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# A Natural and Anthropogenic Squeeze of the Monsoon Tidal Inlet †

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**Abstract:** This study investigates the influences of natural and human-induced spatial blocking on the morphological and hydrodynamic features of the Tien Chau tidal inlet. It is observed that the absence of the downdrift barrier island and the appearance of the headlands form a squeeze tidal inlet. Moreover, anthropogenic factors, including urbanization and aquacultures, block a large part of the flood-tidal delta. These natural and human-induced spatial restrictions have significant influences on the hydro and morphodynamic characteristics of the inlet. In order to obtain more insight, a schematized numerical model was constructed in the Delft3D model and validated using measured field data.

**Keywords:** squeeze; climate change; numerical model; field measurement; monsoon tidal inlet; human constructions

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## 1. Introduction

Ky Lo river basin located in Phu Yen District, Quang Ngai Provinces, Vietnam, covers approximately 1180 km$^2$. The Ky Lo river basin reaches the East Sea in the south region of the Xuan Dai Bay through a narrow inlet named Tien Chau tidal inlet. This tidal inlet environment was the study area (Figure 1). Xuan Dai Bay is bound by relatively steep, sandy shorelines and has a large entrance with free exchange to the Southeast sea. Because of the significant water exchange during the tidal cycle, The Xuan Dai Bay can be considered tide-dominated, even it is located on a low meso tidal coast [4]. Xuan Dai Bay can be divided into two major regions associated with the two prominent headlands. The north headland mostly shelters the northside area of the Xuan Dai Bay, and the southeast headland covers the southside area of the Xuan Dai Bay (Figure 2). The north headland provides a natural protective barrier and blocks incoming waves from the north and east directions. Thus, tidal processes tend to dominate the former region. A southeast headland provides shelter from waves that are coming from the east and north direction. The Tien Chau tidal inlet is located in the south area of Xuan Dai Bay. Most incoming waves at this location are from the southeast direction. Therefore, a mix of tide and wave processes tend to dominate this area.

Situated at the South of Xuan Dai Bay, the Tien Chau tidal inlet locates in a tropical monsoon region with a distinct dry and wet season [10] coinciding with the Northeast monsoon and Southwest monsoon, respectively [1]. From November to April, the dry season is characterized by little rain, dryness, and moderate temperature (20-300C). The wet season is from May to October and is characterized by high rainfall, humidity, and high temperature (30-400c). The Tien Chau tidal inlet is filling with sediment [12]. The deposition of sediment around the tidal inlet negatively influences the operation of boats and ships in this region. It is suggested that the water depth at some regions in the ebb-tidal delta region is only about one meter during low-tide water. Only small boats of less

than 50 horsepower can transport in these conditions, and local fishing vessels cannot access the Tien Chau finishing port. This is a typical problem of tidal inlets located in the central region of Vietnam [11].

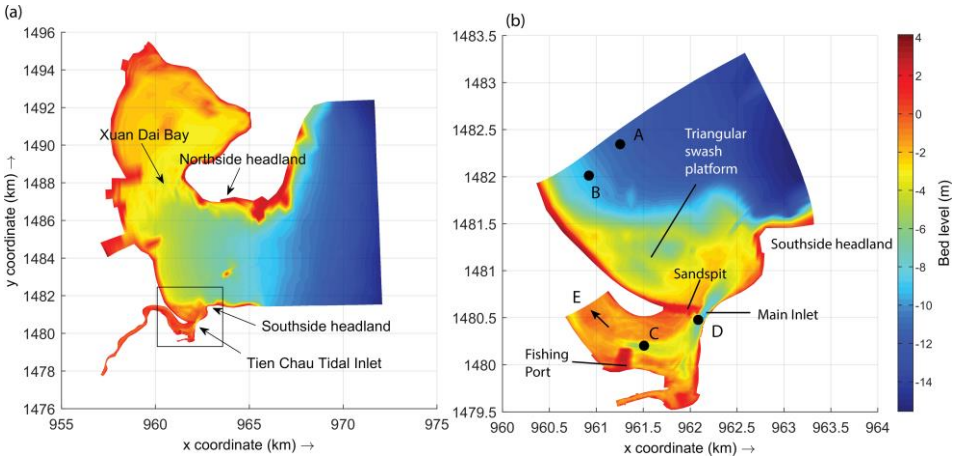


**Figure 1.** (a) Overall location of the study area, Tien Chau tidal inlet connects Tien Chau Estuary and the South East Sea. (b) The zoom-in descriptions of the main entrance of the region with descriptions including the inlet, the Fishing Port, the updrift sand spit, the southside headland of the Xuan Dai Bay. The detailed measured bathymetry of the study area (in 2019) and observation stations A, B, C, D, and E (in 2019) are included.

**Figure 2.** Tien Chau tidal inlet captured by drone in 2019. It is observed that many houses are constructed at the downdrift barrier of the inlet. The sandspit at the updrift side moving toward the Southside.

It is observed that the Tien Chau tidal inlet anchors next to a headland and is bordered on its opposite side by a sandspit (Figure 1 & 2). In this condition, most of the incoming waves were blocked by the southside headlands (Figure 1 & 2). Moreover, the river discharge during historical flooding events can be six times larger than that during normal conditions [11]. Furthermore, it is observed that the human constructions, including the aquacultures and housing in the flood-tidal delta and in the downdrift barrier, took the place of the flood-tidal delta. It is observed that the updrift sand spit of the tidal inlet keeps fluctuating toward the ebb-tidal delta [11]. Understanding the hydrodynamics and morphodynamics processes of monsoon tidal inlets that are affected by the river discharge, sheltered and constricted by human constructions and headlands is still in its infancy. Therefore, the main objectives of this study are to understand the primary morphological and hydrodynamic processes of such inlet systems.

## 2. Materials and Methods

In order to obtain more insight into the physical processes of the study area, a field measurement campaign was conducted. Important hydrodynamic and morphological characteristics of the system were examined. In addition, a schematised model of the study area was constructed in Delft3D. The model was calibrated and validated using the measured data. The Tien Chau Estuary region's primary field measurement data sets are the topography of the study area, the water level at the Tien Chau tidal inlet, and the flow at the Tien Chau tidal inlet and the wave height at the Tien Chau coast. The current & water level data were collected using Acoustic Wave and Current Profiler (AWAC). The wave data was recorded using Wave droid.

Moreover, a schematised model of Tien Chau Estuary was constructed in Delft3D. The model Delft3D was chosen as a numerical solver as it contains the necessary physical processes, including the drying and wetting of large tidal flats, the interaction between wave and current, and sediment transport [5]. Delft3D-FLOW has been commonly used to simulate hydrodynamics and morphodynamics in shallow water environments, including tidal inlet systems [6].

## 3. Results

Figure 3a illustrates the water levels at the Tien Chau fishing harbor (station C) from 2nd June and 9th June 2019. One high and one low tide per day can be seen in the time series of the water level. The mean spring tidal range is around 1.5 m. Thus, the tidal regime of the system can be classified as micro-tidal [4]. The form factor is 1.96, indicating that the Tien Chau estuary can be classified as mixed and mainly diurnal [2]. Moreover, the falling period is larger than the rising period. Therefore, the Tien Chau tidal inlet experiences tidal asymmetry [3].

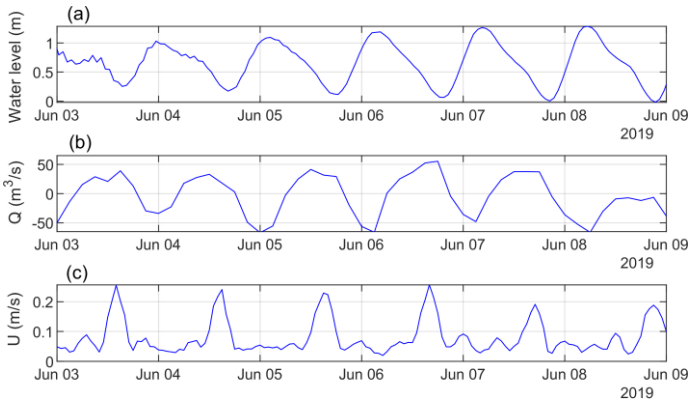


**Figure 3.** Typical forcing conditions at the Tien Chau tidal inlet, data collected between 2nd June and 9th June 2019 including (a) Measured water levels at the fishing harbor (station C); (b) Hourly discharge at the tidal inlet (station D); (c) depth-averaged streamwise velocity at the harbor (station C).

Figure 3b shows the discharge time series measured by ADCP at station D, at the main tidal inlet. The tidal prism (P) is estimated at approximately 2.4x10$^6$ m$^3$ by $P = \frac{1}{2}\int_0^T |Q(t)dt|$ [2]. P is the tidal prism, $Q(t)$ is discharge at the inlet, and T is a tidal cycle. Figure 3c illustrates the magnitude of the depth-averaged streamwise velocity at the fishing harbor. The maximum velocity is approximately 0.25 ms$^{-1}$. The peak currents at this location typically occur during the low tide and are associated with the maximum discharge at the inlet entrance.

Figure 4. a, b sketch the major morphological characteristic features of a normal tidal inlet located in a mesotidal/mixed energy region [2] and that of the Tien Chau tidal inlet, respectively. In the Tien Chau tidal inlet, the downdrift barrier is absent, and the southeast

headland provides a natural barrier blocking most of the incoming waves from the north-east direction. As a result, in the ebb-tidal delta of the Tien Chau tidal inlet (Figure 4b), the left and right swash bars, which are usually formed in a usual tidal inlet (Figure 4a), are merged into a single large triangular swash bar platform (see Figure 1b and 4). A terminal lobe is located at the outer edge of the triangular swash bar. In the flood-tidal delta, different tidal flats also tend to migrate and merge into a large tidal flat region (Fig 4b). This tidal flat region is directly attached to the sand spit and located next to the main channel of the inlet.

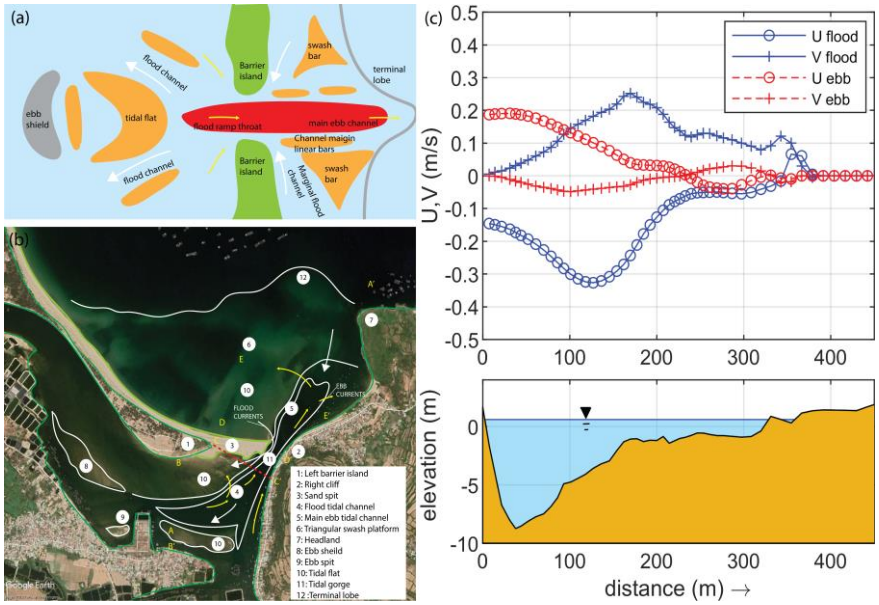


**Figure 4.** The major morphological features of (a) a regular tidal inlet located in a mesotidal/mixed energy (Bosboom and Stive, 2021); (b) the Tien Chau inlet: an asymmetry, sheltered and squeezed located in a monsoon region with micro-tidal/moderate energy; (c) Profiles of depth-averaged streamwise velocities (circles) & transverse velocities (plusses) extracted from the numerical model during the flood period (blue) and ebb period (red) near the throat of the inlet (section C-C').

Moreover, as described previously, it is also observed that the construction of houses, fish farms, and fishing port blocks the development of the downdrift barrier and limits the accommodation space in the flood-tidal delta. In these conditions, the spatial restriction disturbs the dynamic equilibrium of the tidal inlet system and prevents the inlet from "fluctuating" toward its new equilibrium stage under the combined influences of sea-level is rises and annual river floods. The sand spit and the accommodation space of the system tend to be pushed toward the outer delta. Assuming that there is no change in the longshore drift, then the amount of the sediment accumulated in the outer delta will increase continuously, and the tidal inlet is continuously filling with sediment. In this sense, the term squeeze, which has been widely used for coastal regions [7] and ecological systems [8], can also be adopted for the Tien Chau tidal inlet.

Figure 4c shows the numerical results of the distribution of the depth-averaged streamwise and transverse velocity at the crosssection C-C' near the throat of the inlet (see Figure 4b). It is suggested that the water depth in the main channel increases to 8.5 m. During the flood period, the depth-averaged streamwise velocity reaches its maximum value of around 0.32 $ms^{-1}$ at the middle of the transition slope between the shallower tidal flat and the main channel (x = 120 m). The depth-averaged transverse velocity is positive, and its maximum value is about 0.3 $ms^{-1}$. This means that the direction of the flood currents is also toward the left bank. It is observed that a single main channel is flanked by the flat area on the flood tidal delta and the triangular swash region on the ebb-tidal delta.

In this context, the hydrodynamics of the flood-tidal delta is similar to that of a compound channel (see lower panel of Figure 4c) consisting of a floodplain, transition slopes,

and a main open channel [9]. Thus, from a fluid mechanics perspective, the squeeze phenomenon of the Tien Chau tidal inlet may be approached as similar to the squeeze of a floodplain channel. The width of the floodplain region was reduced due to the construction of fish farms [9].

## 5. Conclusions

This study investigated the forcing conditions, morphological features, and hydrodynamic characteristics of an asymmetry tidal inlet located in a monsoon region, sheltered by headlands, and affected by human constructions. Morphological features of the inlet were identified and studied using measured data in combination with satellite imagery. A numerical model was built to determine the depth-averaged streamwise and transverse velocity profile at the inlet. It is suggested that the north and southeast headlands of Xuan Dai Bay offer a natural barrier blocking most of the southeast and north coming waves. A wave-built sand spit elongated from the updrift sand barrier island can be clearly observed. Moreover, it is observed that the human constructions block the development of the downdrift sand barrier island and the accommodation space in the flood-tidal delta. In this context, the term squeeze was adopted for the Tien Chau tidal inlet. This phenomenon makes the morphological features of the Tien Chau tidal inlet different from that of a regular inlet. Small tidal flats tend to merge to a large one and are more dominant around the inlet and the ebb-tidal delta. The triangular swash bar in the ebb-tidal delta and the tidal flats in the flood-tidal delta are located next to the main inlet, forming a compound channel. The sand spit tends to fluctuate toward the outer delta, and more sediment tends to be deposited in the ebb-tidal delta. Now the generic understanding of the hydrodynamic and morphological features of the Tien Chau tidal inlet has been clarified. Future work will further prove the squeeze hypothesis adopted for the Tien Chau tidal inlet by applying different scenarios of the numerical simulations.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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