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Risk-based optimization of land reclamation

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ABSTRACT

Large-scale land reclamations are generally constructed by means of a landfill well above mean sea level. This can be costly in areas where good quality fill material is scarce. An alternative to save materials and costs is a 'polder terminal'. The quay wall acts as a flood defense and the terminal level is well below the level of the quay wall. Compared with a conventional terminal, the costs are lower, but an additional flood risk is introduced. In this paper, a risk-based optimization is developed for a conventional and a polder terminal. It considers the investment and residual flood risk. The method takes into account both the quay wall and terminal level, which determine the probability and damage of flooding. The optimal quay wall level is found by solving a Lambert function numerically. The terminal level is bounded by engineering boundary conditions, i.e. piping and uplift of the cover layer of the terminal yard. It is found that, for a representative case study, the saving of reclamation costs for a polder terminal is larger than the increase of flood risk. The model is applicable to other cases of land reclamation and to similar optimization problems in flood risk management.

1. Introduction

Ship container trade has been growing rapidly over the last decades resulting in large container terminal expansions around the world. Large-scale land reclamations are often required for the construction of these new terminals. Port operators generally demand terminals which are well above extreme water levels, to minimize risks of flooding of the terminal due to storm surges. For example, the second Maasvlakte port expansion in The Netherlands is built at a level of +6.1 m mean sea level, corresponding to a 1/10,000 per year protection level [1].

A 'conventional terminal' is a terminal where the whole land reclamation is filled to the desired elevation which corresponds to a certain protection level, as shown in Fig. 1. This solution requires large volumes of good quality fill material that is typically dredged from the sea. In areas where this material is scarce, these types of reclamations can be very costly due to high volumes and high costs of fill material. As an alternative, the terminal can be designed as a polder to reduce the reclamation cost. In this case, the terminal yard lies below the quay wall level around or even below the mean outside water level, see Fig. 1. This design is referred to as a 'polder terminal' in this paper. The quay wall structure of the polder terminal not only traditionally retains soil and water, but will also serve as the flood defense for the polder terminal yard.

Polders are defined as low lying areas enclosed by flood defences that require drainage systems to control the water levels inside the system. Polders are often found in river delta's or low lying coastal areas. In The Netherlands, large parts of the nation consist of polders, and most of the country is protected from flooding by systems or 'rings' of flood defences [3]. Typical polders are also found in other large river delta's such as New Orleans, Sacramento and Bangkok. The Suvarnabhumi airport in Bangkok is built in a polder on a flood pain close to mean sea level. Instead of raising the surface level of the airport, it was built as a polder protected by flood defences and with drainage systems [4].

Preliminary studies showed that a polder terminal is technically feasible in low-lying areas, and that it appears to be attractive in areas where low quality subsoil is present and reclamation cost is high [5]. The difference between quay wall and terminal yard levels would be fully compatible with requirements for modern dual-trolley ship-to-shore gantry cranes [5] and thus not affect logistics. Table 1 summarizes some advantages and disadvantages of a polder terminal when compared to a conventional terminal.

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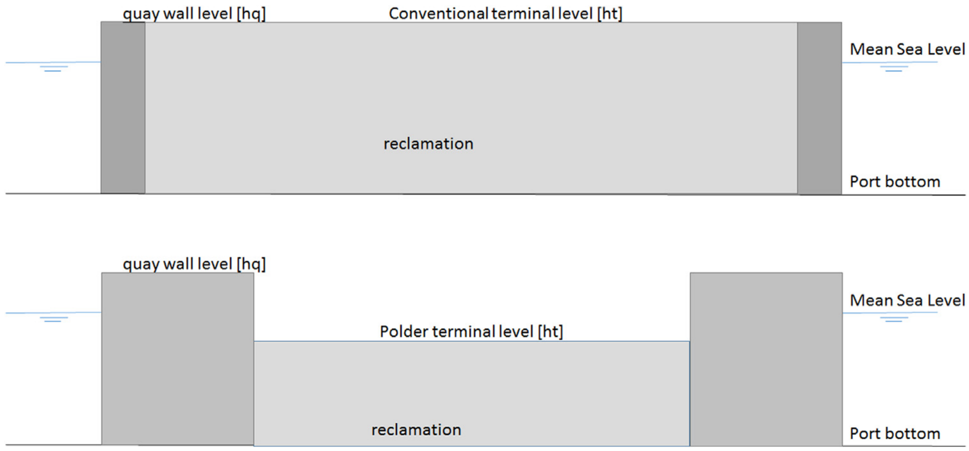

Fig. 1. Schematic cross section conventional terminal (top) and polder terminal (bottom) [2].

Table 1
Advantages and disadvantages of a polder terminal over a conventional terminal.

Advantages polder terminal	Disadvantages polder terminal
Lower volume of reclamation material	Increased vulnerability for flooding due to low terminal yard level (at or below mean sea level)
Lower reclamation cost	Complex quay wall design due to multi functionality as quay wall and flood defense
Less settlement in underlying subsoil	Larger terminal area required for water storage as well as additional drainage systems
Shorter construction time	Longer turnover time for container handling
Lower environmental impact due to lower volumes of reclamation fill	
Water storage in polder can be used for fresh water collection	

Earlier studies did not assess the potential investment savings and flood risk of a polder terminal. In this paper, (flood) risk is defined as the product of probability and economic consequences. Flooding is a typical low probability high consequence hazard. Probabilistic methods are often used to assess the probability of these hazards, based on the occurring loads (e.g. the water levels) and strength (e.g. the retaining height and structure) of the flood defences. Flood simulations and damage models are then used to assess the consequences of flooding.

Risk-based methods are often used to optimize design [6] and maintenance [7] of civil engineering structures and systems. Past risk management studies in the field of port planning and design have addressed port layout and logistics [8], safety and security in port operations [9], specific hazards of wave overtopping [10] and optimization of failure probabilities of port structures [11]. These studies did not address the issue that is treated in this paper, i.e. the risk-based optimization and design of the overall (protection) system and reclamation based on costs.

In the broader field of civil engineering probabilistic and/or risk-based methods are commonly used to optimize design and maintenance for coastal flood defences [12,13] river flood defences [14], and breakwaters [15]. These optimizations generally focus on a single variable, for example the retaining height of a flood defense. For the (polder) land reclamation two variables need to be taken into account in the optimization, the terminal level, and the level of the surrounding flood defense, the quay wall level (see Fig. 1). To find optimal values for both levels, a more complex method is required and engineering boundary conditions need to be taken into account as well.

The objective of this paper is to develop a risk-based method which can be applied to optimize land reclamations. The method will be applied to compare the conventional and polder terminal concepts to find optimal values for the quay wall and terminal levels. Engineering boundary conditions that determine the minimal polder level will be incorporated in the approach. To determine the economic feasibility of the polder terminal, the present value of the cost over the lifetime of both the conventional and polder terminal are estimated, considering both the investment cost as well as the annual flood risk. Insight in cost and risk is essential for decision makers of large civil engineering projects such as port expansions [16,17].

This paper is structured as follows: Section 2 describes the methodology used to determine the optimal quay wall and terminal level for both the conventional and polder terminal. A case study is treated in Section 3 after which the results and implications are discussed in Section 4. Section 5 contains concluding remarks and recommendations.

2. Methodology

2.1. General

The present value of the cost of a terminal consists of the initial investments and residual flood risk over the lifetime of the terminal. These costs are minimized to determine the optimal combination of quay wall and terminal level, under civil engineering boundary conditions. This approach is based on the approach used by the Delta Committee in the Netherlands to determine the optimal protection level of the flood defences [13,18]. After the flood disaster in 1953, a statistical approach to determine the storm surge levels was used to determine the probability of exceedance of a certain water level, which represents overflow failure of the flood defense. Both the investment cost and the flood risk are determined by the flood defense level; an increase of the dike height results in higher investment cost and lower risk due to the lower probability of flooding. Recent work improved the principles found by van Dantzig, see [19].

This paper builds on, and extends, these existing methods [20,21], by adding the dependence of flood risk on a second variable, which is the terminal (reclamation) level. The damage of flooding is determined by the flood depth, which is the level