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Entrance/exit losses and cross-sectional stability of double inlet systems

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A B S T R A C T

This study investigates the effect of entrance/exit losses on the cross-sectional stability of double inlet systems. The inlet is in equilibrium when the sand transport into the inlet equals the sand transport out of the inlet. The velocity amplitude corresponding with the equilibrium cross-sectional area is referred to as the equilibrium velocity ($\sim$1 m s^{-1}). This equilibrium is stable when after a perturbation the cross-sections of both inlets return to their original equilibrium value. The amplitudes of the inlet velocities are obtained using a lumped-parameter model in which the basin water level fluctuates uniformly (pumping mode) and where the inlets are schematized to prismatic channels. The system is forced by a semi-diurnal tide, where amplitude and phase may differ between the two inlets. Previous studies concluded that for double inlet systems no stable equilibriums can be found. However, in these studies entrance/exit losses were neglected. In the present study entrance/exit losses are included in the dynamic equation of the inlets.

Using an analytical model it is shown that entrance/exit losses and a difference in the two ocean tidal amplitudes are a prerequisite for the existence of stable equilibriums. Furthermore, the effects of the addition of bottom friction and inertia to the dynamic equation are investigated using a mathematical *continuation method*. The results show that, provided entrance/exit losses are considerably larger than bottom friction and inertia, stable equilibriums are possible. These conclusions are supported by observations in the Ria Formosa, southern Portugal. Care should be taken in using the stability model described in this paper as a predictive tool due to simplifications in the model and the uncertainty in determining certain parameter values including inlet length, entrance/exit loss coefficient, bottom friction factor and equilibrium velocity. To alleviate these shortcomings suggestions are made for future research.

1. Introduction

Barrier island coasts are highly dynamical systems that serve as a first defense for the hinterlying mainland. Examples are the Wadden Sea coast of the Netherlands, Germany and Denmark (Ehlers, 1988), the coast of the Gulf of Mexico, the U.S. East Coast and Ria Formosa in Southern Portugal. These barrier island coasts are a concatenation of tidal inlet systems, in which a tidal basin or back-barrier area is connected to the ocean or sea by one or more tidal inlets.

Tidal inlet systems in sandy environments consist of different elements including ebb tidal delta, inlet channel and basin. Restricting attention to inlets where river flow has a minor impact the dimensions of the various elements are a result of tide and waves. The interest here is in the equilibrium and stability of the cross-sectional area of the inlet channel; the channel connecting ocean and basin. Referring to Escoffier (1940) the cross-sectional area of a tidal inlet takes on a value such that the sand transport into the inlet equals the sand transport out of the inlet. The velocity amplitude corresponding with the equilibrium cross-sectional area is referred to as the equilibrium velocity. Based on observations Escoffier suggested an approximate value of 1 m s^{-1}, the exact value depending somewhat on the volume of littoral drift. The actual cross-sectional area oscillates around this equilibrium value. By opening a new inlet or as a result of land reclamation the deviation from the equilibrium value can become so large that the cross-sectional stability is challenged and one of the inlets closes. It is therefore of importance to assess if and under what conditions stable equilibrium configurations of multiple tidal inlet systems are expected to exist.

As a first step to investigate multiple tidal inlet stability, van de Kreeke (1985, 1990) studied the stability of a double inlet system. He used a lumped-parameter model to describe the hydrodynamics

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of the system. In the lumped-parameter model the dynamics of the flow in the inlet is governed by inertia, entrance/exit losses and bottom friction on the one hand and the pressure gradient across the inlet on the other hand. For a more detailed description of the model, see Section 2.1. Similar to Keulegan (1951) van de Kreeke simplified the dynamic equation by only retaining the quadratic bottom friction and pressure gradient while neglecting inertia and entrance/exit losses. The double inlet system was assumed to be in equilibrium if the velocity amplitude in the inlets equals the equilibrium velocity taken as approximately 1 m s^{-1}. The forcing off the two inlets consisted of a simple harmonic tide with equal amplitude and phase. The main conclusion was that for these conditions no stable equilibrium(s) exist, i.e. ultimately one of the inlets would close. Furthermore, he suggested that a similar conclusion holds for multiple-inlet systems.

Several observations, however, have shown that multiple-inlet systems are potentially stable for a long period of time. Examples are Gasparilla Sound in western Florida (Escoffier, 1977), the Dutch Wadden Sea (Louters and Gerritsen, 1994) and Ria Formosa in southern Portugal (Salles et al., 2005). These observations suggest that the assumptions of the lumped-parameter model used by van de Kreeke (1985, 1990) might be too restrictive and do not take into account important (nonlinear) processes, such as tidal distortion (e.g. Boon and Byrne, 1981). To overcome these restrictions, state of the art process-based models describing the complex flow field (e.g. Salles et al., 2005; Dias et al., 2009) and resulting sediment transport and bottom changes (e.g. Dastgheib et al., 2008) have been used. Although progress has been made many of these models are still in a developmental state. For this reason, in evaluating cross-sectional stability investigators have used a semi-empirical approach in which the hydrodynamics is described by the aforementioned lumped-parameter model and the equilibrium is governed by the condition that the velocity amplitude equals the equilibrium velocity. Examples are Pass Cavallo-Matagorda Pass, a double inlet system in Texas (van de Kreeke, 1985); St Andrew Inlets, a double inlet system in Florida (Jain et al., 2004); and the Frisian Inlet, a single inlet system in The Netherlands (van de Kreeke, 2004). In these studies the lumped-parameter models were calibrated and validated using observed water level and velocity data. A comparison between the results of a 2-D finite difference hydrodynamics model and a lumped-parameter model is presented in Herman (2007), which shows that the lumped-parameter model captures the dynamics of the inlet flow.

Among other applications, the lumped-parameter model including inertia and bottom friction was used to carry out stability calculations for the Marsdiep-Vlie system: a double inlet system in the Dutch Wadden Sea (Brouwer et al., 2007). The argument to neglect the entrance/exit losses was that the inlets in this system are relatively long and therefore the entrance/exit loss term is small compared to the bottom friction term. The calculations did not result in stable equilibriums even when taking different forcings off the two inlets.

Recent observations in the Ria Formosa (Pacheco et al., 2010, 2011a) seem to contradict the earlier findings reported in van de Kreeke (1990) and Brouwer et al. (2007), which suggest that double inlet systems cannot be in equilibrium. Ria Formosa is a shallow lagoon in the southern part of Portugal connected to the Atlantic Ocean by multiple inlets. These inlets have persisted on a historical time scale. In particular the sub-system consisting of the two inlets Faro and Armona and connecting a single basin to the ocean can be considered in stable equilibrium as will be discussed in more detail in Section 6. A characteristic of this double inlet system is that inlets are relatively short and therefore entrance/exit losses are not necessarily small compared to bottom friction losses. The objective of the present study is to investigate the role of the entrance/exit loss term in cross-sectional stability of double inlet systems with special reference to the double inlet system Faro–Armona.

2. Governing equations and methods

2.1. Governing equations

In this study the double inlet system is schematized to a single basin connected to the sea or ocean by two tidal inlets (Fig. 1). The basin is relatively small and deep and the tidal inlets are prismatic channels with diverging sections on either end. In this paper the focus is on cross-sectional stability. Following Escoffier (1940) an inlet is in equilibrium if the amplitude of the inlet velocity equals the so-called equilibrium velocity $\hat{u}_{\mathrm{eq}}$. Escoffier took this velocity to be 0.9 m s^{-1}. Later Bruun et al. (1978) suggested a value of 1 m s^{-1}. The equilibrium is stable when after a perturbation of the equilibrium, the cross-sectional areas return to their original equilibrium values.

For inlets that are in equilibrium and assuming average weather conditions (as opposed to storm conditions) there is a balance between the volume of sediment entering and leaving the inlet. The volume entering the inlet is taken as a constant fraction of the littoral drift and the volume leaving the inlet is taken proportional to a power of the ebb tidal velocity amplitude (van de Kreeke, 1998). The sediment is uniformly distributed over the inlet length and sediment exchange between inlet and basin is assumed to be negligible. Under these assumptions, the rate of change of the cross-sectional area can be written as (van de Kreeke, 1998)

$$\frac{\mathrm{d}A_k}{\mathrm{d}t} = \frac{M}{L}\left(\left(\frac{\hat{u}_k}{\hat{u}_{\mathrm{eq}}}\right)^n - 1\right), \quad k = 1, 2. \tag{1}$$

Here A_k is the cross-sectional area of inlet k (m^2); t is time (s); L is the inlet length (m); M is a constant fraction of the littoral drift (m^3 s^{-1}); $\hat{u}_k$ is the cross-sectionally averaged velocity amplitude in inlet k (m s^{-1}), calculated using the lumped-parameter model; $\hat{u}_{\mathrm{eq}}$ is the equilibrium velocity (m s^{-1}). For the inlet velocity $\hat{u}_k$ equal to $\hat{u}_{\mathrm{eq}}$, $\mathrm{d}A_k/\mathrm{d}t = 0$. This implies that the inlet system is in equilibrium. n is a power whose value depends on the adopted sand transport law. Values of n range between 3 and 6 (van Rijn, 1993). Eq. (1) is used to calculate the unit vectors in the flow diagram, Fig. 2. The direction of these vectors in the neighborhood of the equilibrium determines whether the equilibrium is stable or unstable. Linearizing Eq. (1) it can be shown that in the neighborhood of the equilibrium the direction of these unit vectors becomes independent of n. Therefore, the value of n does not play a role in the stability of the equilibrium. In the calculations n was somewhat arbitrarily given a value of 3.

The response of the inlet cross-sectional area and the equilibrium state is governed by the amplitude of the inlet velocities $\hat{u}_k$. These velocities are calculated using a lumped-parameter model. In this model the dynamics of the flow in the diverging sections is

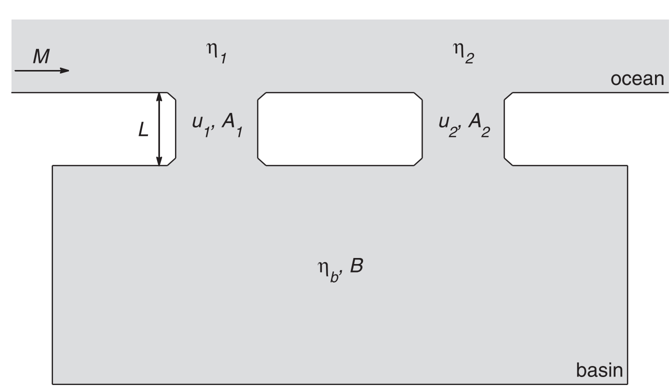

Fig. 1. Schematization of a double inlet system draining a single basin. For an explanation of the symbols, see Section 2.1.