysis based on this lecture. There are already many books on this subject. I feel, however, that there is no book that gives the knowledge or techniques required by the engineering practice or that the engineer can refer in their daily job. Many books deal with only the theoretical field, but there are many issues that cannot be discussed only by theory. So I especially focused on these topics. Soon after the publication of the Japanese book, Prof. Ansal and Dr. Tönük, Bogazici University, Turkey, suggested me to write an English version of this book. I omitted many theoretical descriptions in the Japanese version, but I think it would be better to add some theoretical parts for the foreign readers, which was also a suggestion by Dr. Tönük. So this is quite a new book.

This book deals with the total stress analysis, and the effective stress analysis or the liquefaction analysis is not considered partly because the effective stress analysis is more difficult compared with the total stress analysis and partly because another volume may be required to write the introductory part of the liquefaction analysis.

The author wishes sincere thanks to Prof. Wakamatsu who gave a chance to publish the Japanese book, and Prof. Ansal and Dr. Tönük who suggested the English version. Thanks are extended to Drs. Ohya, Port and Airport Research Institute, and Dr. Miura, Oyo cooperation, for their pre-reading of the Japanese version. Thanks are also extended to Dr. Tönük and Prof. Bhattacharya, University of Surry, UK, who checked my English.

Notes for Reading This Book

This book follows SI unit system (Promotion committee of SI unit 1999). In other words, kN, m, and s are used for force, length, and time, respectively. Unit for pressure is expressed by kPa instead of kN/m^2. In the field of seismology, Gal

(gal) has been used for acceleration, but it is not used in this book although it is possible as exceptional treatment. In the same manner, kine has been frequently used for velocity, but is not used in the book, either, because it is a non-SI unit. When converting the old unit system into the SI units, acceleration of gravity g is usually taken as 9.8 m/s^2, but 10 m/s^2 can also be used. Error of 2 % appears by this interpolation, but it is an acceptable error in many fields of engineering.

All the figures and equations are given using the SI unit. In the field of the geotechnical engineering, many empirical equations have been developed, and they are usually valid only in the specified unit. They are also rewritten in the SI unit system in this book.

Recently, information and data are published not only in the technical paper but also in the website. Here, unlike the technical paper, contents of the web are sometimes revised or erased, in which case the reader cannot find the data. In this book, the valid date of the existing website is shown in brackets [ ].

Abbreviations are used for several Japanese organizations which appear frequently in this book. They are as follows

AIJ: Architectural Institute of Japan
JAEE: Japan Association for Earthquake Engineering
JGS: Japanese Geotechnical Society
JSCE: Japan Society of Civil Engineering
JSSMFE: Japan Society of Soil Mechanics and Foundation Engineering, renamed JGS in 1995
PARI: Port and Airport Research Institute
PWRI: Public Work Research Institute

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Contents

Chapter 1
Propagation of Earthquake Waves in the Ground and Fundamentals of Earthquake Motion

Fundamental knowledge on the amplification and the attenuation of the earthquake waves, which is necessary to understand the wave propagation in the ground, is introduced in this chapter.

1.1 Wave Propagation from Source to the Site

An earthquake occurs at a fault, and the earthquake waves propagate from the fault to the site that an engineer is interested in. Paths that the earthquake waves propagate are schematically shown in Fig. 1.1. Several important features should be noted in this figure. Firstly, the path is separated into three regions. Secondly, there are two types of waves called body wave and surface wave. Finally, the path of the body wave is not linear but curves.

Waveforms of the surface and the body waves are schematically shown in Fig. 1.2 with traces of soil particle for the surface wave case. Concerning the earthquake resistant design, body wave is the most important one, which is again classified into two types of waves termed as P-wave and S-wave.

P-wave is the wave that arrives first at a site; the name "P" indicates primary. As the direction of the propagation and the direction of vibration are parallel, the P-wave is sometimes called as longitudinal wave. Since the density of the medium varies with the propagation, it is also called a compression wave or a compressional wave.

The "S" of S-wave indicates secondary, which means that S-wave arrives at a site secondly after the P-wave arrival. Since the direction of the wave propagation and the direction of the vibration are perpendicular to each other, it is also called as transverse wave. In addition, since it causes shear deformation in the medium, it is also termed as shear wave. When the soil particle vibrates in the plane of the wave

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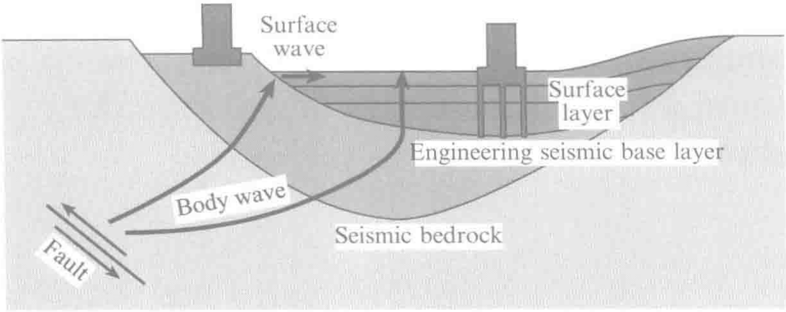

Fig. 1.1 Propagation of earthquake wave

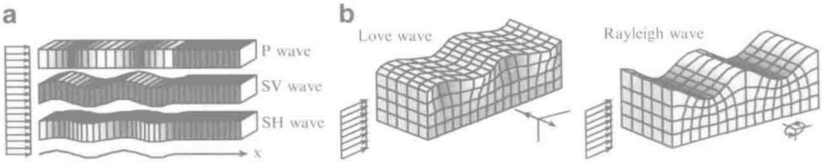

Fig. 1.2 Types of earthquake waves. (**a**) Body waves. (**b**) Surface wave

propagation, the S-wave is called as SV wave, and it is called SH wave when the soil particle vibrates out of the plane. Distinction between two waves is not necessary in the one-dimensional analyses although it is frequently called as SH wave. The SV waves are treated in the ordinary two-dimensional analysis.

As described in the next section (Sect. 1.1.2), earthquake wave propagates vertically when it is close to the ground surface. Consequently, the P-wave creates up–down or vertical vibration, and the S-wave causes horizontal vibration. Among these two body waves, the S-wave is the important wave in the earthquake resistant design. Therefore, almost all the content of this book deals with the S-wave; when a term "wave" appears, it refers to the S-wave. If the boundaries between any two layers are not perfectly perpendicular to the direction of the wave propagation, both P- and S-waves are refracted even though the incident wave is either P- or S-wave. These waves are called as PS or SP converted waves. Additionally, perfectly vertical wave propagation is just an approximation to observed wave phenomena. Therefore, vertical motion cannot be considered to be caused only by the P-wave and in exact sense horizontal motion only by the S-wave. However, it is also true that predominant horizontal motion is caused by the S-wave and vice versa. Therefore, for simplicity, the earthquake wave is assumed to propagate in the vertical direction, and the horizontal motion is caused only by the S-wave through this book.

A surface wave is generated by the interference of body waves radiated from the fault with a free surface. As schematically shown in Fig. 1.1, it is usually generated at an edge of a basin and propagates in the horizontal direction. The name "surface wave" is because it propagates along the ground surface. Similar to the difference between SH and SV waves, there are two kinds of a surface wave. The one vibrates perpendicular to the plane of wave propagation and is called as Love wave, and the other one that vibrates in the plane of wave propagation is called as Rayleigh wave. Wave amplitude of a surface wave is largest at the ground surface and attenuates quickly with depth. Surface waves have another characteristic called dispersion, i.e., wave velocity depends on frequency. Amplitude of the wave is large, but at the same time, wavelength is long. Therefore, acceleration due to surface waves is not significantly considered in the design of ordinary structures. However, in the design of the underground lineal structures, it should be considered because of its large displacement (Committee of gas facility standard 2000). In addition, surface waves travel long distances because of their long wavelengths and may affect ultra-tall structures that have long natural periods. For example, ultra-tall buildings in Tokyo vibrated and were damaged during the 1983 Nihonkai-chubu earthquake (Kinoshita and Ohtake 2000) (epicentral distance is about 450 km) and during the 1984 Nagano-ken-seibu earthquake (Editorial committee of records of Nagano-ken-seibu earthquake 1986) (epicentral distance of about 200 km). Similar phenomena were also reported in Tokyo during the 2000 Tottoriken-seibu earthquake (epicentral distance is about 580 km) and 2003 off Miyagi earthquake (epicentral distance is about 350 km). Likewise, the cause of the oil tank fire at Tomakomai, which is about 200 km far from the epicenter of the 2003 Tokachi-oki earthquake, is resonance due to the long period wave (JSCE Earthquake Committee 2003). Therefore, they require consideration in the earthquake resistant design, but this is not a subject in this book partly because it is not considered in the current design specifications and partly because the analysis is very difficult for practicing engineers.

1.1.1 Path of Wave Propagation and Analysis Region

It is a complicated problem to analyze the whole region shown in Fig. 1.1, i.e., from fault to site, in a single analysis. The problem is not easy partly because computer power is still not sufficient enough and partly because soil data in whole region is not sufficient. This whole region is divided into three subregions by setting two base layers which are called the seismic bedrock and the engineering seismic base layer. The latter is the generally used concept in Japan, but may not be common outside Japan although similar concept is used as explained in Sect. 3.1.

Seismic bedrock is widely known as the base layer. Two following concepts are introduced regarding the definition of seismic bedrock (Toki 1981):

1. Layer that behaves individually regardless of local site structure
   This definition indicates that the local site conditions have to be excluded in the definition of bedrock as the local site condition affects the earthquake motion at

the ground surface significantly. The seismic bedrock in this definition should satisfy the following two conditions:

(a) The seismic bedrock spreads in certain extent, and mechanical properties in this layer are homogeneous.
(b) Variation of mechanical properties and structure of the layers below the seismic bedrock is minor than those above it.

2. The shallowest layer that can reflect the earthquake motion characteristics at the fault in the earthquake resistant design of structures

This definition comes from the structural design point of view and indicates that the base depth is selected providing that the thickness of the superficial layers is sufficient if the natural period above the base is a little longer than the natural period of structures.

The earthquake motion observed at the interested site $R(t)$, as a function of time t, can be evaluated from the occurrence $Q(t)$ at the source (fault), behavior $P(t)$ from source to the bedrock, and amplification characteristics $G(t)$ from bedrock to the ground surface (AIJ 1987) as

$$R(t) = Q(t) \otimes P(t) \otimes G(t) \tag{1.1}$$

where $\otimes$ indicates convolution. Here, $G(t)$ is separated into two parts as shown in Fig. 1.1, i.e., a path from the seismic bedrock to the engineering seismic base layer and a path above it. It is noted that Eq. (1.1) holds when there is no interaction between each part. In other words, earthquake motion is assumed as propagating in one way from seismic bedrock to the engineering seismic base layers, and reflected wave from the surface layer does not alter the incident wave to the surface layer. This definition is compatible with the first definition of the seismic bedrock described above. It is, however, noted that this assumption does not always hold (Yoshida et al. 2005), which will be discussed in Sect. 15.8.

It is necessary to understand the general feature of the S-wave velocity structure in order to understand the earthquake wave propagation. Earthquakes occur at a fault in the earth crust above the upper mantle. The representative value of the S-wave velocity is about 3.5 km/s in the upper earth crust (Kinoshita and Ohtake 2000). The seismic bedrock is mainly composed of granite for which the S-wave velocity is about 3 km/s (Irikura 1978). The S-wave velocity of the engineering seismic base layer is defined to be between 300 and 700 m/s in Japan and will be explained in detail in Sect. 3.1.

The S-wave velocity decreases in the superficial layers. It is about 100 m/s in the soft soil sites in the urban area. Since man activities densify the subsurface layers, 100 m/s may be the minimum value in the urban area, but it can have much smaller values in the country or undeveloped areas. In general, S-wave velocity becomes smaller as the depth becomes shallower partly because the soil is consolidated and solidified more at greater depths and partly because the elastic modulus as well as the wave velocity depends on the confining stress.

Although both density and wave velocity are necessary in discussing the wave propagation characteristics, bedrock is defined only by the wave velocity since the densities of the rock and soil are similar to each other, of the order of 2 t/m^3.

1.1.2 Path of Body Wave Propagation

One of the important features shown in Fig. 1.1 is that the path from the fault to the site is not straight but curved. This behavior is strongly related to the aforementioned wave velocity structure.

A boundary between two layers with different S-wave velocities V_1 and V_2 is schematically shown in Fig. 1.3a. Snell's law indicates the relationship between the incident angle θ_1 and the refraction angle θ_2 as follows:

$$\frac{\sin \theta_2}{\sin \theta_1} = \frac{V_2}{V_1} \tag{1.2}$$

This law can be applied not only to the earthquake waves but also to other waves such as sea waves and lights. As a comprehensive example, let us consider the situation shown in Fig. 1.3b. You are sitting at point A in the shore and see a drowning person at B in the sea. The problem here is that which path is the fastest to arrive at. A straight line AB is not an optimal path because distance in the sea (very low speed) is longest. Although the distance in the sea is shortest in the rectangular path ACB, distance in the shore is the longest. Therefore this path is again not an optimal path. The optimal path ADB lies between these two ultimate paths, and it can be found from Eq. (1.2).

Change of the refracted angle evaluated from Eq. (1.2) is shown in Fig. 1.4 by two different expressions. For example, setting $V_1 = 3{,}000$ m/s (seismic bedrock), $V_2 = 150$ m/s (soft ground), and $\theta_1 = 45°$, refracted angle is computed as $\theta_2 = 2°$, which indicates that the wave propagates nearly in the vertical direction. This can be demonstrated again by adapting to sea waves.

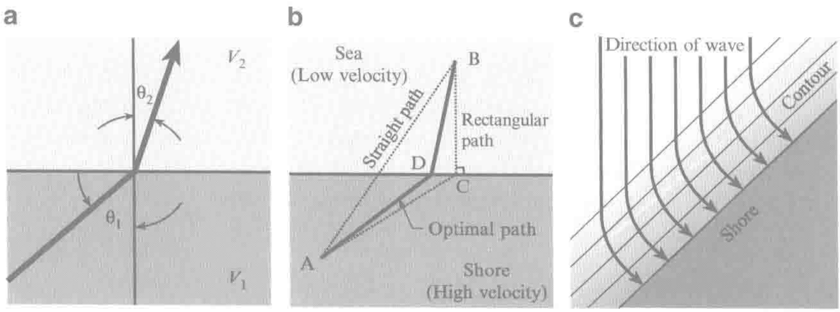

Fig. 1.3 Refraction of waves. (**a**) Refraction of wave. (**b**) Action near shore. (**c**) Sea waves at shore

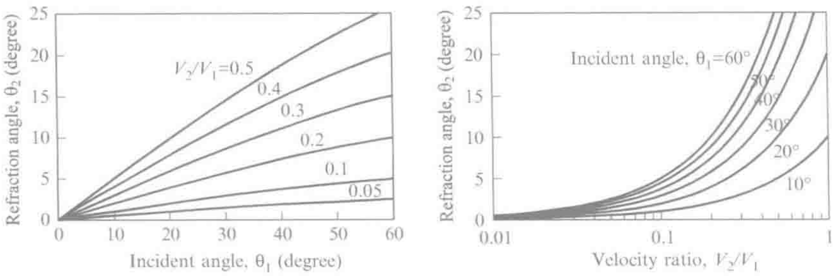

Fig. 1.4 Incident angle vs. refraction angle

When you see sea waves coming toward you on the shore, you feel that the wave front is parallel to the shore line. According to the wave theory, the wave velocity is obtained by $\sqrt{gh}$ where g is the acceleration of gravity and h is the depth of the seabed; wave velocity becomes smaller as closer to the shore. Therefore, as shown in Fig. 1.3c, the path curves are perpendicular to the shore when the waves come close to the shore since equi-depth contours are parallel to the shore. As a conclusion, phenomena that earthquake waves propagate in vertical direction as they approach the surface and that sea waves travel perpendicular to the shore are the same mechanism.

1.2 Amplification of Earthquake Wave

There are significantly different wave propagation characteristics between the path from the fault to the seismic bedrock and the path from the engineering seismic base layer to the ground surface. The wave radiates in all directions in the former case, whereas it propagates in one direction in the latter case.

When the wave radiates in all directions, the amplitude becomes smaller as the wave front expands, while the distance from the fault increases. This phenomenon is known as attenuation of the earthquake waves, and an example is shown in Fig. 1.5. Here PGA and PGV in the ordinate denote the peak ground acceleration and velocity, respectively.

On the other hand, attenuation of this kind does not occur when the wave propagates in one direction, but different mechanisms work and as a result amplification and/or attenuation (deamplification) occurs. The mechanisms that cause amplification are explained in this section, and the rest is shown in the next section. There are four mechanisms that amplify the earthquake wave.

1.2.1 First Mechanism: Change of Wave Velocity

Let us consider the sea wave case again to understand this mechanism. When the sea wave propagates toward the shore, wave velocity becomes smaller as explained