Impact Objectives

- Develop seismic metamaterials
- Achieve two ambitious and novel experiments where 1,000 seismic sensors are set up on two seismic metamaterials

Research that really resonates

***Professor Richard Craster*, *Dr Andrea Colombi* and *Dr Philippe Roux* are part of a project that seeks to demonstrate that metamaterial physics can exist at the very large scale in geophysics. Below, they describe the project, metamaterials and the importance of a multidisciplinary approach**

Professor Richard Craster

Dr Andrea Colombi

Dr Philippe Roux

Can you begin by explaining a little about the META-FORET project?

RC: The META-FORET project came about from the following questions: why should complex wave physics be limited to experiments at very small scales? As waves obey similar propagation equations whatever their origin, why are there so few observations of the effects of advanced wave physics at the geophysics scale, for example? Of course, the answers to these deliberately provocative questions are multiple. What can be achieved in terms of wave manipulation and control at the laboratory scale turns out to be very challenging, if not impossible, at larger scales, where the deployment of numerous autonomous sensors is often another practical limitation. Our project aims to fill this gap in terms of large-scale wave manipulation with a multidisciplinary approach devised by a team of physicists, geophysicists and engineers who share a common interest in wave propagation in complex media.

In lay terms, what are seismic metamaterials?

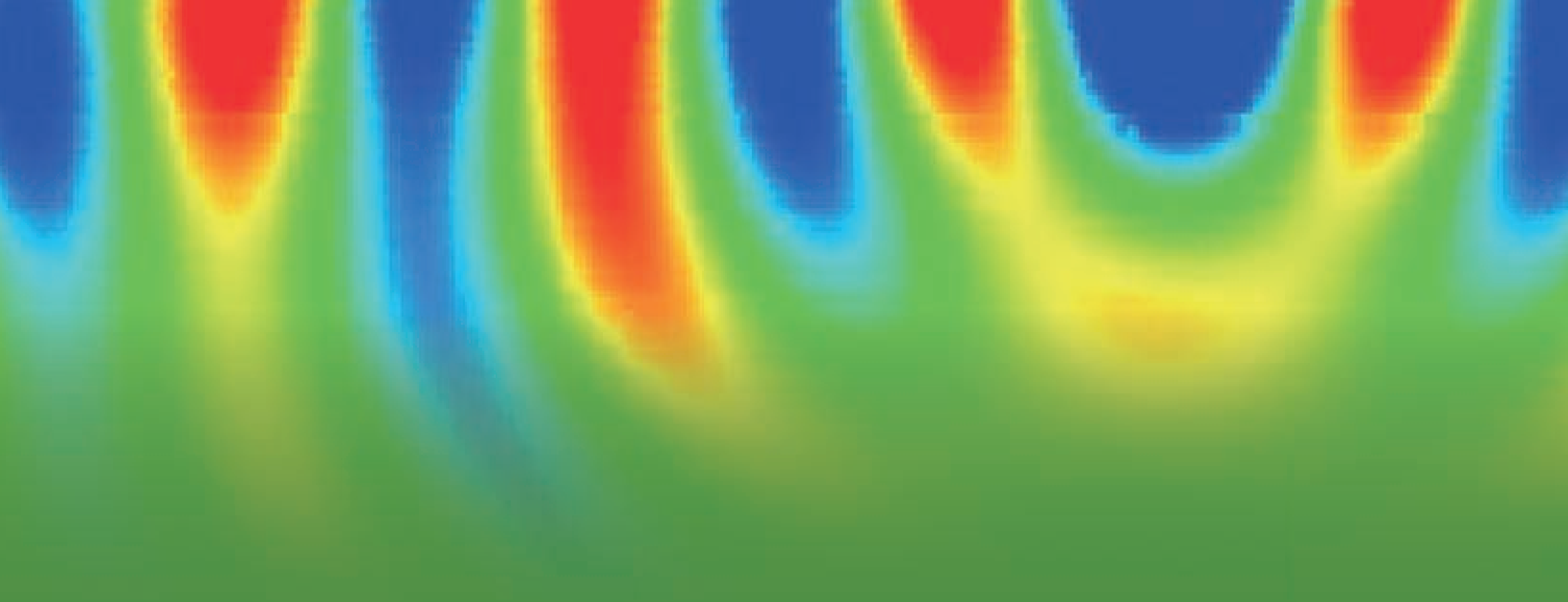
PR: Seismic metamaterials are materials – such as soil, rock or another elastic medium – that have small, resonant elements. Metamaterials normally refer to a bulk medium that is structured. It is more precise (and probably easier) to describe our devices as metasurfaces. Different concepts of seismic metasurface could be designed. For example, a seismic metasurface consists of an array of resonators placed on top of the soil or rock (or within it). This could consist, for instance, of an array of pillars or rods placed on the surface. The pillars or rods (or, in the case of the META-FORET project, the trees) have resonances and these resonances can then be used to interfere with the incoming waves (from urban noise, railways, seismic activity, etc.) to redirect or block them.

META-FORET brings together physicists, geophysicists and engineers. Why is a multidisciplinary approach so important to this research area?

AC: The META-FORET project aims to experimentally test geophysical configurations from which metamaterial physics inducing seismic cloaking and/or seismic protection can be conclusively demonstrated. An essential route from physics to geophysics will be to demonstrate through numerical simulations and laboratory-scale experiments that such up-scaling is meaningful; that is, we will precisely show that the metamaterial designs applied using small objects at the laboratory scale actually lead to large-scale demonstrations at the geophysics scale. Manipulating (the use of a collection of long vertical tree-like resonators outside the ground or concrete-like inclusions inside the ground, with both systems behaving as a seismic metamaterial) is completely fundamental for the future understanding of wave cancellation or wave bending for seismic surface waves. Translating the required physics from the laboratory scale to the geophysics scale is highly challenging, and so the success of the project is dependent on a wide range of expertise from a variety of different fields.

How long have the three of you been collaborating and what kind of research have you previously worked on together?

RC: We have worked together for a relatively short time and we have mainly worked together on interpreting and designing elastic metamaterial devices. This collaboration was initiated by Colombi, who came to my group at Imperial College London as a Marie Curie Fellow from Roux's group at the Institute des Sciences de la Terre (ISTerre) in Grenoble. It is a nice example of how the EU Marie Curie scheme, by encouraging the mobility of researchers, facilitates collaborations and the exchange of ideas.



Good vibrations

*The **META-FORET** project involves a team of physicists, geophysicists and engineers who are all focused on large-scale wave manipulation. The ultimate aim of the project is to prove the effectiveness of metamaterial devices in redirecting seismic waves, which will have broad applications*

Broadly speaking, seismic waves are waves of energy that move through the Earth's layers. These waves can be created by a wide range of different events, including earthquakes, volcanic eruptions and man-made explosions, all of which can cause untold damage to buildings and infrastructures the world over. However, there are other problems that might not be so immediately apparent. Ambient seismic noise caused by ground vibrations can be a real issue when they occur at locations where highly sensitive scientific measurements need to be made. In this instance, preventing or cloaking the vibrations made by seismic waves is highly desirable but not easily achieved.

Until very recently, experiments involving complex wave physics were only performed at very small scales. While this is obviously beneficial to developing and deepening scientific understanding, observing the effects of advanced wave physics at the geophysics scale would have far more potential for applications.

WAVING GOODBYE TO LARGE-SCALE WAVES

To translate these very small-scale experiments to geophysics scales, META-FORET was established. The project is focused on several areas of investigation, including the use of resonators. Materials with small resonant elements, known as seismic metamaterials or metasurfaces, have properties that can help to interfere with seismic waves in such a way as to move them away from an area or block them entirely. The META-FORET team aims to apply this phenomenon in the context of large-scale wave manipulation by bringing together physicists, geophysicists and engineers from academic and industrial institutions across France, Germany and the UK.

Following a first attempt with buried concrete columns in 2013 conducted by some of their French colleagues, the team performed an experiment in a forest where the dense collections of trees acted as coupled resonators to cancel seismic surface waves that were generated nearby from a controlled seismic source. The experiment showed that the seismic metamaterial concept was viable on a large scale (that is, further than 100 metres in distance). For many real-world vibration problems, the resonance frequencies of trees are too high (above 40 Hz) to be useful in practical applications for seismic protection. Nonetheless, the team had demonstrated that it was possible to reach these targets in the future.

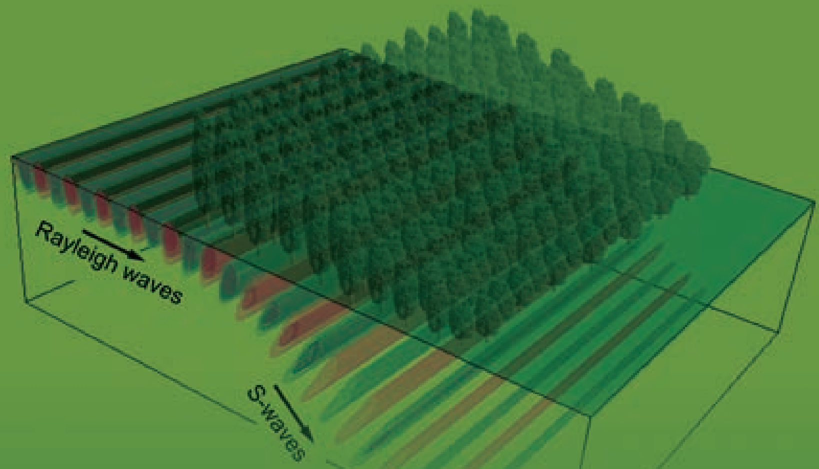
EVEN BUILDINGS CAN THWART THE WAVES

Now that the premise has been proven to be viable and effective, researchers are exploring the potential of other objects and materials to act as resonators. 'Research is underway to place resonators within the ground. These can be large dense metal or concrete blocks with springs or connectors. We have mainly investigated pillars, rods or vertical resonators,' explains META-FORET researcher Professor Richard Craster. 'To be efficient, a resonator must be massive, generate a large contrast of mass and elastic properties, and at the same time be well coupled to the soil in order to both allow the capture of the seismic energy and re-inject enough seismic vibrations into the ground.'

In the near future, the team plans to use wind turbines that function as a scaled up version of the trees that formed part of the earlier experiment. However, excitingly, strong resonators for seismic waves could also be tall buildings, so there is now wide interest in exploring the ways in which clusters of tall buildings interact. It might yet prove possible for the buildings themselves to scatter, deviate and even cancel the surrounding ground vibration. 'It is reasonable to imagine that overall coupling at the urban scale may have a complex response that can be characterised as a giant geophysical metamaterial, where a cluster of buildings gives rise to a new type of wave propagation physics,' observes another META-FORET researcher, Dr Philippe Roux. 'Soil-structure coupling at urban scale has been detected at Mexico City after the 1985 Michoacan earthquake, with the downtown seismic ground motion showing long duration monochromatic beatings as a result of the building resonance.'

PHYSICAL AND GEOPHYSICAL APPLICATIONS

If the META-FORET researchers are able to confirm their suspicions, the findings could lead to significant physical and



> *'Why should complex wave physics be limited to experiments at very small scales? As waves obey similar propagation equations whatever their origin, why are there so few observations of the effects of advanced wave physics at the geophysics scale?'*

geophysical applications. For instance, it would be possible to exploit forbidden frequency bands to cancel ambient seismic noise at locations where ground vibrations are an issue. Similarly, the sub-wavelength focusing that results from an analogous dispersion curve inside a metamaterial could be exploited to design lenses of waveguides to control and manipulate seismic waves locally.

As metamaterials are engineered to allow full control of the wave propagation in designated frequency ranges, it might be possible, in the next 10 to 20 years, to define a urban metamaterial based on the urbanisation scheme to produce beneficial effects on the response of structures and seismic casualties.

THE POTENTIAL OF POPLAR TREES

The success of the first experiment, where 1,000 seismic sensors were deployed in a forest of pine trees, has encouraged the team to continue with its efforts on coupled resonators. As such, the researchers are currently preparing their second experiment, which will take place in 2019. The group's initial strategy is concerned with working with a particular spatial distribution of long and thin vertical inclusions in the ground, which could create a special seismic lens. This would divert surface waves away from the inner region, leaving the central zone almost untouched. 'Our initial strategy requires the strong involvement of our industrial partner Menard, which is specialised in buried rigid inclusions constructed as a ground improvement solution,' explains Dr Andrea Colombi, a META-FORET team member. 'Initially developed by Menard in France to support structures such as industrial buildings, the Controlled Modulus Columns (CMC) are predominantly used for sites with soft cohesive soils.'

However, the team is also considering performing the second experiment in a forest of poplar trees, which are much stronger resonators than the pine trees studied in 2016. Poplar trees are often more than 40 metres tall and weigh around 1.3 tonnes each, making them far larger than pine trees. As such, the researchers expect to observe seismic surface wave cancellation at much lower frequencies (around 15 Hz). While such an outcome would still be a bit too high in frequency, it would be much closer to the seismic waves generated by destructive seismic events (between 1 and 5 Hz).

In addition, a forest of poplar trees tends to be spatially organised with a regular distribution of trees every 7 metres, compared with the random distribution seen in the first experiment. Such a configuration will be interesting to study, especially since it resembles phononic crystals, which form part of another branch of metamaterial physics. The team expects to observe new phenomena within a forest of poplar trees, making this avenue of research particularly intriguing.

Ultimately, the physics surrounding metamaterials is becoming more established and there is growing interest in its real-world application potential. With META-FORET's multidisciplinary and transnational collaborative approach, the project is particularly well-positioned to contribute to these developments.

Project Insights

FUNDING

This project is financed by Agence Nationale de la Recherche (ANR), Université Grenoble Alpes, Centre National de la Recherche Scientifique (CNRS), Observatoire des Sciences de l'Univers de Grenoble (OSUG) and Xylofutur. It is also supported by funding from the Engineering and Physical Sciences Research Council (EPSRC), Imperial College London, Leverhulme Trust, European Commission and Swiss National Science Foundation

PARTNERS

ISTerre (France) • Institut Langevin (France) • Institut Fresnel (France) • Imperial College London (UK) • Menard (France) • GFZ (Germany) • CNPF (France) • Multiwave (France/Switzerland)

CONTACT

Professor Richard Craster
Professor of Applied Mathematics

T: +44 2075948554
E: r.craster@imperial.ac.uk
W: https://metaforet.osug.fr/

BIOS

Professor Richard Craster's research interests are in applicable, industry-focused mathematics and engineering. This revolves around the study of waves, in electromagnetism, acoustics or elasticity, through structured composite materials.

Dr Andrea Colombi studied engineering in Italy before completing a PhD at ETH Zurich specialising in computational elastodynamics and imaging. After spending time as a postdoc in France and the UK, he is now back at ETH Zurich where he works on projects that require in-depth understanding of wave phenomena.

Dr Philippe Roux is a physicist based at ISTerre. In the last 10 years, his research has focused on experimental demonstration, with the idea that complex wave phenomena observed and measured in controlled laboratory-scale environment can also be performed at a larger scale.