Applied Ocean Research 69 (2017) 116–125

Contents lists available at ScienceDirect

Applied Ocean Research

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

On incipient motion of silt-sand under combined action of waves and currents

Liqin Zuo[a,b], Dano Roelvink[b], Yongjun Lu[a,*], Shouqian Li[a]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, 34 Hujuguan Road, Nanjing, 210024, China
[b] IHE Delft Institute for Water Education, PO Box 3015, 2601 DA Delft, The Netherlands

ARTICLE INFO

Article history:
Received 14 April 2017
Received in revised form 8 September 2017
Accepted 17 October 2017
Available online 5 November 2017

Keywords:
Threshold of sediment motion
Silt
Cohesive force
Additional static water pressure
Shields curve

ABSTRACT

Sediment incipient motion is a fundamental issue in sediment transport theory and engineering practice. Silt has transitional behavior between cohesive and non-cohesive sediment and its incipient motion is still poorly understood. This study aims to find an expression for incipient motion from silt to sand from a unified perspective and analysis. From the analysis of forces, using the derivation method for the Shields curve, an expression for sediment incipient motion is proposed for both silt and sand under conditions of combined waves and currents. The differences and similarities in the sediment motion threshold were analyzed under the effects of waves and currents, and fine and coarse sediment. The Shields number was revised by introducing the cohesive force and additional static water pressure, which indicates that this study could be seen as an extension of the Shields curve method for silt. A number of experimental datasets as well as field data were used to verify the formula. The effect of bulk density on fine sediment was discussed and tested using experimental data.

1. Introduction

Sediment movement occurs when instantaneous fluid forces (entraining forces) on a particle are just larger than the instantaneous resisting forces (stabilizing forces) [1]. This phenomenon is called sediment incipient motion or threshold of sediment motion. Sediment incipient motion is a traditional topic, and is one of the fundamental issues in sediment transport theory and practice.

Sediment grain size is an important factor affecting sediment incipient motion. Basically, distinguished by grain sizes, sediment can be classified into gravel, sand, silt, and clay. Normally, sediment with grain size less than 63 μm (silt + clay) is defined as cohesive sediment and sediment with grain size larger than 63 μm is defined as non-cohesive sediment [2]. For larger particles, sediments behave in a non-cohesive manner, i.e. there is almost no consolidation and the surface erodes particle by particle. For smaller particles, the sediments behave in a cohesive manner, i.e. they consolidate relatively slowly and the surface erodes in aggregates [3]. However, recent field observations and flume experiments have shown that silty sediment or silt-dominated sediment has a special behavior, which is neither like typical sand (non-cohesive) nor like typical mud (cohesive). Erosion tests have suggested that silt-enriched mixtures exhibit cohesive-like behavior [4], but flocculation has not been observed based on settling experiments on silt (with clay contents less than 10%) [5,6]. Silt is often referred to as pesudo-cohesive or semi-cohesive sediment, to be differentiated from non-cohesive or cohesive materials. Silt may hold dual features of non-cohesive and cohesive sediments.

The initiation of motion of non-cohesive sediments (sand and gravel) has been well studied with both experimental and theoretical works. In contrast, relatively little experimental or theoretical work has been done on the initiation of motion of sediments consisting of cohesive particles [7]. In particular, the behavior of silty sediment is poorly understood [8]. Incipience of motion of cohesive sediment has been studied by some scholars e.g. [3,4,7,9,10]. For cohesive sediments, the cohesive force is much larger than gravity and plays an important role in the resisting forces. Flocculation and consolidation are important physical processes and the floc size and bulk density play a dominant role in controlling the incipient motion conditions of cohesive sediments [7,9]. Migniot [11] suggested that the threshold of clay motion follows a direct relation with bulk density.

Since the Shields' curve is not very accurate for fine sediment beds, van Rijn proposed empirical calibration factors (cohesive

---

[*] Corresponding author.
E-mail addresses: l.zuo@un-ihe.org (L. Zuo), yjlu@nhri.cn (Y. Lu).

https://doi.org/10.1016/j.apor.2017.10.005
0141-1187/

Nomenclature

Selected Notation

a	Coefficient
A	Wave amplitude
C_d	Drag force coefficient
c_{gel}	Gelling volume concentration
$c_{gel,s}$	Maximum volume concentration of sand bed
C_L	Lift force coefficient
d	Diameter of bed material
d_{25}	Grain size for which 25% of the bed material is finer
d_{50}	Median size of sediment
D_*	Dimensionless particle size
F_c	Cohesive force
F_D	Drag force
F_L	Lift force
F_V	Wave inertia force
f_w	Wave friction coefficient
F_δ	Additional static water pressure
g	Gravitational acceleration
h	Water depth
H	Wave height
k_s	Roughness height
$\mathrm{Re}\, d_*$	Non-dimensional sediment Reynolds number
Re_*	Shear Reynolds number
s	Relative density
T	Wave period
u_0	The flow velocity near the sediment particle
$\mathrm{u_c}$	Mean current velocity
u_m	Maximum wave orbital velocity
$u_{0,cr}$	The critical velocity on the particles near the bed
u_*	Shear velocity
W	Gravity force (submerged particle weight)
y	Distance above bottom
β	Compaction coefficient
δ	Thickness of laminar layer near wall
δ_s	Thickness of bound water
ε_k	Cohesion coefficient
θ_{zc}	Revised Shields number (incipience number)
θ_c	Shields number
υ	Kinematic viscosity coefficient
ρ	Water density
ρ_s	Sediment density
ρ_0	Dry density
ρ_0*	Stable dry density
ρ'	Wet density
ρ'^*	Stable wet density
τ	Shear stress
τ_c	Critical shear stress
$\tau_{cr,0}$	Critical shear stress from Shields curve
τ_{wm}	Maximum wave shear stress
$\tau_{wc\max}$	Maximum shear stress beneath combined wave and current
τ_{wcmean}	Mean shear stress beneath combined wave and current
ϕ	Angle between wave and current
$\phi_{cohesive}$	Cohesive effects coefficient
$\phi_{packing}$	Packing effects coefficient
χ	Correction parameter

effects and packing effects) for fine sediments [12]. Considering the cohesive force, Tang [13] and Dou [14] proposed a critical velocity for fine sediments. Lick et al. [7] proposed a theoretical description for the fine sediment initiation of motion, including the cohesive forces between particles, as well as changes in bulk density. Righetti and Lucarelli [3] proposed a threshold criterion for incipient motion of cohesive-adhesive sediments, which was also an extension of the Shields curve. Mehta and Lee [8] studied the sediment motion threshold of cohesive materials with $d < 2\,\mu\text{m}$ and proposed some parameters to describe the incipient motion, such as floc density, solid volume fraction, and cohesive force. However, these parameters do not change gradually within the silt size range; instead, they vary rapidly over a comparatively narrow range, which may possibly be represented by a single size for practical purposes. With respect to the threshold condition for motion, Mehta and Lee [8] suggested that the 10–20 μm size may be considered to practically be the dividing size differentiating cohesive and cohesionless sediment behavior, while Stevens [15] proposed that 16 μm was the boundary between sediments that flocculate significantly and those that do not. These theories indicate that the threshold of silt sediment with grain sizes larger than 10–20 μm could be described by grain size, which brings the possibility to extend the cohesionless sediment incipient motion theory to silt sediments.

Earlier studies of the threshold for sediment motion started from uniform flow conditions, and many formulas were proposed. There are two types of formulas: one is based on critical velocity, where the critical condition is expressed by depth-averaged velocity, e.g. [13,14,16], and the other type is based on critical shear stress, where the critical condition is expressed in terms of shear stress; the most widely used is the Shields curve [17,18]. Shields [18] proposed a critical value for the Shields number, $\theta_c = \tau_c/[(\rho_s - \rho)gd]$, as a function of the grain Reynolds number. This theory greatly improved the level of understanding of sediment movement. Here τ_c = critical shear stress, ρ_s = the sediment particle density, ρ = the density of the fluid, g = the acceleration of gravity and d = the sediment particle diameter. The Shields criterion is an empirical relation which is quite general as it applies for any type of fluid, flow, and sediment, as long as the sediment is cohesionless.

Under wave or oscillatory flow conditions, the study of incipient motion of sediment has largely followed the study methods for uniform flow. There are some empirical formulas that have established critical conditions with wave peak orbital velocity [19–22]. Some scholars, e.g. [23,24], established formulas by combining flume experimental data with theoretical analysis. The Shields curve was extended to wave conditions by some scholars, such as [25–27]. Under combined wave-current conditions, the formulas for uniform flow or waves are usually applied to determine the critical conditions of sediment incipient motion, however, the dynamic conditions in the formulas need to be changed to those under the combination of waves and currents. There are mainly two categories. The first one is the Shields curve. Experiments and theoretical studies proved that the Shields curve could also be used in wave and wave-current conditions [25,27–30]. According to van Rijn [1], initiation of motion in combined current and wave motion can also be expressed in terms of the Shields parameters, provided that the "wave period-averaged absolute bed-shear stress" is used. For the second but more fundamental method, the basic shape of the formula was deduced from a mechanical analysis, and then the coefficients in the formula were determined by experimental data. Bagnold and Taylor [31], Manohar [21] and Dou et al. [23] presented expressions for the critical velocity, critical shear stress, or critical wave height using this method.

From the foregoing review it can be concluded that, although the sediment threshold criterion for motion has been studied extensively and many formulas have been proposed, existing formulas are either limited to flow or wave conditions, or limited to a narrow range of sediment grain size, or too empirical. Therefore, research on sediment incipient motion is still drawing worldwide attention. In natural coastal conditions, waves and currents always coexist. This study aims to find an expression for sediment incipient motion