



# Mangrove forest against dyke-break-induced tsunami on rapidly subsiding coasts

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**Abstract.** Thin coastal dykes typically found in developing countries may suddenly collapse due to rapid land subsidence, material ageing, sea-level rise, high wave attack, earthquakes, landslides, or a collision with vessels. Such a failure could trigger dam-break tsunami-type flooding, or “dyke-break-induced tsunami”, a possibility which has so far been overlooked in the field of coastal disaster science and management. To analyse the potential consequences of one such flooding event caused by a dyke failure, a hydrodynamic model was constructed based on the authors’ field surveys of a vulnerable coastal location in Jakarta, Indonesia. In a 2 m land subsidence scenario – which is expected to take place in the study area after only about 10–20 years – the model results show that the floodwaters rapidly rise to a height of nearly 3 m, resembling the flooding pattern of earthquake-induced tsunamis. The depth–velocity product criterion suggests that many of the narrow pedestrian paths behind the dyke could experience strong flows, which are far greater than the safe limits that would allow pedestrian evacuation. A couple of alternative scenarios were also considered to investigate how such flood impacts could be mitigated by creating a mangrove belt in front of the dyke as an additional safety measure. The dyke-break-induced tsunamis, which in many areas are far more likely than regular earthquake tsunamis, cannot be overlooked and thus should be considered in disaster management and urban planning along the coasts of many developing countries.

## 1 Introduction

The utilization of coastal areas has dramatically increased over the last century. The growing population of most countries has brought about an extensive conversion of natural coastal landscapes to agriculture, aquaculture, residential, and industrial usages. About 23 % of the world’s population now lives within 100 km of coastlines, and population densities in coastal areas are about 3 times larger than the global average (Small and Nicholls, 2003; United Nations, 2006; Valiela, 2006). In fact, many of the world’s largest cities have developed close to the sea. Jakarta, the capital of Indonesia, is one such coastal megacity, with a population exceeding 9.6 million (as of 2010), and covering a total land area of 662 km<sup>2</sup>, plus approximately 2.5 million daily commuters from neighbouring cities (Djaja et al., 2004; Firman et al., 2010). The population growth rate reached 1.39 % yr<sup>-1</sup> over the period of 2000–2010 (Central Board of Statistics, 2010), which has made Jakarta one of the most densely populated cities in the world, and it is expected to reach 30 million inhabitants by 2030.

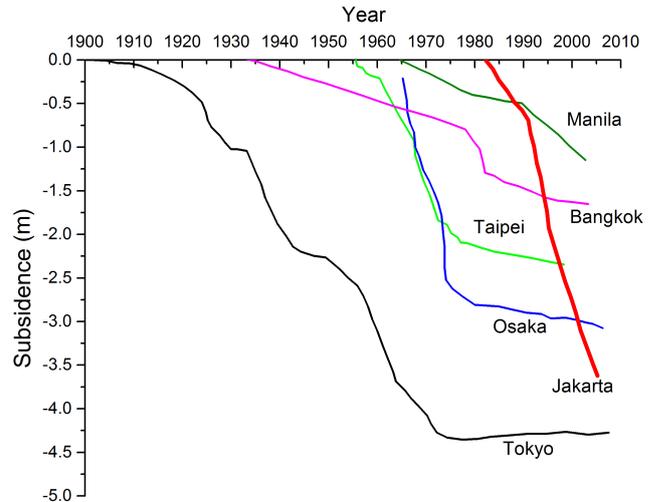
As a consequence of this rapid development, Jakarta has been facing many urban development issues. Amongst these, land subsidence appears to have become particularly serious over the last couple of decades. This problem was clearly recognized as far back as 1978, when substantial cracks were found in buildings and a bridge in downtown Jakarta (Djaja et al., 2004), and subsidence rates along the coast have progressed at a rate of 9.5 to 21.5 cm yr<sup>-1</sup> in the period between 2007 and 2009 (Chaussard et al., 2013). This problem has been mostly caused by the widespread practice of ex-

tracting water for industrial uses, and has led to severe damage to buildings and infrastructure, increases in the extent of flooded areas, the destruction of local ground water systems, and an increase in saltwater intrusion (Braadbaart and Braadbaart, 1997; Ng et al., 2012). If groundwater extraction continues at the current rate, it has been estimated that Jakarta will sink a further 5–6 m by 2100 (Brinkman, 2012). As the Jakarta Coastal Development Strategy (Ministry of Infrastructure and the Environment, 2012) urges, policymakers and city officials should prioritize solving the land-subsidence problem as soon as possible, which obviously requires finding alternative provisions of clean water for the city.

Land subsidence due to the extraction of groundwater is a problem that has been faced by many other megacities in Asia (Fig. 1). However, the current subsidence rate in Jakarta appears to be the fastest among the historical series of cities in the region, which seem to have all substantially slowed down in recent years. If effective countermeasures to mitigate land subsidence are not undertaken in Jakarta, future coastal or fluvial flooding events will likely cause greater damage than what is expected at present, especially given the increased exposure due to population growth and migration to coastal areas. Budiyo et al. (2016) point out that the largest driving influence on future flood risk in this city is land subsidence, exceeding other factors such as sea-level rise, changes in extreme precipitation, and land use change, based on the global climate models (GCMs) and a hydrology model. From 2000 to 2050 the potential flood extent is estimated to increase by 110.5 km<sup>2</sup>. Land subsidence is responsible for 88 % of this increase (Takagi et al., 2016a).

The authors are also concerned that land subsidence will rapidly lead to a decrease in the stability of coastal dykes, which even at present appear to be too thin and fragile to permanently hold back seawater (Fig. 2). Given the current rate of subsidence it is clear that the height of the dykes will need to be raised to compensate and keep communities behind them safe. However, it is feared that this type of fragile dyke could collapse at any moment due to the subsidence, sea-level rise, the ageing of reinforced concrete, earthquakes, landslides, or a collision with vessels. This would inevitably cause what the authors have termed a “dyke-break-induced tsunami”, which would rapidly engulf the densely populated low-lying areas and likely cause massive loss of life.

The authors coined the term dyke-break-induced tsunami (or dyke-break tsunami) to clearly illustrate to members of the public the danger and phenomenon that could be caused by the rupture of a coastal dyke. Local people are often unaware of the dangers posed by violent inundation events. For example, superstrong Typhoon Haiyan in 2013 caused a massive storm surge, claiming more than 6000 lives in the Philippines, even though the meteorological agency in the Philippines issued a typhoon warning with a potential storm surge height up to 7 m a day before the landfall. According to the authors’ post-disaster survey, however, a number of local inhabitants could not realize what would happen due to storm



**Figure 1.** Land subsidence in Asian megacities (Kaneko and Toyota, 2011; Takagi et al., 2016a).

surge as many of them had only just heard the term for the first time. Many people expressed the view that it would have been better for authorities and media to describe it by a simpler vocabulary such as a tsunami (Takagi et al., 2015; Esteban et al., 2015, 2016; Mikami et al., 2016). In this regard, the term “flood” (Indonesian: “banjir”) is unlikely to evoke the real danger that would be caused by a dyke-break event, since local inhabitants may imagine a gradually increasing persistent inundation as it always happens, particularly in Jakarta. Based on this consideration, the authors purposely coined dyke-break-induced tsunami to get people to easily imagine the serious consequences that could arise from the break of a dyke.

The authors consider that the risk of dyke-break tsunamis is far greater than regular earthquake tsunamis in Jakarta. Indeed, Indonesia is located in a tectonically active area where different plates (the Eurasian, Indo-Australian, Pacific, and Philippine sea plates) converge. Along the plate boundaries, there have been many earthquakes and volcanic activities. Some of the earthquakes and volcanic activities generated tsunamis, which have caused severe damage to coastal areas in Indonesia many times (Latief et al., 2000; Rynn, 2002; Brune et al., 2010; Paris et al., 2014). However, since Indonesia is composed of many islands and surrounded by different oceans and seas, each coastal area has a different frequency and magnitude of tsunamis. The north of Jakarta faces the Java Sea, which is surrounded by Borneo and Java Islands. According to Horspool et al. (2014), coastal areas along the Java Sea including Jakarta have a relatively low possibility of experiencing a large tsunami, compared with other areas, such as Indian Ocean coasts of Sumatra and Java Islands and coastal areas along the Molucca Sea. This is because there have been few major earthquakes recorded in the Java Sea,



**Figure 2.** Coastal areas around Jakarta (photos taken by the authors during field surveys in the period between May 2015 and February 2016). (a) A thin coastal dyke protecting a community experiencing rapid subsidence (district of Pluit, northern Jakarta). Leakage of seawater through a concrete joint was observed during the authors' visual inspection on 6 February 2016. The sea level was 1.3 m higher than the road. (b) The town centre of Pluit, with a high population density and long narrow paths. (c) Mangrove conservation site in Jakarta (see Fig. 3 for its location) (d) Mangrove rehabilitation site in the Jakarta Fishing Port (see Fig. 3 for its location). The mangrove belt is around 20 m thick and can effectively protect the port basin from wind waves.

and also because tsunamis, even if generated, will be blocked by many islands and narrow straits.

In the present paper the authors will assess the consequences that the collapse of coastal dykes would have on such a vulnerable area by means of a detailed flood simulation based on a recent topographical survey in Jakarta. As a potential relatively low-cost countermeasure, the authors propose the plantation of mangrove forests in front of the thin concrete dyke to increase the resilience of the structure and reduce flow velocities and damage in the event of a break. The effectiveness of such mangrove forests will also be evaluated by the numerical model.

## 2 Methodology

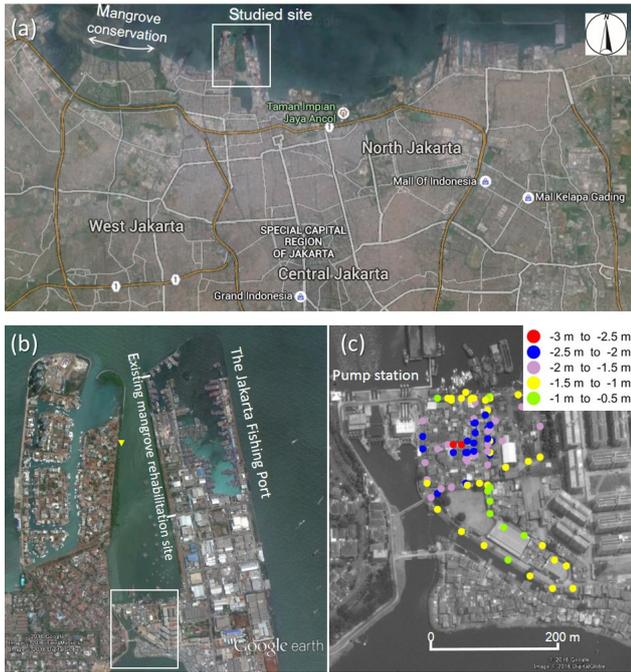
This section describes the basic data for the flood simulation which were obtained by the field investigation. Essentially, the authors fear that a dyke such as the one in Pluit is structurally deficient and is unlikely to withstand the excessive water pressures imposed on it during extremely high tides. Thus, countermeasures such as the planting of mangroves in front of it would be beneficial to improve its stability and reduce the consequence of a potential failure. The numerical model used will be briefly explained later in the paper.

### 2.1 Field investigation

The authors conducted a series of field surveys along the coastline of Jakarta (Fig. 3) in January 2015, May 2015, September 2015, February 2016, and May 2016 in order to investigate the current situation of Jakarta's coast and identify the potential coastal hazards affecting local communities. After these surveys, the authors clearly identified the Pluit district as one of the most vulnerable coastal communities in Jakarta, and carried out a precise topographical survey of the district (Fig. 3c). This area is particularly important for flood protection in the city as it has a pumping station, Pluit pump station, which is the largest in Jakarta, with a discharge capacity of nearly  $50 \text{ m}^3 \text{ s}^{-1}$  (JICA, 2013). Thus, the study of the area is not only important from the point of view of the consequences that a rupture would have for the local population, but also because of the potential disruption for Greater Jakarta due to the malfunction of this important facility.

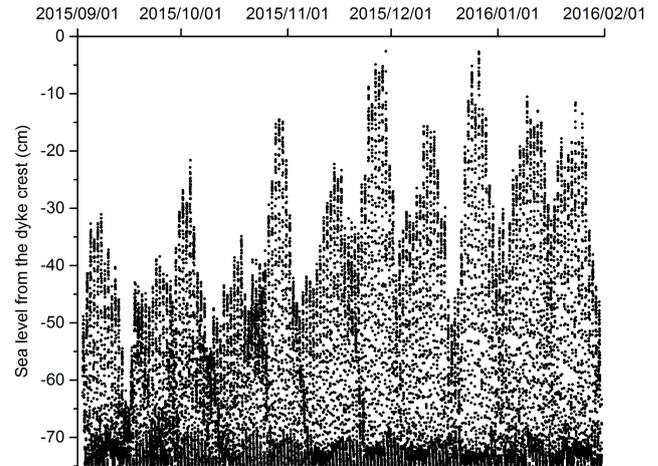
### 2.2 Land subsidence scenarios

Coastal dykes in Jakarta need to be periodically heightened in order to keep up with the continuing land subsidence of the city, though this leads to a progressive decrease in structural stability. The dykes have already been overtopped, with



**Figure 3.** (a) Map of central and northern Jakarta, (b) Study area, which is adjacent to Jakarta's largest fishing port. A yellow inverse triangle indicates the location of the installed pressure sensor, and (c) the district of Pluit, in which the authors measured ground elevations with a laser rangefinder (Fig. 2b). The ground elevations were adjusted to the highest water level shown in Fig. 4.

Fig. 5 (left) showing the situation during the 2007 historical floods, and were subsequently raised after the event. However, the dyke freeboard has almost disappeared after just 6 years (Fig. 5, right), demonstrating the rapid subsidence which has taken place in this period. In this sense, Chaussard et al. (2013) indicated that the rate of subsidence observed near the district of Pluit was  $21.6 \text{ cm yr}^{-1}$  in the period between 2007 and 2009. As explained earlier, it is clear that effective countermeasures against land subsidence have not yet been put in place in Jakarta. Therefore, the authors have simply assumed that the current pace of land subsidence will continue for a while, with overall ground levels being 2 m lower than at present within the next 10–20 years. It is clear that this level of 2 m could be an overestimate if adequate policies are put in place. For example, the “100-0-100” sanitation policy issued by the Ministry of Public Works (PU) aims to provide 100 % of water supply needed for the Jakarta metropolitan area by 2019 and thereby stop the rapid subsidence (Budiyono et al., 2016). However the authors consider that this is unlikely to happen in the short term, and thus flood simulations were performed for both present conditions and this future scenario, as illustrated in Fig. 6.



**Figure 4.** Sea level in Pluit bay with reference to the top of the dyke (Fig. 3b). Note that the top of the graph represents the top level of the dyke, and the y axis represents the maximum water level with reference to that point. Sea levels were recorded at 10 min intervals between September 2015 and February 2016, and were derived by subtracting atmospheric pressures from total pressures.

### 2.3 Mangrove plantation for mitigating floods

Indonesia has the world's largest proportion of mangrove surface area, though currently less than half its original extent (Global Nature Fund, 2007; Rasmeemasuang and Sasaki, 2015). Mangroves usually grow in locations sheltered from waves and in areas between the mid-tide level and the highest high water spring tide. Within this intertidal zone, species have different preferences for elevation, salinity, and frequency of inundation (Global Nature Fund, 2007; Ellison, 2009).

One of the advantages of applying mangroves as a flood protection strategy is that they can be expected to naturally respond to increased sea levels or land subsidence, and thus do not require expensive maintenance, unlike a concrete dyke system which has to be periodically upgraded to keep up with the pace of subsidence. Mangroves are considerably resilient with regards to protecting against shoreline change (Alongi, 2008). Gunderson et al. (2002) uses the term “ecological resilience” when talking about such abilities of ecosystems to recover from disturbance. Basically, accretion in these wetlands may be brought about by an accumulation of organic matter produced by the plants themselves (Valiela, 2006). In fact, available data on the piling-up rates suggest that many coastal marshes accrete at rates well comparable to sea level rise (e.g. Wood et al., 1989; Reed, 1990; Lynch et al., 1989; Day and Templet, 1989; Parkinson et al., 1994; Kearney et al., 1994).

*Avicennia marina*, commonly known as white or grey mangrove, is predominant in Jakarta and is particularly important to attenuate waves in the area (Oka et al., 2004; Herison et al., 2014). Jakarta Bay is relatively calm in terms of



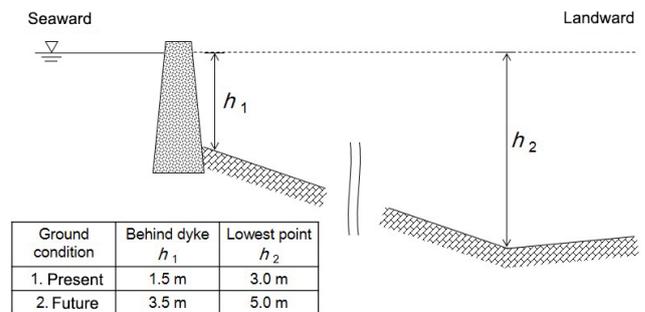
**Figure 5.** The district of Pluit in Jakarta is situated below sea level. The area suffered extensive inundation during high tide on 26 November 2007 (left). The thin dyke protecting the settlement was raised by about a metre after the 2007 high-tide event by the local government, obstructing people’s view of the sea. The photo was taken on 18 October 2013 (right). (Photos: courtesy of Brinkman, J. J., Deltares).

its wave climate, and is also characterized by a high sediment flux from the many rivers in the area. The district of Pluit is particularly well sheltered from high waves, owing to the presence of two salient landfills (Fig. 3b), which can be considered as an ideal location for mangrove rehabilitation. In fact, a mangrove rehabilitation project was already implemented at the Jakarta Fishing Port nearby Pluit (Fig. 3b), and the effectiveness to reduce waves and stabilize the port break-water has been acknowledged (Oka et al., 2004).

Another advantage of mangroves as a flood protection strategy is that they would effectively absorb wave energy or tidal current. The present study thus also analyses scenarios where a 20 m mangrove belt would be created in front of the concrete dyke of Pluit, which would essentially be similar to other existing mangrove protection in the vicinity (Oka et al., 2004). However, the extent of energy absorption by mangroves largely depends on tree density, diameter, bed slope, bathymetry, characteristics of waves, and tidal condition (Alongi, 2008; Rasmeemasuang and Sasaki, 2015). It should also be noted that a lack of contemplated design against sea-level rise and/or land subsidence will cause the created mangrove to end up being submerged under mean sea level, resulting in the loss of its function against potential coastal floods. Thus, it is clear that more detailed analysis would be required to identify the ideal dimension of the mangrove belt for a particular site, though that is outside the scope of the present paper.

**2.4 Numerical model and settings**

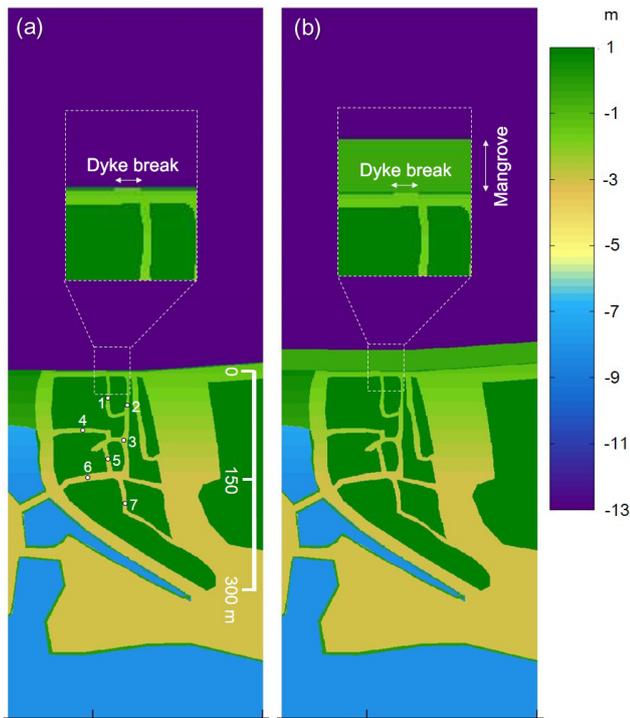
Delft3D-FLOW was used to simulate a flood which rushes into the low-lying area of Pluit after a hypothetical break in the dyke. In combination with a flooding scheme for advection in the momentum equation, the algorithm referred to as “drying and flooding” in this numerical model is expected to give a good representation of rapidly varying flows with large water-level gradients as a result of dam breaks (Stelling et al., 1986; Stelling and Duinmeijer, 2003; Deltares, 2011).



**Figure 6.** Schematic view of the topography considered in the numerical simulation. Scenario 1: present topography constructed based on the authors’ recent surveys. Scenario 2: future topography after experiencing an additional 2 m land subsidence.  $h_1$  denotes the height from the water level behind the dyke,  $h_2$  the height at the lowest location in the district of Pluit.

The simulation domain encompasses an area that includes the district of Pluit. A fine computational grid size (50 cm wide) was used throughout the domain, with 844 004 nodes reproducing small pedestrian paths with widths as narrow as 2 m. The topography data were created based on the authors’ own recent measurements (Fig. 7). The lower half of the plots indicated in Fig. 3c shows a ring road which is relatively higher (−1.0—−1.5 m) than the lowest elevation part of the town (−2.5—−3.0 m). There were some corners where the ground measurement was not possible because of the difficulties in access to the area due to the presence of an off-limits area or informal settlement, despite the fact that the elevations of the land appear to be lower than that of the road. Thus instead of using the measured elevation along the road, the elevation of the lower half of the domain in Fig. 7 was conservatively assumed to be the same as the lowest part of the town.

Although the length of the initial breach in the dyke and how this would propagate to nearby sections is unpredictable, the present study assumed a failure length of 20 m (which ap-



**Figure 7.** Elevation topography used in the simulation, measured from the highest sea level which occurred between September 2015 and February 2016. **(a)** Present ground elevations and buildings (dark green). **(b)** Present elevations, together with a 20 m mangrove belt in front of the dyke. Notes: the enlarged view focuses on the dyke-break section, assumed to be 20 m long. The numbers 1 through to 7 indicate the output points of the computational results.

proximately corresponds with two successive concrete units of the dyke system which protects this community) would occur, as shown in Fig. 7. Then, the dyke-break-induced flow was reproduced by imposing a constant sea level in the bay throughout the simulation, which ran for 20 min of real time. Since the simulation runs for such a short duration, seawater passes through the community and accumulates only in the lowest part of the computational domain, making it possible to avoid imposing pseudo-open boundaries on the land. Velocity and inundation depth changes with time were plotted for seven locations along several small paths amongst the houses in the area.

One of the most important numerical settings in any flooding simulation is Manning's  $n$  value, particularly when simulating an urban area with many buildings. The present simulation assumes a uniform value of  $0.06 \text{ (s m}^{-1/3}\text{)}$  over the land area, according to previous studies (e.g. MLIT, 2012; Takagi et al., 2016b). It is noted that a larger Manning's  $n$  value may need to be used when a flood causes catastrophic damage to buildings over a wide area (Koshimura et al., 2009; Takagi and Bricker, 2014; Bricker et al., 2015). However, extensive destruction of buildings is not expected

as a consequence of a limited dyke failure, as discussed in the following section, and thus a moderate  $n$  value appears reasonable.

Although there is some uncertainty in the  $n$  number that should be used for mangroves, a value of 0.15 was used in this study, according to the work of Arcement and Schneider (1984), in which the  $n$  value was assumed to lie between 0.10 and 0.20 for extremely dense vegetation. Since mangroves usually grow in the range between mid-tide level and the highest high water spring tide, the water depth in the mangrove area was assumed to be 50 cm, considering also the tidal range in Jakarta Bay of about 1 m (Takagi et al., 2016a).

Although the present study uses Manning's  $n$  value for the representation of the resistance to the water flow due to the mangrove roots, it should also be noted that other parameters such as drag coefficients related to Reynolds number, plant length, diameter, and vegetation density would have to be taken into account in evaluating more precise hydrodynamics in mangrove vegetation (e.g. Mazda et al., 1997; Mendez and Losada, 2004; Losada et al., 2016).

### 3 Results and discussion

Figure 8 presents time variations of the flood in terms of flood depth, velocity, and their product, referred to as the depth–velocity product, for the four scenarios described in the preceding sections (namely representing the present or future elevations, and whether a mangrove belt in front of the dyke is considered for each of them). All the results indicate that the floodwater would arrive at the small paths a few minutes after the breach, covering the entire town within 10 min. This clearly demonstrates that land subsidence inevitably poses a great flood risk, and that this will substantially increase as subsidence progresses. It is also noted that the rise in water level is not gradual, but rather abrupt, which resembles the pattern of earthquake-induced tsunamis.

A large-sized water flume experiment in Japan found that a 60-year-old man did not experience any strong feelings of fear when he walked against a water flow as high as his crotch with speeds of up to  $0.8 \text{ m s}^{-1}$  (Suga et al., 1995). However, he felt intense fear when the flow reached a height of 1 m or a velocity of  $1 \text{ m s}^{-1}$ , which effectively prevented him from walking without a supporting rope. Nishihata et al. (2005) confirmed through the same type of experiments that the maximum inundation depth at which adult males and females (aged from 21 to 59) can safely evacuate is 0.7 m or less. Takagi et al. (2016b) also found that the family members featured in a video taken during the storm surge caused by Typhoon Haiyan which hit the Philippines in 2013 could cross a flooded street because the flow speed and depth were both not too large,  $0.6 \text{ m s}^{-1}$  and 0.6 m, respectively.

Wright et al. (2010) propose a depth–velocity product of  $1.0 \text{ m}^2 \text{ s}^{-1}$  as the general safe limit for pedestrians through a comprehensive study undertaken by a project for the New

South Wales (NSW) State Emergency Service (SES). However, a plot of the relationship between human's instability and flow regime appears to be scattered by multiple factors such as surface material; subject actions – either standing or moving –, experience and training, clothing and footwear and physical attributes, including muscular development and/or other disabilities; and the definition of stability limit (i.e. feeling unsafe or complete loss of footing) (Cox et al., 2010). Jonkman and Penning-Rowsell (2008) also emphasize that friction instability appears to occur earlier than moment instability (toppling) for the combination of shallow depth and high velocities. Thus, the depth–velocity product criterion suggested by Wright et al. (2010) could become optimistic for some adverse conditions. For example, regarding physical differences between an adult and a child, Cox et al. (2010) suggests that for children with a height and mass product of between 25 and 50 (m kg), low hazard exists for flow values of a depth–velocity product  $< 0.4 \text{ m}^2 \text{ s}^{-1}$ .

Given these criteria, pedestrians would be at great risk over the entire area, especially for the scenarios that do not consider the mangrove belt in front of the dykes, as shown in Fig. 8a and c. On the other hand, the simulations show that mangroves could substantially reduce the physical impact of the flood and enable pedestrians to evacuate to safer locations, as shown in Fig. 8b and d.

The depth–velocity product can also be used as a criterion to investigate whether buildings can collapse or not. Residential house damage can be determined by the depth–velocity product ( $dv$ ) by following the classification given by Pistrika et al. (2010):

- inundation damage ( $dv < 3 \text{ m}^2 \text{ s}^{-1}$ )
- partial damage ( $3 \text{ m}^2 \text{ s}^{-1} \leq dv < 7 \text{ m}^2 \text{ s}^{-1}$ )
- total destruction ( $dv \geq 7 \text{ m}^2 \text{ s}^{-1}$ ).

According to this classification it is clear that houses can withstand much stronger floodwaters than pedestrians, as expected. Figure 8 shows how it is unlikely that any of the buildings in the area would suffer any structural damage, given that depth–velocity products would generally be below  $3 \text{ m}^2 \text{ s}^{-1}$ . Thus in the event of any dyke failure, the residents should immediately evacuate to any house in the area that is two storeys or higher, rather than attempt to follow the narrow paths connecting to distant places on relatively higher elevations.

The two scenarios with a mangrove belt suggest that both flood depth and velocity would be significantly reduced by their presence, compared with the cases without such countermeasures. It is also interesting to note that mangroves may contribute to the smoothening of the flood stream by creating a large friction due to their dense root systems. Essentially, a sudden dyke-break would produce substantial waves in addition to uniform floodwater, if the mangroves are not present, as shown in Fig. 8c. Even though the flood depth is not different, walking in an almost uniform flow would probably be

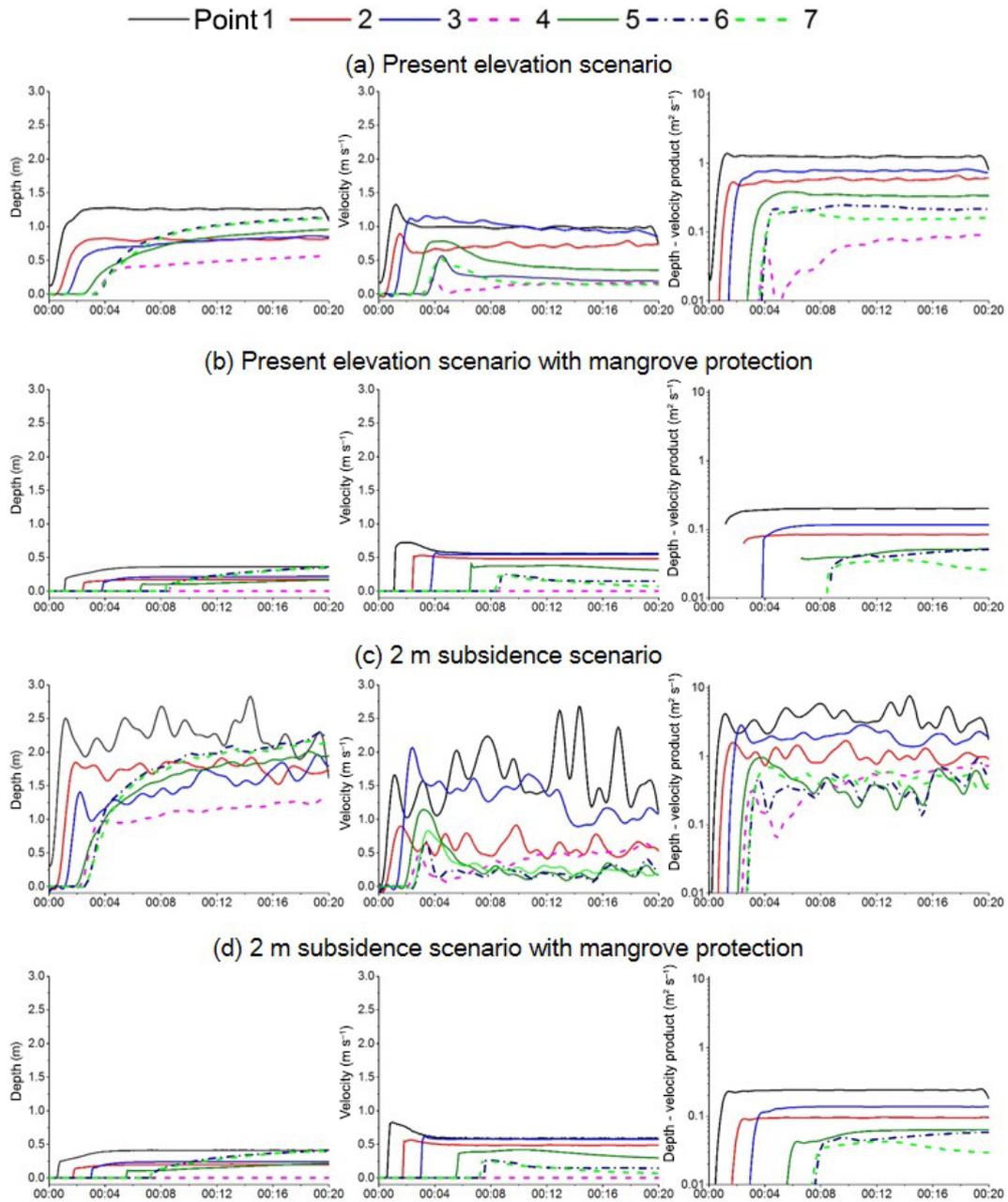
easier than in a strong turbulent flow. It is clear that developing a mangrove belt can significantly improve the resilience of vulnerable coastal communities. Nevertheless, it should be noted that the wild oscillations found in Fig. 8c could also be induced by model instabilities to some extent. Thus, more precise mechanisms on turbulence in flows should be further investigated by using a 3-D hydrodynamic model which is able to simulate strong turbulence rather than the depth-integrated model such as used in the present study.

One important difference between the two types of tsunamis mentioned in this paper, namely the dyke-break tsunami and earthquake-induced tsunami, is that a flood caused by the former event will remain over the ground for a long duration, whereas an earthquake tsunami typically recedes in a relatively short period due to backwash. Thus, the event of dyke-break is not only a matter for local community, but would have a significant effect over a much wider region. As mentioned earlier, the largest pumping station in Jakarta is located in the district of Pluit, and has been playing a vital role in discharging the storm water that accumulates over the Jakarta metropolitan area into the bay. If a dyke-break tsunami occurred, floodwater would remain over a long period of time, and consequently the pump system might be crippled, resulting in the malfunction of economic activities, people's daily lives, and the traffic system in the Great Jakarta region. Thus, it should be recognized that the protection of this local dyke is not only a local issue but also essential for flood control in the entire city, which is of great importance to the entire country given the importance of the area to the national economy.

#### 4 Conclusions

In the present paper the authors coined the term dyke-break-induced tsunami (or, simply dyke-break tsunami), and attempted to highlight the dangers and extensive damage that such an event could cause to extremely low-lying areas in Indonesia. For this purpose, a detailed case study was conducted in the district of Pluit in Jakarta, where the densely populated community has been suffering rapid rates of land subsidence, in excess of  $10\text{--}20 \text{ cm yr}^{-1}$ . The hydrodynamic simulation, conducted using a fine computational grid, estimated that the floodwater would engulf the populated area through its narrow paths in a question of a few minutes. In the 2 m subsidence scenario, expected to be reached within the next 10–20 years, the depth–velocity products exceed the pedestrian evacuation limit of  $0.4\text{--}1 \text{ m}^2 \text{ s}^{-1}$  all throughout the town, and could seriously endanger any resident in the streets.

This study also demonstrates that the impact of the flood would be substantially mitigated by planting a mangrove belt in front of the dyke, due to two mechanisms: (1) a reduction in floodwater velocity and depth and (2) a flow smoothening effect, which mitigates the danger of turbulent flow. The



**Figure 8.** Simulated water depth (left), velocity (centre), and the depth–velocity product (right) at seven locations along the small paths shown in Fig. 7. **(a)** Present elevations, which were reproduced based on the authors’ survey. **(b)** Present elevations with a 20 m mangrove belt, **(c)** 2 m land subsidence scenario, and **(e)** 2 m land subsidence scenario with a 20 m mangrove belt.

effectiveness of mangroves is expected to become more pronounced with the progress of land subsidence. Although this study only deals with one small community in Jakarta, any developing countries or coasts are likely to encounter similar issues when faced with rapid industrialization and population growth. Thus, the risk of dyke-break-induced tsunamis should be considered in coastal disaster management and urban planning, and this study demonstrates how planting man-

groves could potentially be a good way to increase the resilience of these coastlines at a relatively low cost.

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