RISK BASED DESIGN OF LAND RECLAMATION AND THE FEASIBILITY OF THE POLDER TERMINAL

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ABSTRACT

New ports are mostly constructed on low lying coastal areas or in shallow coastal waters. The quay wall and terminal yard are raised to a level well above mean sea level to assure flood safety. The resulting 'conventional terminal' requires large volumes of good quality fill material often dredged from the sea, which is costly. The alternative concept of a 'polder terminal' has a terminal yard which lies below the outside water level and is surrounded by a quay wall flood defence structure. This saves large amounts of reclamation investment but introduces a higher damage potential in case of flooding and corresponding flood risk. Important conditions for the feasibility of a polder terminal are low pervious subsoil and high reclamation cost. Further, a polder terminal requires a water storage and drainage system, against additional cost. A risk-based analysis of the optimal quay wall height and polder level is performed, which is an optimization (cost benefit analysis) under two variables. The overtopping failure mechanism proves to be the dominant failure mechanism for flooding. During overtopping the water depth in the polder terminal is larger than on the conventional terminal, resulting in higher damage potential and corresponding flood risk for the polder terminal. However, the reclamation savings prove to be larger than the increased flood risk: the 'polder terminal' could save 10 to 30% of the total cost (investment and risk) demonstrating that it to be an economically attractive alternative to a conventional terminal.

Keywords: Container Terminals, Flood Risks, Optimization, Polder Terminal, Probabilistic Design.

1. INTRODUCTION

Container trade has been growing rapidly in the last decades resulting in large container port expansions around the world. New ports are mostly constructed on low lying coastal areas or in shallow coastal waters. Port operators generally demand terminals well above extreme water levels, to minimize flood risks. The terminal is built at this level to assure flood safety (low, acceptable flood probabilities). The resulting 'conventional terminal', shown in figure 1, requires large volumes of good quality fill material typically dredged from the sea. In areas where this material is scarce these reclamations could be very costly due to high cost of fill material (order > 10 €/m^3).

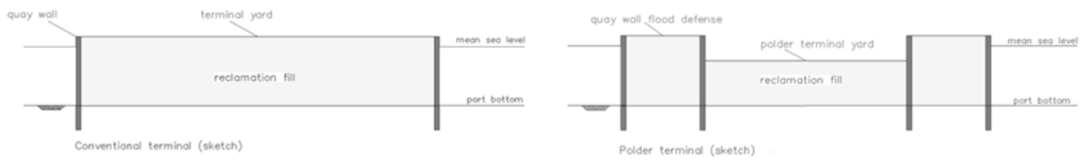

Figure 1: Cross section conventional terminal (left) and polder terminal (right)

The 'polder terminal', shown in figure 1 (right), is developed as an alternative to the 'conventional terminal': the terminal yard would lie at or below the outside water level and be surrounded by a combined quay wall flood defence structure, as shown in figure 1. The quay wall structure of the polder terminal not only 'traditionally' retains soil and water, it will also act as the flood defence for the polder terminal yard. The structure may consist of two sheet pile walls forming a cofferdam or a gravity structure such as a caisson. Preliminary studies showed that polder terminals could be feasible in any low-lying area in the world, specifically areas where low quality subsoil is present and reclamation cost are high (van Beemen, 2010).

A polder terminal requires smaller volumes of fill material, which save reclamation cost. Due to a higher damage potential of the polder terminal yard during a flood, the polder terminal will have an increased risk of flooding. As a result of the lower reclamation height less settlement of the subsoil is expected, which is especially attractive for low quality subsoil often found in river deltas. In addition to the increased cost due to the higher risk of flooding a polder terminal requires a water drainage system to drain excess water out as a result of rainfall and/or seepage. This will also result in an increase of the total costs compared to the conventional terminal and the requirement of extra space inside the terminal (about 5% of the total area).

1.1. Objective

The objective of this paper is to investigate the technical and economic feasibility of the polder terminal in comparison with the conventional terminal. For this purpose a risk based framework is developed to determine the total cost consisting of investment and risk for both the polder terminal and the conventional terminal. The total cost are then minimized to determine the optimal quay wall height and polder level under civil engineering boundary conditions. Further, an assessment is made to determine the most suitable quay wall flood defence structure for a polder terminal.

2. METHODOLOGY

A risk framework is developed to determine the optimal quay wall flood defence level and polder depth, by minimizing the total costs which contain the summation of the investment and present value of the risk.

$$\text{Total cost (TC)} = \text{Investments (I)} + \text{Risk (R)} \quad (1)$$

This approach is similar to the approach used by the Delta Committee to determine the optimal crest height of dikes in the Netherlands (van Dantzig, 1960). 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 determines overtopping failure of the flood defence (Vrijling, 2001). Both the investment cost and the flood risk are related to this flood defence level; an increase of the dike height results in higher investment cost and lower risk due to the lower probability of flooding. The optimal dike height is found by minimizing the total costs, see equation 1.

The risk framework approach developed in this paper contains one major difference with the approach used by the Delta Committee: this paper not only relates the investment cost and risk to the flood defence level (dike height) but also to the polder depth (in the case of the polder terminal). The resulting total cost function is not dependant on one variable, as with the approach of the Delta Committee, but on two variables: the flood defence level [h_q] (dike crest height) and the polder level [h_p].

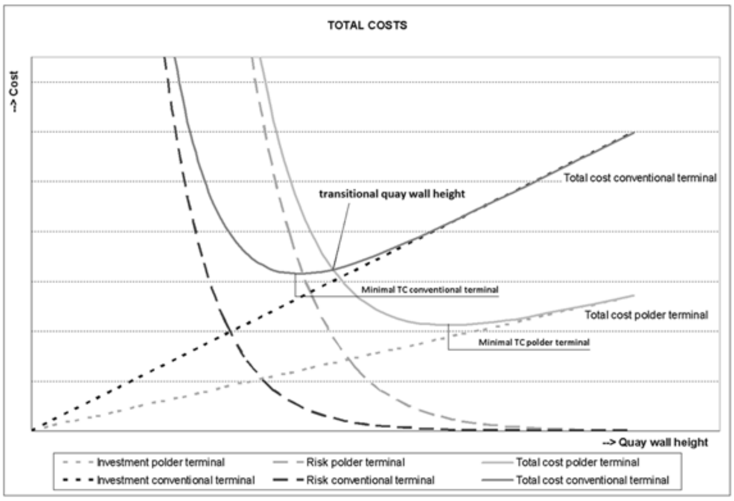

Figure 2: Risk framework optimization for a conventional and a polder terminal (conceptual graph)

If both a conventional and a polder terminal are built with the same crest height the investment of the conventional terminal is higher than the investment of the polder terminal due to the larger fill required, see figure 1. However the risk of the conventional terminal is expected to be lower than that of the polder terminal, due to the lower inundation depth and corresponding damage potential during a flood as shown in the figure.

The flooding depth of the conventional terminal is equal to the difference in height between the water level and the terminal level. A polder terminal will however 'fill up' to a large extent, depending on the duration of overtopping. As flood damage depends on the inundation depth (increased damage for increased water depth) (Jonkman et al, 2008), this will result in higher damage potentials for the polder terminal than the conventional terminal. Flood risk is calculated by the multiplication of the probability of flooding and the damage of flooding. Thus, given a certain terminal level, a polder terminal is expected to have lower investment cost and higher risk than a conventional terminal resulting in lower total costs (investments and risk), as shown in figure 2.

3. RISK FRAMEWORK

The risk framework approach to optimize the quay wall flood defence and polder level is based on existing approaches (Slijkhuis et al, 2001) (Vrijling et al, 1998). First an assessment of the risks involved is made.

3.1. Risk assessment

Risk of flooding is defined as the multiplication of the probability of flooding and the consequence. An assessment is made of possible flood scenarios occurring in the polder terminal. A distinction is made between (permanent) flooding with high water levels, defined as ‘Large scale flooding’, and (temporary) flooding with low water levels, defined as ‘Small scale flooding’. A fault tree showing failure mechanisms resulting in flooding of a polder terminal is shown in figure 3.

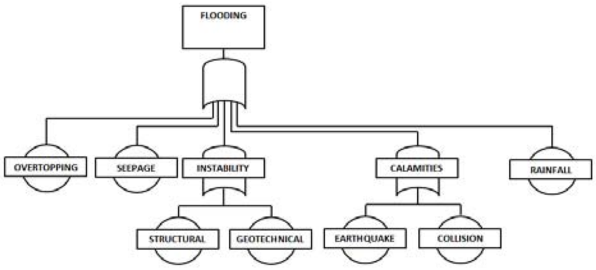

Figure 3: Fault tree for flooding of polder terminal

3.1.1 Large scale flooding

Large scale flooding, due to failure of the flood defence system, is determined as floods with water depths in excess of 0.5 meter. The consequences are substantial down time of port operations and large damage to containers and facilities. Overtopping failure determines the required flood defence level (reclamation level) for both the conventional and polder terminal. The required flood defence level has the largest influence on reclamation costs and flood risk, making overtopping the dominant failure mechanism. Seepage occurs due to a level difference of the outside water level and inside polder terminal level. In sandy subsoil the amount of seepage is large requiring large drainage pumps and large storage capacity in the polder. In clayey subsoil the amount of seepage is less. For a polder terminal to be feasible low pervious subsoil is therefore required.

Structural and/or geotechnical stability is assured by designing the quay wall flood defence structure according to guidelines in CUR211 and ‘Leidraad Kunstwerken’, which require a maximum probability of structural failure of 1% of the probability of overtopping. This includes failure due to calamities such as earthquake and ship collision, which largely depend on local conditions.

3.1.2 Small scale flooding

Small scale flooding is related to water depths below 0.5 meters and occurs due to excess water inside the polder because of insufficient storage or drainage capacity. Excess water inside the polder could be the result of overtopped water, seepage or rainfall (structural failure or calamities will result in ‘Large scale flooding’). The consequences are temporary down time of port operations and minor damage to containers and facilities.

Overtopping can be neglected by designing a sufficiently high crest level of the flood defence. As stated earlier, in areas with low pervious subsoil the amount of seepage is negligible. Small scale flooding is therefore determined by the amount of rainfall, which is drained through a water storage and drainage system in the polder terminal yard with sufficient capacity. For the case study explained in section 4.1 a practical calculation is made of the investment and risk of such a system. This resulted in total cost in the order of 10^7 €, which is low compared to the total cost of the polder terminal (order 10^9 €), see section 4.

3.2. Risk framework

An economical optimization is used to determine the optimal reclamation levels for both the conventional terminal and the polder terminal, based on the summation of the investments and risk.

3.2.1 Optimization polder terminal

The investment of the polder terminal, [I_{polder}] (€), are determined by the variable quay wall, [I_q] (€/m), and reclamation, [I_p] (€/m), cost. Both are assumed to be linearly proportional to the quay wall height, [h_q] (m), and polder level, [h_p] (m). The relation is depicted in equation 2.

$$I_{polder} = I_q * h_q + I_p * h_p \quad (2)$$

The linear relationship between the quay wall height and cost hardly deviate from the actual nonlinear relation (within the bandwidth of +/- 25%) (de Gijt, 2010). The present value of risk of the polder terminal is determined by the probability of flooding, [P_f] (yr^{-1}), multiplied with the consequence, [D_{polder}] (€/m) and divided by the reduced interest rate, [r'] (-). The reduced interest rate is the difference between the real interest rate, [r] (-), and economic growth [g] (-): r'=r-g.

$$R = P_f * D_{polder} / r' \quad (3)$$

The probability of flooding is determined by the overtopping failure mechanism. During overtopping the inundation of the polder depends on the probability that an extreme water level exceeds the quay wall height, [h_q] (m), the probability of extreme water levels is described with an exponential distribution with constants A and B:

$$P_f = e^{-\frac{h_q - A}{B}} \quad (4)$$

As determined before not only overtopping but also other failure mechanisms determine the probability of flooding, however these failure mechanisms do not influence the required flood defence height and polder level. These failure mechanisms could be taken in to account by adding an additional failure budget to the overtopping failure probability (CUR211, 2005).

The consequence of a flood in the polder terminal is determined by the summation of a constant level of damage, [D_0] (€), the direct damage to port facilities, [D_i] (€/m), and indirect damage, [D_t] (€/yr) due to down time, [t_{flood}] (yr), of the port (economic loss). The direct damage depends on the inundation depth (Pimontel, 2006), which is the level difference between the quay wall and terminal yard: h_q-h_p. It is assumed during overtopping the polder is flooded completely, not taking the time required to fill up the polder in to account. A short calculation with the flow rate law of Torricelli resulted in a flooding time of 4.5 hours, which is less than an average extreme water level of about 6 hours, thus verifying this assumption.

$$D_{polder} = D_o + D_i*(h_q - h_p) + D_t * t_{flood} \quad (5)$$

By summation of the investments and risk of the polder terminal equation 6 is found for the total cost of the polder terminal [TC_{polder}] (€). This function will be minimized to find the optimal combination of quay wall height and polder level.

$$TC_{polder} = I_q * h_q + I_p * h_p + P_f * D_{polder} / r' \quad (6)$$

The polder level has a linear contribution to the total costs. The 'transitional quay wall height' is defined as the level where the total cost of the conventional terminal is equal to the total cost of the polder terminal, independent of the polder level. To determine this level one should minimize the total cost function to the variable polder level.

$$\frac{\delta TC_{polder}}{\delta h_p} = I_p - \frac{e^{-\frac{h_q - A}{B}} * D_i}{r'} = 0 \Rightarrow h_{q;transition} = A - B * \ln\left(\frac{I_p * r'}{D_i}\right) \quad (7)$$

For quay wall heights higher than the transitional quay wall height a polder terminal has lower total cost whereas for quay wall heights lower than the transitional quay wall height the conventional terminal has lower total cost, this is shown in figure 2. Thus the polder terminal is attractive for quay wall heights higher than the transitional height [$h_{q;transition}$] (m). For quay wall heights higher than the transitional quay wall heights, the additional risk of constructing a polder terminal is lower than the additional investment required to construct a conventional terminal (and vice versa for quay wall heights lower than the transitional quay wall height).

The total cost decrease with decreasing polder level, which demonstrates the linear influence of the polder level to the total cost. In this case the lowest possible polder level determines the minimal total cost.

The minimal total cost (for a given polder level) is determined by minimizing the total cost function (equation 6) to the variable quay wall height, see equation 8. The solution of this equation is a Lambert function: an infinite row (exponent [-(x-a) / b] = 1 / x). Such a function can only be solved numerically, through iterations. Concluding: after determining the boundary for the polder level the economic optimal quay wall height (higher than the transitional height) can be found by solving equation 9 numerically.

$$\frac{\delta TC_{polder}}{\delta h_q} = I_q + \frac{e^{-\frac{h_q - A}{B}} * D_i}{r'} - \frac{1}{B}\frac{e^{-\frac{h_q - A}{B}} * \left[D_0 + D_i(h_q - h_p) + D_t(t_{flood})\right]}{r'} = 0 \qquad (8)$$

$$e^{-\frac{h_q - A}{B}} = \frac{I_q * r' * B}{\left[\left[D_0 + D_i(h_q - h_p) + D_t(t_{flood})\right] - D_i * B\right]} \qquad (9)$$

In conclusion, it is determined that for quay wall heights higher than the 'transitional quay wall height' the polder terminal is economically more attractive than the conventional terminal. The minimal total cost are found for the lowest possible polder level, this level is bounded by requirements of stability of the quay wall flood defense and port logistics (as determined in the next paragraph). Finally, the optimal quay wall height is found numerically with equation 9.

3.2.2 Optimization of polder depth

The stability of a gravity structure (caisson) is investigated to determine the lowest possible polder level. Three different extreme loading cases are distinguished dependent on the polder level, illustrated in figure 4 and explained in the next section.

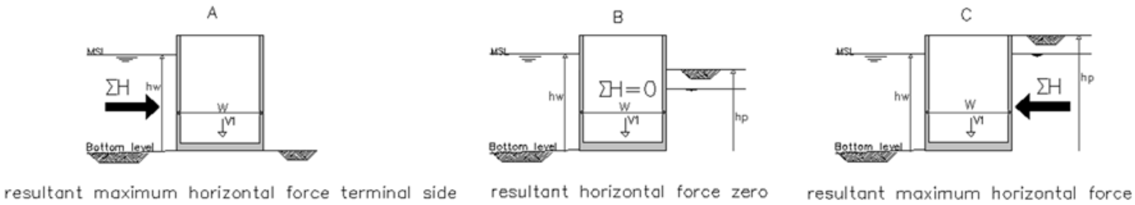

Figure 4: Horizontal forces on quay wall flood defence

The failure mechanisms of a gravity structure are piping, rotational instability, sliding instability, insufficient bearing capacity and, in the case of a polder terminal, uplifting of the polder. Figure 4 shows that, depending on the polder depth, the quay wall flood defence retains a resultant horizontal water pressure from the sea side (left) or a resultant horizontal soil pressure from the terminal side (right), between these two extremes an optimal point is found where the resultant horizontal force is zero (middle).

Safety against piping is obtained by using seepage screens, when a polder depth below Mean Sea Level is designed. Stability of a gravity structure against failure due to rotation, sliding and bearing capacity is obtained by the own weight of the structure. As the height of the structure is determined by overtopping failure the width is the remaining variable to determine the weight. The required weight depends on the polder depth as shown in figure 5. The figure clearly shows that the structure requires minimal weight at the location where the resultant horizontal force is zero (point B), this is the optimal polder depth.

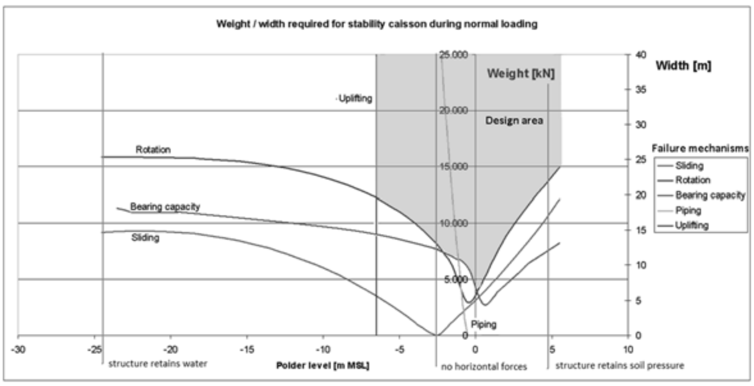

Figure 5: Required width of gravity structure related to the polder level (depth) for case study (4.1)

The maximum polder depth possible is found at the uplifting boundary of the polder, which is determined by the balance between the upward water pressure under the impervious layer and the weight of the soil on top of the impervious layer. The grey area in the graph shows the design area of the quay wall flood defence. Concerning port logistics the level transition between quay wall and port terminal is fully compatible with requirements for modern dual-trolley ship-to-shore gantry cranes (van Beemen, 2010).

Minimal total cost are found for the maximum polder depth, not the optimal polder depth, because the reclamation cost (determined by the polder level) form a larger percentage of the total cost compared to the quay wall cost. This investigation was made for gravity structures; it is however advised to perform a similar investigation for the application of sheet piles as a quay wall flood defence.

3.2.3 Optimization conventional terminal

Where the polder terminal optimization depends on both the quay wall height and the polder yard, the conventional terminal optimization only depends on the terminal height [h_t] because $h_t = h_q = h_p$. The resulting equations for investments, damage and total cost are shown in equations 10 – 12. The optimal terminal level, with corresponding minimal total cost, is found with equation 13.

$$I_{conventional} = (I_q + I_p) * h_t \quad (10)$$

$$D_{conventional} = D_o + D_t * t_{flood} \quad (11)$$

$$TC_{conventionaL} = (I_q + I_p) * h_t + P_f * D_{conventional} / r' \quad (12)$$

$$\frac{\delta TC_{conventional}}{\delta h_t} = (I_q + I_p) - \frac{1}{B}\frac{e^{-\frac{h_t - A}{B}} * D_{conventional}}{r'} = 0 \Rightarrow h_{t;optimal} = A - B * \ln\left[\frac{(I_q + I_p)*B*r'}{D_{conventional}}\right] \quad (13)$$

4. RESULTS

With the mathematical relations found in the previous section the optimal levels and corresponding total cost of a polder and conventional terminal can be found to determine whether the polder terminal is a feasible concept.

4.1. Case study parameters

A case study is made inspired by the Tuas Singapore port expansion project, where Royal HaskoningDHV proposed a polder terminal design in 2011. The terminal has a rectangular shape, the polder terminal area is 5% larger than the conventional terminal due to required space for a water drainage and storage system. The subsoil consists of low quality clayey layers and reclamation cost are expensive (order 20 €/m^3).

Table 1: Case study input parameters

Design parameter	Variable	Value	Unit
Current port depth	d	-25	m MSL
Area conventional terminal	A_c	$3.0 * 10^6$	m^2
Area polder terminal (+5%)	A_p	$3.2 * 10^6$	m^2
Quay wall cost per meter retaining height, per running meter	I_q	1,700	€/m^2
Reclamation fill cost (sand is scarce)	I_p	20	€/m^3
Exponential distribution of water levels	A, B	A=2.87 / B=0.15	-
Constant flood damage of conventional terminal	D_0	$180 * 10^6$	€
Direct flood damage of polder terminal dependant on depth	D_i	$360 * 10^6$	€/m
Indirect damage cost due to down time of the port	D_t	$20 * 10^6$	€/week
Reduced interest rate	r’	0.05	-

4.2. Comparison conventional and polder terminal

The minimal total cost and corresponding optimal quay wall height and polder level for the polder terminal and terminal level for the conventional terminal are shown in table 2. The minimum polder level (maximum depth) is determined by the uplifting boundary which lies at 6.5 meter below Mean Sea Level, see figure 5. To compare, the total cost of a conventional terminal with the same terminal height as the quay wall height of the optimal polder terminal is added as well as a polder terminal with polder level at Mean Sea Level.

Table 2: Total cost of container terminals at Tuas, Singapore

	Quay wall level [m MSL]	Investment [mln €]	Risk [mln €]	Total cost [mln €]	Total cost [€/m^2]	Difference
Optimal conventional terminal	+3.8	2,090	12	2,102	701	0

Optimal polder terminal (polder at -6.5 meter MSL)	+4.5	1,585	2	1,587	496	-29%
Reference cases						
Comparison: conventional terminal at +4.5	+4.5	2,130	0.1	2,130	710	+1%
Optimal quay height (polder at 0 meter MSL)	+4.3	1,950	2.5	1,953	610	-13%

By definition the conventional terminal and polder terminal have equal costs at the transitional quay wall height of in this case +3.6 meter MSL.

5. DISCUSSION

From the optimization it is concluded that a polder terminal could produce savings between roughly 10 and 30%. The percentage of reclamation saving as well as the risk prove to be independent of the total polder area, because both the reclamation and damage cost depend on the total polder area.

A sensitivity analysis was made to determine the sensitivity of the approach to deviating reclamation costs. It showed that the polder terminal is particularly feasible in areas with expensive reclamation cost (order > 10 €/m^3). For cheaper reclamation cost the conventional terminal is a better alternative. Afore mentioned limitations of the approach are the assumed linearity of the relation between quay wall cost and retaining height (which in fact is nonlinear) and the actual probability of flooding which is higher then the probability of overtopping.

A number of other remarks can be made. Firstly, the required soil improvement cost is not taken in to account, which could differ largely between both designs. As a conventional terminal will have a larger fill, larger settlements are expected compared to the polder terminal. This would actually benefit the polder terminal design. Secondly, in the damage estimation no loss of life or ‘reputation damage’ is taken in to account. Further, port operators generally do not want their port to flood, making them risk averse. Models are available to take risk aversion in to account (Slijkhuis et al, 2000). Port operators could also choose to take risk mitigation measures like flood insurance. Finally, an increase of the total cost of the polder terminal is expected compared to the conventional terminal due to the water drainage system required. A short calculation proves that the increase in cost is insignificant (order of 10^7 €) compared to the total cost (order of 10^9 €). It is therefore advised to conservatively design a water drainage system based on the local extreme rainfall intensities.

6. CONCLUSIONS, LIMITATIONS AND FURTHER RESEARCH

In this paper the feasibility of the polder terminal is investigated through a new risk framework approach which optimizes the total cost consisting of the investment and risk. In the ‘traditional’ optimization the investments and risk were determined by one variable: the flood defence level. In the new approach the investments and risk are determined by two variables: the flood defence and polder level (or depth), which models the investments and flood risks of a polder more accurately. This approach proved to be a useful tool to optimize the flood defence and polder levels of a polder terminal. Further research in the application of this approach in a more common polder (dike and terp model) is advised. Using the relations found in this paper it could be determined whether for a certain situation investments in dike height or terps (polder level) are better.

Considering the polder terminal, the concept is particularly feasible at locations with high reclamation cost (order > 10 €/m^3). Low pervious subsoil is required to limit the amount of seepage in the polder. The resulting total cost of the polder terminal is significantly lower (order 10 – 30%) than the total cost of the conventional terminal, demonstrating that the polder terminal is an attractive alternative for a conventional terminal. The magnitude of the reclamation saving depends on the polder terminal depth; deeper polders result in larger savings. The polder depth is bounded by the uplifting failure mechanism.

The concept of the polder terminal is investigated for container terminals, however the concept could also be applied for other (non-container) port terminals or a more common dike – terp model, more research could provide new insights in these areas. When designing a new container terminal the chosen terminal levels should not only based on minimal total cost but also take the return period of inundation and the risks involved in to account.

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