Extreme Mechanics Letters 8 (2016) 30–37

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Seismic waves damping with arrays of inertial resonators

Younes Achaoui [a,1], Bogdan Ungureanu [a,b,1], Stefan Enoch [a], Stéphane Brûlé [c], Sébastien Guenneau [a,*]

[a] *Aix-Marseille Université, CNRS, Centrale Marseille, Institut Fresnel UMR 7249, 13013 Marseille, France*

[b] *Faculty of Civil Engineering and Building Services, Technical University "Gheorghe Asachi" of Iasi, 43, Dimitrie Mangeron Blvd., Iasi 700050, Romania*

[c] *Dynamic Soil Laboratory, Ménard, 91620 Nozay, France*

ARTICLE INFO

Article history:
Received 5 August 2015
Received in revised form 31 January 2016
Accepted 1 February 2016
Available online 18 March 2016

Keywords:
Wave propagation
Mechanical metamaterials
Seismic protection
Band gaps

ABSTRACT

We investigate stop band properties of a theoretical cubic array of iron spheres connected to a bulk of concrete via iron or rubber ligaments. Each sphere moves freely within a surrounding air cavity, but ligaments couple it to the bulk and facilitate bending and rotational motions. Associated low frequency local resonances are predicted by an asymptotic formula. We find complete stop bands in the range [16, 21] Hz (resp. [6, 11] Hz) for 7.4 m (resp. 0.74 m) diameter iron spheres with a 10 m (resp. 1 m) center-to-center spacing, when they are connected to concrete via steel (resp. rubber) ligaments. The scattering problem shows that only bending modes are responsible for damping: rotational modes are totally overwritten by bending modes. Regarding seismic applications, we consider soil as a host medium, in which case the low frequency stop band can be enlarged through ligaments of different sizes that allow for well separated bending and rotational modes. We finally achieve some damping of elastodynamic waves from 8 to 49 Hz for iron spheres 0.74 m in diameter, connected to soil with six rubber ligaments of optimized shapes. These results represent a preliminary step in the design of seismic shields placed around, or underneath, foundations of large civil infrastructures.

1. Introduction

Inserting stone blocks between a structure and its foundation is one of the first attempts to reduce vibrations and this can be traced back to the sixth century BC. In 1950, the first specialized damping devices for earthquakes were developed and civil engineers started to implement different mechanisms to mitigate seismic damage to buildings, but with relatively weak and non-earthquake resistant structures [1]. Nowadays civil engineers protect buildings in particular with metal springs, ball bearings and rubber pads, all of them designed to mitigate the energy from seismic waves [1]. In earthquake engineering, the structure could be designed with additional passive energy dissipation systems integrated in the frame structure (dampers, rubbers) or semi-active dampers [2]. However the objective of this article is to illustrate that buried structures in the soil (foundations, buried levels of the buildings, etc.), could directly act, in the near future, on the seismic signal itself coming at the base of the buildings. In that sense, we preliminary demonstrate with numerical models, that we achieve filtering of frequencies by means of a buried device made of resonating iron spheres. This capability of the device to filter frequencies offers wide range of applications in soil–structure interaction (ISS), particularly if the

* Corresponding author.
E-mail address: sebastien.guenneau@fresnel.fr (S. Guenneau).

[1] Y. Achaoui and B. Ungureanu are equal contributors.

http://dx.doi.org/10.1016/j.eml.2016.02.004

foundations are designed both for their bearing capacity and as local resonant elements.

2. Concept of seismic protection

In general, seismic waves are vibrations that travel through the Earth carrying energy released during an earthquake. Seismic waves transport energy from the focus and when their longitudinal (P) and transverse (S) components meet the surface, their energy is partly converted into waves that propagate along the Earth surface. Such Rayleigh waves, which have one compressional and one shear components, are characterized by wavelengths ranging from meters to decameters what corresponds to frequencies from a few tens of Hertz to less than 1 Hz, where the velocity of the wave is decreasing, since the higher frequency components are more effectively attenuated during wave propagation. The fact that these surface waves have a lower speed, hence typical wavelengths much smaller than underground (bulk) waves, makes them the most destructive seismic waves for civil infrastructures built on sedimentary soils, due to the well-known phenomenon of resonance disaster [3,4]. Indeed, when seismic waves propagate through soft superficial alluvial layers or scatter on strong topographic irregularities, refraction or scattering phenomena may strongly increase the amplitude of ground motion. At the scale of an alluvial basin, seismic effects involve various phenomena, such as wave trapping, resonance of whole basin, propagation in heterogeneous media, and the generation of surface waves at the basin edge [3,4]. Due to the surface wave velocity in superficial and under-consolidated recent material (less than 100–300 m s^{-1}), wavelengths of surface waves induced by natural seismic sources or construction work activities are shorter than those of earthquake generated direct P (primary, i.e. longitudinal compressional) and S (secondary, i.e. transverse shear) waves (considering the 0.1–50 Hz frequency range), from a few meters to a few hundreds of meters. These are of similar length to that of buildings, therefore leading to potential building resonance phenomena in the case of earthquakes [3,4].

Most common technical solutions for structural protection are dampers, wave scatterers, resonators, rubber isolation etc. [2]. Here, we propose a radically different concept based on low frequency stop bands associated with meter-scale inertial resonators that might help with preventive measures of earthquake risk management in civil engineering and building structures. Indeed, recent scientific advances in total or partial reflection band gaps (due to periodicity) and invisibility (artificial anisotropy via transformation physics) for elastic waves in plates, as well as wave magnitude damping (using Helmholtz's resonators), have opened new avenues in seismic metamaterials. A way to counteract the devastating effect of seismic waves is to design the shape of inclusions in the soil in order to tune stop bands in accordance with building's fundamental period and its harmonics. Although it is illuminating to draw analogies with control of elastic waves in plates, we have to take into consideration that seismic protection is much more complex than the dispersion/molding of the Lamb waves in thin, heterogeneous plates whose elastic properties are more straightforward to model and characterize. This, in particular, is due to the complex properties of the soil (viscoelastic, anisotropic and irregular propagation medium).

Mechanical resonance is the tendency of a building to respond with a larger amplitude when the frequency of the incoming seismic wave oscillations matches the building's natural frequency of vibration (called resonant or natural frequency). It may cause violent swaying and even catastrophic failure - a phenomenon known as resonance disaster [1]. These resonant frequencies of the buildings can be calculated and are indeed taken into account in the design of their structures. The analysis could be carried out for free vibrations with an idealized single degree of freedom oscillator (S.D.O.F.O with oscillators). The global matrix expression describing the displacement of a multi-oscillator system, neglecting the damping matrix for a pre-design study, leads to the equation $| K - \omega_n^2 M \,|= 0$ with K the stiffness matrix in a linear case of the lateral force, M, the mass matrix and $\omega_n = 2\pi/T_n$ the eigenfrequencies associated with the building's periods T_n [3,5–7]. Using S.D.O.F.O typical eigenfrequencies of a five storey concrete building are found to be in the range 1–100 Hz.

The first in situ experiment of a deflection shield for seismic waves led by the Ménard company in collaboration with the Fresnel Institute near the Alpine city of Grenoble in 2012 has unveiled some similarities between acoustic waves in plates and surface seismic waves [8,9] and this prompted researchers to envision the large-scale analogs of acoustic metamaterials [10–23], with a coined name seismic metamaterials [8]. Similarly to multiple scattering and locally resonant effects experimentally observed in microsonic and hypersonic phononic crystals around 1 GHz [24–26], experimental results in [4,8,27] have validated the possibility to prohibit frequencies around 50 Hz i.e. at the upper frequency range of interest as suggested by the S.D.O.F.O. model and further paved the way to explore locally resonant subwavelength structures that might improve such Bragg-based seismic shields.

The purpose of the present letter is to highlight the mechanisms offered by a new class of seismic metamaterials based on subwavelength inclusions that may enable a drastic attenuation of earthquakes. These can be achieved by engineering the frequency stop bands dedicated to seismic waves by converting the latter to evanescent waves in order to protect a sensitive area (schematics shown in Fig. 1). We numerically demonstrate that seismic waves can be molded by changing the field propagation properties, by placing a cubic array of resonators in the seismic wave path.

3. Low frequency stop bands with inertial resonators

We start by analyzing propagation of bulk waves through a homogeneous and isotropic elastic medium, with Comsol Multiphysics, applying in this finite element software Floquet–Bloch boundary conditions on either sides of a periodic cell of side length $a = 10$ m in order to compute band diagrams. In this case, it is well-known that compressional and shear waves display non dispersive