Effects of wave-induced two-dimensional seepage flow on sediment incipient motion

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ABSTRACT

Sediment incipient motion is the first stage of the whole process of local scour around a marine infrastructure. Most previous investigations ignored seepage flow on the mobility of bed particles except a recent study including the effects of vertical seepage flow in the prediction of sediment motion. In this paper, a new model further combing the vertical and horizontal seepage force is proposed. The modified Shields parameter by considering two-dimensional seepage is derived. Then, the effects of wave and soil parameters on sediment incipient motion are analyzed. It was found that lower water depth and saturation, higher wave height, shear modulus and permeability, will remarkably increase both modified Shields parameters and the gaps of the results considering vertical and two-dimensional seepage forces. Therefore, the horizontal seepage cannot be ignored.

KEY WORDS: Shields parameter; Sediment incipient motion; two-dimensional seepage force; analytical solution; OpenFOAM®

INTRODUCTION

As the first step of sediment incipient motion in the process of local scour, the critical Shields number is an important threshold condition for the sediment moving from a static condition. Numerous studies (Shields, 1936; Bagnold, 1960; Yalin, 1977) proposed various criteria. In most criteria, the Shields parameter has been commonly used to determine the threshold condition of sediment incipient motion.

Initially, the Shields parameter was used for the unidirectional flows in a flat or near-flat bed. Later, several modifications to the conventional Shields diagram have been proposed for different sediments based on laboratory tests. For example, Madsen and Grant (1976) modified the Shields Criterion obtained for an oscillatory flow. They concluded that the Shields parameter is essential to consider the influence of the sediment incipient motion under the action of wave in the prediction of the local scour. Le Roux (2001) proposed a simple method to predict the threshold of particle transport under oscillatory waves, which was valid for grains of varying size and density in a laminar or turbulent flow. Whitehouse et al. (1988) and Chiew et al. (1994) modified the Shields diagram for a sloping bed with an inclination angle.

The essence of sediment incipient motion is that the driving force acting on the particles is greater than the resistance. In most previous studies, the mean grain size ($d_{50}$) was the only soil parameters involved in the prediction of local scour. They ignored the influence of seepage as well as other soil characteristics. In fact, the concept of seepage has been adopted into the criterion of liquefaction (Jeng, 1997; Zen et al., 1998). The discussion of application of seepage on local scour are also available in the literature. Cheng et al. (1997) and Sumer et al. (2011, 2013) found that seepage had a great effect of sediment incipient motion by experimental research. Qi and Gao (2014) reported that the wave-induced upward seepage brings the sand-bed more susceptible to scouring by a series of experiments. Xia (2014) theoretically examined the effect of wave induced seepage on the sediment incipient motion, which was based on the boundary-layer approximation for a porous seabed (Mei and Foda, 1981). Recently, Guo et al. (2019) modified the Shields parameter by considering the vertical seepage, and established numerical models to discuss the impact of seepage force on sediment incipient motion under an oscillatory flow. Later, Li et al. (2020) further considered the effects of upward seepage on the local scour beneath a pipeline through their CFD model. However, the aforementioned studies only considered the upward seepage, although it should be either two-dimensional or three-dimensional problem.

The aim of this paper is to include the combination of vertical and horizontal seepage in the conventional Shields number. The wave-induced seepage is calculated by two methods. They are: (1) the analytical model for the wave-induced seabed response in an infinite seabed (Hsu et al., 1993; Jeng, 2018), and (2) the numerical model (PORO-FSSI-FOAM, Liang et al., 2019, Duan et al., 2019). Based on theoretical models, the influence of wave and soil parameters on modified Shields parameters will be discussed.