ELSEVIER

Soil Dynamics and Earthquake Engineering 28 (2008) 593–604

SOIL DYNAMICS AND EARTHQUAKE ENGINEERING

www.elsevier.com/locate/soildyn

Dynamic parameters of structures extracted from ambient vibration measurements: An aid for the seismic vulnerability assessment of existing buildings in moderate seismic hazard regions

Clotaire Michel[a,*], Philippe Guéguen[a,b], Pierre-Yves Bard[a,b]

[a] *Laboratoire de Géophysique Interne et Tectonophysique, Université Joseph Fourier, CNRS, Grenoble, France*
[b] *Laboratoire Central des Ponts-et-Chaussées, Paris, France*

Received 23 October 2006; received in revised form 23 March 2007; accepted 3 October 2007

Abstract

During the past two decades, the use of ambient vibrations for modal analysis of structures has increased as compared to the traditional techniques (forced vibrations). The frequency domain decomposition (FDD) method is nowadays widely used in modal analysis because of its accuracy and simplicity. In this paper, we first present the physical meaning of the FDD method to estimate the modal parameters. We discuss then the process used for the evaluation of the building stiffness deduced from the modal shapes. The models considered here are 1D lumped-mass beams and especially the shear beam. The analytical solution of the equations of motion makes it possible to simulate the motion due to a weak to moderate earthquake and then the inter-storey drift knowing only the modal parameters (modal model). This process is finally applied to a nine-storey reinforced concrete (RC) dwelling in Grenoble (France). We successfully compared the building motion for an artificial ground motion deduced from the model estimated using ambient vibrations and recorded in the building. The stiffness of each storey and the inter-storey drift were also calculated.

Keywords: Ambient vibrations; FDD method; Existing buildings; Modal model; Seismic vulnerability; Grenoble

1. Introduction

Knowing the dynamic parameters of a structure (e.g. a building or a bridge) may be useful: (1) to calibrate its elastic properties for numerical modelling, (2) to detect the modification of its behaviour after retrofitting or damage, (3) and, finally, to predict its behaviour under earthquakes. The linear dynamic behaviour can be fully described by the modal parameters: resonance frequencies, modal shapes and damping ratios. These parameters mainly depend on the storey masses, which remain unchanged whatever the state of the structure, and the storey stiffnesses, which are influenced by the structural modifications such as reinforcing and damage. It can also be representative of the quality of the material (e.g. the equivalent Young's modulus of the cracked or undamaged concrete) and of the structural design (e.g. irregularity of the shear resistance or soft storey). All large-scale vulnerability assessment methods (e.g. Refs. [1–3]) identify the stiffness regularity of buildings as one of the main parameters controlling their seismic resistance. The stiffness is also the basic parameter needed to draw the capacity curve of buildings, which is the basis of recent large-scale vulnerability assessment methods (e.g. Refs. [1,3,4]). One of the greatest difficulties within such methods is the lack of information on existing buildings. Within vulnerability assessment, we have to deal with questions on, for example, ageing, structural design, quality of materials and the building state.

Assessing the stiffness of each storey, and therefore the modal shapes of the structure, is then a critical point for the evaluation of the dynamic properties of existing buildings and hence to predict their seismic response and vulnerability.

*Corresponding author. Tel.: +33 4 76 82 80 71; fax: +33 4 76 82 81 01.
E-mail address: cmichel@obs.ujf-grenoble.fr (C. Michel).

0267-7261/$ - see front matter
doi:10.1016/j.soildyn.2007.10.002

The ratio between transverse and longitudinal frequencies can, for example, provide information on the relative stiffness in perpendicular directions that may expose a lack of stiffness and may help in structural design understanding. Comparing the frequencies and mode shape before and after the shaking [5–7] allows the evaluation of damage. This method requires knowledge of the initial state of the structure in such a way that the modification due to damage can be observed. For example, comparisons of frequencies among a group of identical buildings can quantify the damage level of each building [8]. Based on the integrity threshold concept [9], and with only limited structural information, the integrity of the building under seismic shaking can be estimated using the experimental modal shape deduced from forced or ambient vibrations (AVs).

Ambient vibrations provide information about the modal parameters of a structure that we can extract using modal analysis methods. There are many different techniques to identify the "natural" modes of a structure, which can be divided into parametric and non-parametric methods. In the first category, the parameters of the considered model are updated to fit the recorded data in frequency or in time domain (see Ref. [10] for details). In the second category, the methods use only signal processing tools so that they are more user-friendly and easier to implement. Moreover, existing civil engineering structures are often difficult to model relevantly so that it is necessary to test these approaches before any more complicated method. For example, the Peak Picking (PP) method consists in taking the frequency peaks of average spectra for each sensors placed at different points. The frequency domain decomposition (FDD [11]) is an improvement of the PP method. It consists of decomposing the power spectral density (PSD) matrices into single-degrees-of-freedom systems by singular value decomposition.

The main goal of this paper is to demonstrate the utility of techniques using AV recordings to complement and improve seismic vulnerability investigations of existing buildings. AVs recorded in buildings are processed for estimating the dynamic parameters of the building based on modal parameter estimates (Fig. 1). Because of its low cost and the efficiency of operational modal analysis, the ambient vibration method is well adapted to large-scale analysis for which a large set of buildings has to be analysed. We first describe the FDD method we used in this study, one method among a large set of other existing methods. Then we propose the shear beam model, adapted to our recording layout to approximate the motion of a building. An analytical solution is proposed to estimate the stiffness at each storey as a function of the modal shapes. We apply this theoretical work to a building located in Grenoble (France). We estimate its modal properties using ambient vibration tests and recordings of a ground motion induced by a bridge demolition (BD) in the same area. We then validate the modal model derived using modal parameters estimated from AVs by comparing the simulation results of the bridge collapse with real data. Finally, we estimate the stiffness at each storey of this building and the inter-storey drift during the seismic motion and deduce some information about its seismic behaviour.

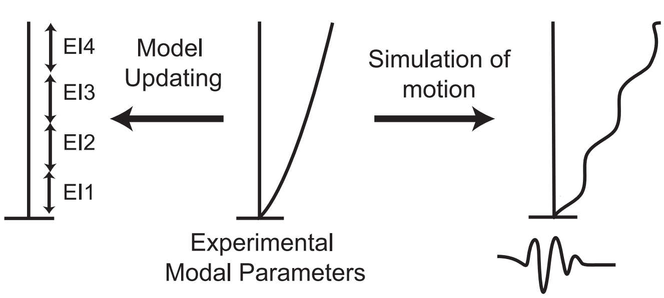

Fig. 1. Overview of this study's scope. We relate, in a simple way, experimental modal parameters of a building (frequencies, modal shapes and damping) to ground-motion parameters (earthquake scenario) and structural parameters (stiffness) for seismic vulnerability assessment.

2. Modal parameters from AV recordings

In the 1930s, US Coast and Geodetic Survey first undertook AV recordings in high-rise buildings and bridges to determine their fundamental periods [12,13]. Until the late 1990s engineers preferred forced vibration tests (traditional modal analysis) because of the accuracy of the corresponding system identification techniques. However, during the last two decades AV recordings are preferred because of their low cost. They are used to determine the behaviour of structures (frequencies and modal shapes) [14,15], to quantify the damage after earthquakes [8,16–18] and to assess the benefit of retrofitting [19,20]. They also allow the calibration of numerical and analytical modelling (model updating) [15,21,22]. AVs are produced by natural sources such as local atmospheric conditions (e.g. the wind and the sea) or by human activities (e.g. traffic and factories). The expected range of acceleration values for ambient vibration tests is 10^{-7} to 10^{-4} g. Therefore, there is no doubt that the low level of the shaking only gives relevant information on the elastic behaviour of the structure. Many authors (e.g. Refs. [17–19,23–26]) showed that nonlinearity affects resonance frequencies when the level of loading increases. This nonlinearity is due to the opening of micro-cracks in the concrete during vibrations, which may decrease temporarily, or permanently the stiffness, and then the resonance frequencies, of the structure. Nevertheless, recent studies showed this decrease may be low for weak to moderate motions [17] and is usually less than 20%, which confirms the interest of conducting AV recordings within buildings.

Recording AVs at different points of a civil engineering structure (e.g. a bridge, a building or a chimney) allows the determination of its modes of vibration through operational modal analysis techniques [27]. The efficiency of the output-only modal analysis algorithms, the low cost of