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A simplified method for calculating the accumulation of irreversible rotations of wind turbine shallow foundations

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Wind turbines represent a convenient source of renewable energy and their diffusion is a fundamental step for reducing carbon dioxide emissions, main responsible for global warming. Turbine towers are characterized by large heights, therefore the wind load induces considerable bending actions at the base of the structure. Although, especially offshore, deep foundations are usually adopted, shallow foundations are still an option in case of onshore installations [1]. These circular shallow foundations are massive concrete structures (Figure 1) that counteract the bending moment with their own weight. The optimization of the design and the extension of the service life are fundamental from both economic and environmental perspectives. These will increase the competitivity of energy production from renewable wind sources over fossil ones, thus boosting the transition toward sustainable energy.

Figure 1: Typical reinforcement cages of reinforced concrete shallow foundations for onshore wind turbine towers (from [1]).

From a geotechnical perspective, the isolated foundations of wind turbines are a peculiar case since the accumulation of vertical settlements and horizontal displacements are not a main concern. On the contrary, the accumulation of excessive rotations due to the wind cyclic loads may reduce the efficiency of the turbine and, in particularly critical cases, define the end of service of the structure.

The accumulation of irreversible rotation during the exercise cyclic loads may be induced by both the development of irreversible strain in the soil and the formation of cracks in the concrete foundation. This second aspect can however be neglected, since, in the current practice, very over-conservative approaches are used to design the reinforcements. Recent experimental small scale tests (Figure 1) proved that, even when stirrups are completely removed, exercise loads do not induce the formation of cracks [2]. Therefore, the accumulation of cyclic irreversible rotation is only due to the soil.

Recently, numerous constitutive relationships accounting for the cyclic behaviour of the soil were proposed [3,4]. These in principle allow to perform finite element analyses capable of reproducing the soil-structure interaction. However, during the foundation design life a very large number of load cycles (up to 10^8) is expected, leading to unacceptable computational times.

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A way to circumvent this problem is the employment of models conceived in the framework of the macroelement approach [5]. This is based on the assumption of reproducing the response of a complex system by using a very small number of degrees of freedom and by introducing an upscaled constitutive law relating generalized stresses (forces and moments) and strains (displacements and rotations). The abrupt reduction in degrees of freedom significantly reduces the computational times. However, the definition of the upscaled constitutive laws and the calibration of its parameters are particularly critical since they will be affected not only by the soil behaviour, but also by the foundation geometry and mechanical properties.

In this work, the authors intend to propose a new one-dimensional macroelement to reproduce the moment-rotation response of shallow foundations for wind turbines. This generalized constitutive law, inspired to the one proposed in [6] for reproducing the lateral response of piles, is conceived in the framework of the bounding surface plasticity theory. The main ingredients of this model are a bounding surface and a mixed isotropic-kinematic generalized strain hardening controlling the ratcheting.

The model is capable of qualitatively reproduce (Fig. 2) the experimental results of [2] and seems to be a very promising approach for design purposes. In addition, the model can also simply be introduced in structural finite element codes allowing to solve soil-structure interaction problems also accounting the turbine tower. This can be used to adequately reproduce the whole system response and to also optimize the tower design to dynamic loads.

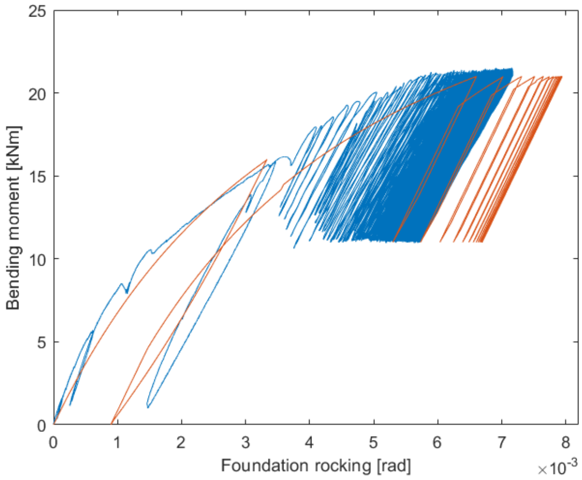

Figure 2: Experimental data from [2] (blue line) vs model results (orange): applied moment versus rocking angle.

Contributor statement

Conceptualization: Luca Flessati & Pietro Marveggio, Formal analysis: Luca Flessati & Pietro Marveggio, Writing: Luca Flessati & Pietro Marveggio

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