TESTING THE TWO-DIMENSIONAL RESPONSE OF A METAMATERIAL-BASED DEVICE FOR ATTENUATING SURFACE GRAVITY WAVES

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INTRODUCTION

It is known that the pressure of anthropogenic origin, combined with natural factors, has contributed both to a worsening of the environmental quality of coastal areas, and to the triggering of erosion dynamics, with retreat of the sandy coast and instability of the rocky one. The main anthropogenic factors are mainly linked to the construction of infrastructures and works for residential and industrial settlements. The most important natural factors of coastal erosion are wind, wave motion, currents, lack of sediments from rivers into the seas and movements of the soil.
We aim at developing and testing in a controlled environment a new device which is based on the concept of MetaMaterials (MMs).
MetaMaterials are engineered structures designed to interact with waves and manipulate their propagation properties, such as phase and group velocity, or to produce effects such as negative refraction, superlensing and absorption (Hussein, 2014; Laude, 2015). They have been developed mostly in the field of electromagnetic and acoustic waves, but nowadays they find applications in diverse fields of physics and engineering. Just to list a few applications, the MMs concepts are applied to seismic protection (Brulè, 2020), noise abatement (Lu, 2009), and non-destructive testing (Miniaci, 2017).
So far, there is a limited body of results involving MMs in the field of fluid dynamics, due to the inherent complexity of the problem, involving the coupling of oscillating bodies inside a fluid, with correlated flow, surface and viscous effects (Hu, 2005).
A MM is usually designed as a periodic arrangement of structures, where the size of the arrangement is comparable or smaller than the wavelength to be manipulated (Demyer, 2013). Such periodic structures may determine the so-called "bandgaps" in the dispersion relation, *i.e.*, ranges of frequencies for which wave propagation is inhibited (Laude 2015).
This key concept inspired the idea (European Patent EP19185446.2) of a device that might be used for wave attenuation. It is a periodic structure (a lattice) of inverted pendula immersed in a fluid. Each pendulum is made up of a spherical mass anchored to the seabed (Figure 1).
The interaction of the wave motion with the pendula can produce a rapid attenuation of the waves, with a marked enhancement of this effect in the proximity of the MMs modal resonances. Preliminary results, obtained in using numerical simulations of the 2D Navier-Stokes equation and in a small wave flume where cylinders, and not spheres, were used, are described in DeVita et al (2021a) and Lorenzo et al. (2022a), respectively.
Lorenzo et al. (2023) reports on quasi 2D experiments in a wave flume. Their physical model approximates the two-dimensional system of Figure 1, since the pendula were built with circular cylinders, hinged at the flume bottom, and the cylinders axis was perpendicular to the flume sidewalls. By analyzing the response of various configurations forced by regular waves, they were able to observe the formation of bandgaps. They concluded that the phenomena causing substantial wave attenuation are mainly two (dissipation and scattering).
High energy dissipation mainly occurs in a relatively broad frequency range which is located close to the natural mode of the single pendulum. Forced by the waves, the pendula oscillate and release their energy into the water in the form of turbulence which is then dissipated in heat.
Relevant wave reflection is a collective behavior. It occurs at narrow bands localized at frequencies which are analytically predictable invoking generalized Bragg-scattering. This phenomenon is due to the nonlinear interaction of several wave modes, one of which is the pendula array itself. Its associated frequency is supposed to be zero, and its wavelength corresponds to the relative spacing of the cylinders.
These two basic phenomena can definitively guide optimization, which is basically a matter of geometry.
The response of the pendula array is more complicated than this. Forced under irregular wave conditions, the same cylinders array can attenuate the incoming wave energy almost at a comparable rate, with respect to regular wave forcing. However, the two basic phenomena described above are more difficult to spot. The complicated wave scattering, together with other underlying nonlinear interactions, randomly enhances the local steepness, triggering dissipative phenomena which then affect the whole spectrum (Lorenzo et al., 2022b).

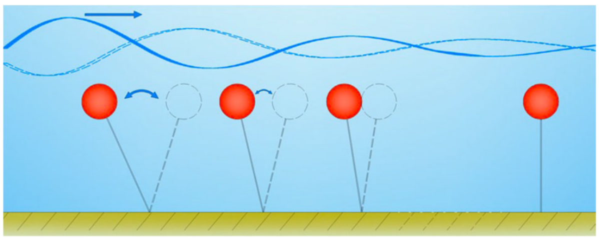

Figure 1 - Two-dimensional representation of the wave attenuator, inspired by the metamaterial concept.

REALISTIC SPHERICAL PENDULA ARRAY

The main purpose of the present communication is to report on a novel experimental study designed to capture the collective behavior of a lattice of fully immersed spherical pendula, anchored at the seafloor, forced by gravity waves.
Even in a scaled experimental setup, by utilizing spherical pendula and studying their behavior in short-crested wave conditions, we are moving a step forward, in terms of

augmented degrees of freedom, towards our main objective. This is the design and optimization of a wave attenuation system based on submerged resonators, capable of providing multidirectional and multifrequency wave damping. The project aims to establish this solution as a technically feasible, economically competitive, and more environmentally friendly approach compared to existing solutions for coastal protection (Figure 2).

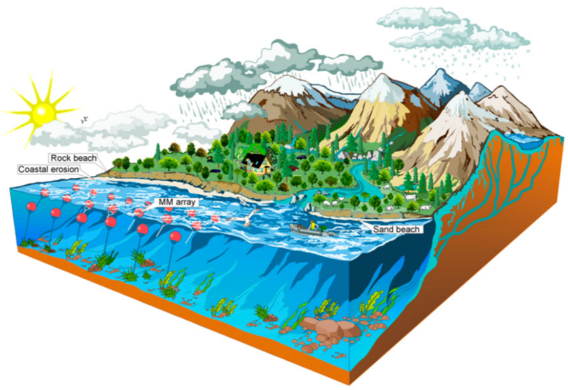

Figure 2 – Sketch of a possible installation of the MM device.

At the time of writing, the experimental study is ongoing. We are first characterizing the behavior of a single sphere in a 2D wave flume. This is relevant for the comprehension of the full device. For a single spherical pendulum, the main part of wave attenuation is determined by energy losses. By adding more pendula in the direction of the wave motion, the total energy loss increases monotonically (e.g., see Seymour and Hanes 1979). For cylinders those result have been reproduced both numerically (DeVita et al 2021a, 2021b) and experimentally (Lorenzo et al., 2022a; Lorenzo et al., 2023).
The second step is the characterization of the collective behavior of a lattice of spheres in 2D wave flume, in long crested wave conditions. As observed for cylinders, it is likely that, adding more rows, collective behavior will emerge (Lorenzo et al., 2023). In long crested conditions the connections between emerging group dynamics and the wave attenuation properties can be possibly described and form a solid basis (a benchmark) for the more complicated 3D configurations.
The final step is the installation of an optimized lattice of spheres in the 3D wave basin of the LIC – Coastal Engineering Laboratory of the Polytechnic University of Bari. Once a deep knowledge of the behavior of the device has been achieved in the presence of the long-crested waves, we will test the device in more realistic conditions, such as typical JONSWAP or Pierson-Moskowitz spectra characterized by different peak frequencies and directional spreading.

ACKNOWLEDGEMENTS
M.O., M.M. and P.P. are supported by Progetti di Ricerca di Interesse Nazionale (PRIN), Project No. 2022WKRYNL. M.O. was funded by Progetti di Ricerca di Interesse Nazionale (PRIN), Project No. 2020X4T57A and by the European Commission H2020 FET Open Boheme, grant no. 863179, and by the Simons Foundation, United States, Award 652354 on Wave Turbulence.

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