ENVIRONMENTAL VIBRATION

Prediction, Monitoring and Evaluation

CHEN Yunmin, TAKEMIYA Hirokazu, Editors

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Preface

Since last couple of decades, high-speed trains, widely known as Shikansen in Japan, TGV in France and ICE in Germany, have been developed and established commercially, commuting passengers at the speed of 300 km/hr between distant places in these countries. Korea, Taiwan, and some other countries/districts in the Pacific Rim are now catching up with the high-speed rail revolution. Furthermore, The maglev system is currently operated to cover short-distance transportation, and is commercially opened for the Shanghai airport transit in China, heralding an exciting new phase in the evolution of surface transport system.

Amid of this transport revolution, there is a pubic demand and awareness for the technological development in harmony with the ecology. The 21st century is extremely sensitive for the increased global and national concerns over the environmental issues. Increasing train speed is normally accompanied by rising in the levels of noise and vibration that may cause significant detrimental effect to the ecology. Natural sustenance mechanism may have irreparable damage due to predominance of the noise and vibration causing elements. Hence the statistical recurrence formulae based on the previous trains fail to predict the future influence of high-speed train operation. In spite of the vibrations induced by train and road traffic, other artificial vibrations from industrial or construction works may also give rise to some detrimental effects on the adjoining ecology. As a result, residents may suffer from uncomfortable vibration and high-precision machines may suffer from malfunctioning. These are now called environmental vibrations and are becoming of special concern in the civil and environmental engineering.

Prediction of traffic-induced vibrations is one of the important themes under the research category of dynamic soil-structure interaction, resultant of the moving axle loads accompanied by some harmonic frequencies. Track-ground interaction generates vibration emission to propagate toward some extent, inducing structure borne vibration as well as ground borne vibration. Therefore, the comprehensive treatment is needed for vibration prediction. Evaluation of vibration should be made in view of the specification regulated by the human perception and machine performance.

In the case that the vibration levels are exceeding the deterministic allowable limits, some countermeasure is necessary. Hence, developing effective vibration countermeasures is of vital importance. We have used trenches and walls so long for screening incoming vibrations to protect existing structures in built-in area from exposure to it. Those barriers near the source are categorized as "active", those around structures to be protected as "passive", and those between as "on wave field". Besides the traditional barriers, some innovative measures should be developed, expecting a definitive breakthrough for vibration mitigation.

In this International Seminar, we received 45 papers covering the fundamental problems of wave propagation in soils, simulation methods for dynamic soil-structure interaction systems, ground and structure vibration analysis, evaluation and mitigation of vibrations, case studies and field monitoring and other related topics on environmental vibrations. We will have a forum to exchange views among academicians and technocrats, sharing the knowledge and collaborating through communication. This International Seminar would definitely be a step forward to a new state-of-the-art and state-of-the-practice in the environmentally conscious community of the 21st century.

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Table of contents

Chapter 6 Others

Chapter 1　Fundamental problems of wave propagation in soils

FORWARD AND INVERSE PROBLEMS OF ELASTIC WAVES IN ENVIRONMENTAL ENGINEERING PART I: A GENERAL REVIEW

Yih-Hsing Pao[1], Genn-Sheng Lee[2] & Yung-Hui Liu[3]

ABSTRACT: This paper is divided into two Parts. In PART I, we review the general theory of elastodynamics and some forward and inverse mathematical solutions of elastic waves related to environmental science and geotechnical engineering. The theories and mathematical solutions form the basis for the method of shallow reflection seismics in geophysics and the ultrasonic nondestructive evaluation of structures and materials in engineering. They are also an essential part for the inverse method of matching data procedures, which is discussed in PARTII.

KEYWORDS: Forward and inverse problems of elastodynamics, Ultrasonic nondestructive evaluation, Reflection seismics, Semi-inverse methods of elastic waves

1 INTRODUCTION

The environment that surrounds us on the surface of the earth is composed of many natural objects such as mountains and lakes, rivers and plains; and man-made objects such as buildings and bridges, trains and airplanes. In science, the contents of these objects are classified as solids, liquids, and gases. At the excitations of mechanical and electromagnetic forces or thermal and chemical actions, all solids deform and all fluids flow. It is thus not an exaggeration to say that the environment is constantly in motion. By motion, it is meant a change of positions in space for a particle or a mass element of a material body, and a change of relative positions for particles with respect to each other. The former is measured in terms of displacement, velocity, or acceleration of the mass element and the latter is expressed by deformation, strain, strain-rate, or velocity-gradient of the body. A particular type of motion is the vibration which is a continuous motion of a mass element to and from its original position in time.

In Mechanics, the vibration is treated as a special form of wave motion which is the propagation of a disturbance from one position to another in a medium with a given speed. The medium may be

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gaseous, liquid, or solid that can carry the disturbance. The disturbance might propagate in the form of transporting material substances (mass elements), or in the form of passing mechanical energy from one point to another without carrying the mass element. Many of the vibrational phenomena encountered in engineering are combinations of both (Timoshenko, 1928)[29].

This lecture addresses at a particular problem of wave motion in elastic solid or fluid that is of interest to environmental scientists and engineers. Our discussion is confined to the forward and inverse problems of elastic waves that are related to the characterization of a medium from the observed wave motion. The medium is modeled in physics as an elastic solid or fluid and the basic theory is the dynamic theory of elasticity originated by Navier and Cauchy in 1820s. The lecture is divided into two parts. The first Part reviews the basic theory of elastodynamics and some mathematical methods to deduce forward and inverse solutions of elastic waves; the second Part presents some of the newly reported methods for treating the inverse medium problems.

The PART I consists of five sections. In Section 2 we summarize the practice of Shallow Reflection Seismics and that of Non-Destructive Evaluation (NDE) of structures and materials to illustrate the inverse problems related to environmental and geotechnical engineering. In Section 3 we discuss the nature of forward and inverse problems of elastic waves. In Section 4 we summarize some of the forward solutions of elastodynamics pertaining to inverse problems. In Section 5 we review some of the semi-inverse techniques for characterizing the medium properties or interior dimensions.

The PART II consists of four sections. In Section 6 we discuss the nature of wave dispersion in multilayered media. In Sections 7 and 8, we review two newly reported ultrasonic techniques for characterizing dispersive layered media, the Matching Transient Data Procedure (MTDP) and the Matching Dispersion Data Procedure (MDDP). In the last Section of Conclusions, we compare these two procedures and discuss their applicability to environmental and geotechnical engineering.

2 SHALLOW REFLECTION SEISMICS AND NDE OF STRUCTURES AND MATERIALS

The basic theory for studying the waves in elastic solid is known as the dynamic theory of elasticity, which includes the concept of stresses and strains, the equations of motion for a continuum, the generalized Hookes' law (the constitutive equation) for elastic solid (Love, 1892)[15]. The theory was developed originally by Cauchy in 1828 to analyze the transmission of light (a transverse wave) in luminous elastic aether. As the basic theory of light, it was replaced gradually by the dynamic theory of electromagnetics proposed by Maxwell in 1864. The theory of elastodynamics found applications later in studying seismic waves generated by earthquake and in analyzing the deformation of elastic solids.

On the other hand, the theory of vibrations was originated in acoustics for studying sound waves and music instruments. Around 1750, D'Alembert developed the one-dimensional wave equation for the transverse vibration of a string. It was applied later to analyze longitudinal vibration of air in an organ pipe, and to longitudinal elastic waves in a thin rod. The wave theory was extended to two-dimensional motion of membranes and plates, and to three-dimensional sound waves in air and liquid (Rayleigh, 1877)[26]. It was finally combined with the theory of elastic waves toward the end of 19^{th} century.

For the study of either wave propagation or vibration, the medium in motion may be regarded as a physical system which is characterized by geometric boundaries and material properties. The agents which excite the motion are regarded as the source of or the input to the system; the motion which is recorded in the form of time-dependent displacement, velocity, acceleration, strain, stress and so on are regarded as the response of or the output from the system. The problem of determining the response from a given source to a known medium is usually called the forward problem, and that of determining the source from a given response is called the inverse source problem. In addition, if the characteristics of the physical system are not clear, the determining of the geometric boundaries and material properties of the medium from a given source and a known response is called the inverse medium problem.

Most of the studies of dynamic or static elasticity in the past were concerned with the forward problem. Major interests in the inverse problem were developed recently in the field of geophysics, ultrasonics, material engineering, and civil engineering. We shall discuss briefly in this Section the Shallow Reflection Seismics and Non-Destructive Evaluation (Testing) to illustrate the inverse medium problems.

2.1 Shallow reflection seismics

Consider the seismic wave profile shown in Fig.1, which is taken from the report by Chien-Ying Wang (1993)[31] for exploring the geological structure of Taipei alluvial basin. The seismic wave profile on left-hand side of the Fig. displays the time series of the reflected signals received by a number of geophones placed on the ground along a 45 meters line running from SW to NE. The vertical axis indicates the recording time of receivers in second. On right-hand side of the Fig., it shows the geological structure at a nearby site (New Park, Taipei) by a borehole test. Layer 1 is the Sung Shan formation of clay and silt about 50 m thick. Layer 2 is Ching Mei formation of gravel and sand about 60 m thick. Layer 3 is Hsin Chuang formation of compact clay about 120 m thick. The base is a layer of sedimentary rock of Tertiary Period. The waves are generated by a point source (a rifle shot, a weight drop, or small explosive) near the surface, and propagate through the layered ground medium. The line of geophones sensed mainly the vertical motion of ground surface.

From the seismic wave profile, geophysicists are able to map out approximately the interfaces, which reflect the signals. With the aid of a rather complex data processing procedure, they can determine further the medium parameters of each layer such as the thickness and P-wave speeds of each layer. The S-wave speeds can also be determined if additional geophones sensitive to

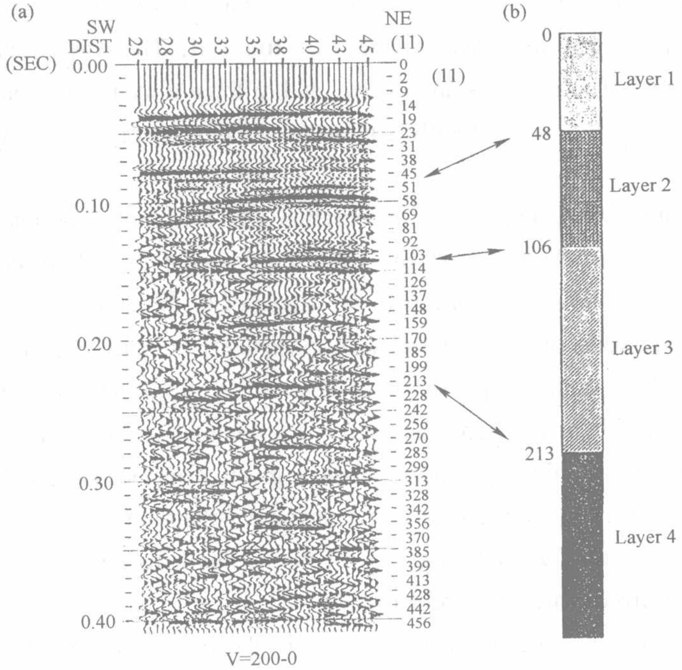

Fig.1 Shallow reflection seismic profile and borehole date[31]

(a) Seismic wave profile at the site of Central Weather Bureau, Taipei.; (b) Geological structure by a borehole test at a nearby site

horizontal ground motion are used.

The aforementioned experiment of shallow ground profile is a compact version of full scale Reflection Seismology (Waters, 1978)[32] used for oil prospecting (down to several kilometers) and Earth mantle exploration (down to 30 km). By modifying the frequency response and resolution of sensing and recording instruments, the same principles and techniques of Reflection Seismology are applied to explore the mantle surface, called the "Shallow Reflection Seismics". The modification enables one to explore ground profile up to 500 meters deep with a resolution of 2 to 10 meters. The depth is limited by the power as well as frequency bandwidths of the explosive source, and the resolution depends on the bandwidths of the source signal (up to 400 hertz) as well as the sensitivity and bandwidths of recording instruments. As a rule of thumb, to achieve good resolution from reflected signal the wavelength of the incident wave should be shorter than one quarter of the typical dimension or thickness of a specimen. Details can be found in the monograph by Yilmaz (2001)[34].

2.2 Non-destructive evaluation (NDE)

At the other end of dimension and frequency spectrum, there is the Non-Destructive Evaluation of structures and materials by ultrasonic or sonic waves (Thompson, 1996)[28]. The objectives of NDE are multifold including the detection of cracks and flaws, the determination of dimensions and interior boundaries, and the characterization of a structure system or a sample mauerial (Chimenti, 1997)[10]. In order to generate and record a sharp signal with broad bandwidth for detecting fine flaws or measuring dimensions of small characteristic length, ultrasonic waves of very high frequencies (MHz ~ GHz, 10^6-10^9) are used.

Shown in Fig. 2 is a laboratory specimen composed of three layers of different materials. An aluminum plate of 2cm in thickness is cemented to a brass plate of 1 cm, which is glued to a block of Perspex (a Plexiglas like material). It models a three-layered plate if the reflected signals from the bottom surface are included in the recording. Otherwise, the specimen models a two-layered half space. The material parameters (density ρ, P-wave speed c_P, and S-wave speed c_S), which are shown also in the Fig. 2, are measured by ultrasonic techniques individually for each layer of materials.

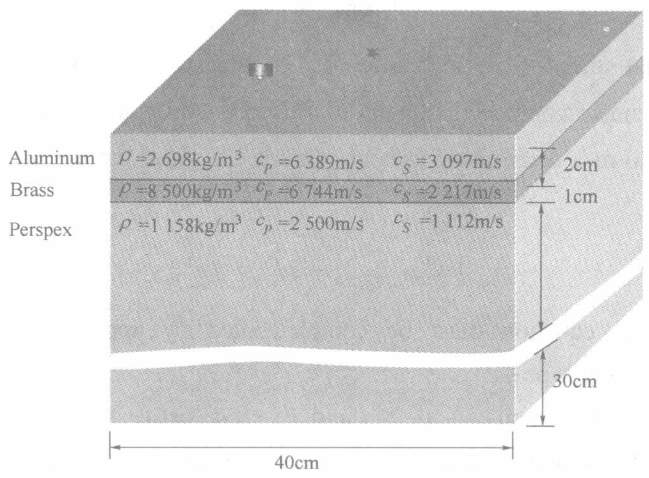

Fig. 2 A laboratory specimen to model a three-layered plate or a two-layered half space

To determine all material parameters and the interior dimension of the composite laminate as a whole based upon one or two ultrasonic experiments is far more difficult than that for each layer separately. Two of the recently reported techniques for characterizing the composite laminate are discussed in PART II. With a change of instrument, the reported ultrasonic techniques are applicable also to elastic waves in sonic range and to seismic waves at low frequencies. Recent developments of ultrasonics are discussed in the monograph by Auld (1990)[4]

3 FORWARD AND INVERSE PROBLEMS OF ELASTIC WAVES

Both techniques of shallow reflection seismics and ultrasonic NDE are based on the theory of elastodynamics, which studies the propagation, reflection, and deflection of elastic waves in liquid and solid media. We summarize briefly the theory of elastodynamics and define what we mean by forward and inverse problems in this Section.

3.1 Equations of elastic waves

The theory of elastodynamics is embodied mathematically in two sets of partial differential