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Risk approach to land reclamation: Feasibility of a polder terminal

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ABSTRACT: New ports are mostly constructed on low lying coastal areas or 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 fill material often dredged from the sea, which is costly. The terminal yard of a 'polder terminal' lies below the outside water level and is surrounded by a quay wall flood defense structure. This saves large amounts of reclamation cost but introduces higher damage potential during flooding and thus an increased flood risk. A risk-based framework is made to determine the optimal quay wall and polder level, which is an optimization (cost benefit analysis) under two variables. Overtopping failure proves to be the dominant failure mechanism for flooding. The reclamation savings prove to be larger than the increased flood risk demonstrating that the polder terminal could be an attractive alternative to the conventional terminal.

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 which are well above extreme water levels, to minimize flood risks. The terminal is built high enough to assure a certain level of flood safety (low flood probability). 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).

The 'polder terminal', shown in Figure 2, 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 defense structure, as shown in Figure 2. The quay wall structure of the polder terminal not only 'traditionally' retains soil and water, it will also act as the flood defense 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 a polder terminal could be feasible in any low-lying area in the world, specifically in areas where low quality subsoils are present and reclamation cost are high (van Beemen, 2010).

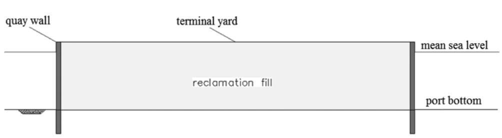

Figure 1. Cross section conventional terminal.

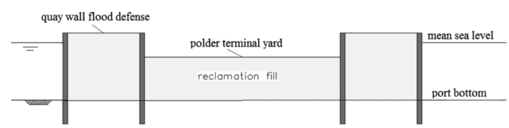

Figure 2. Cross section polder terminal.

A polder terminal requires smaller volumes of fill material, which saves reclamation cost. The flood risk is calculated by the multiplication of the probability of flooding and the damage of flooding. 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 of the polder as a result of rainfall and/or seepage. This will also result in an increase of the total costs compared to the conventional terminal. A disadvantage of the necessity of a water drainage system for a polder terminal is the extra space required for the drainage channels in the polder terminal yard (about 5% of the total area).

1.1 *Objective*

The exact savings in cost and the increased risk of inundation of the polder terminal require further investigation to prove the feasibility of the concept. 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 costs 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 defense structure for a polder terminal.

2 METHOD

A risk framework is developed to determine the optimal quay wall flood defense 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 the overtopping failure of the flood defense (Vrijling, 2001). Both the investment cost and the flood risk are related to this flood defense 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 defense 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

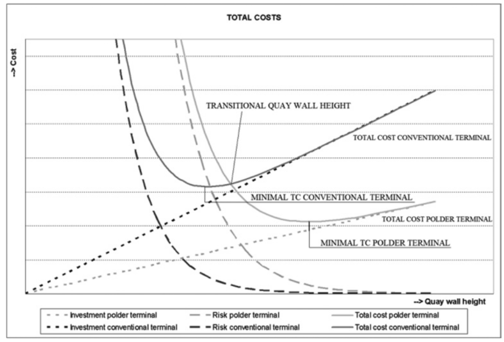

Figure 3. Risk framework optimization for a conventional and a polder terminal (conceptual graph).

variable, as with the approach of the Delta Committee, but on two variables: the flood defense level [h_q] (dike crest height) and the polder level [h_p].

If both a conventional and a polder terminal were 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 3. However the risk of the conventional terminal is expected to be lower than that of the polder terminal, due to the lower possible inundation depth and corresponding damage potential during a flood as shown in the figure.

The flood water 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, during a surge resulting in larger inundation depths. Flood damage depends on the inundation depth (increased damage for increased water depth) (Jonkman et al, 2008), resulting in higher damage potential for the polder terminal than the conventional terminal. 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 3.

3 RISK FRAMEWORK

The risk framework approach to optimize the quay wall flood defense 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 (fault trees)*

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 4.

3.2 *Large scale flooding*

Large scale flooding is related to 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 defense level (reclamation level) for both the conventional and polder terminal. The required flood defense 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 (les permeable) subsoil the amount of seepage is less. For a polder terminal to be feasible low pervious subsoil is therefore required to limit the amount of seepage water entering the polder.

Structural and/or geotechnical stability is assured by designing the quay wall flood defense structure according to the guidelines in CUR211 and 'Leidraad Kunstwerken', which limit the probability of structural failure to 1% of the probability of overtopping. This includes failure due to calamities such as earthquake and ship collision, these mechanisms largely depend on local conditions. Flooding due to rainfall is treated in the next section.

3.3 *Small scale flooding*

Small scale flooding is related to water depths below 0.5 meters and occurs due to excess water inside the polder due to 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 defense. 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, with a resulting total cost of order 10^7 €. Compared to the total cost of the whole polder terminal (order 10^9 €) these additional costs are low.

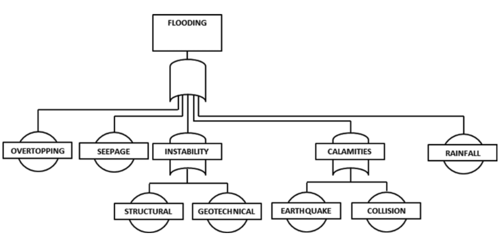

Figure 4. Fault tree for flooding of polder terminal.

3.4 *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, see Equation 1.

3.4.1 *Optimization polder terminal*

The investments 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 proportional to the quay wall height, [h_q] (m), and polder level, [h_p] (m). The relation is depicted in Equation 2.

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

This equation assumes a linear relationship between the quay wall height and cost based on data by de Gijt. The results found with this linear relation hardly deviate from the actual nonlinear relation, which has a bandwidth of approximately +/− 25% of the actual quay wall costs.

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), 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:

$$P_f = e^{-\frac{h_q - A}{B}} \tag{4}$$

As determined before not only overtopping but also other failure mechanisms determine the probability of flooding, however these failure mechanisms do not directly influence the required flood defense 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] (€), (also used for a conventional terminal), 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 (Boer, 2005 & Pimontel, 2006), which is the level difference between the quay wall level and polder 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 practical 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 the assumption.

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

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.

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

In this function 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.

$$\frac{\delta TC_{polder}}{\delta h_p} = I_p - \frac{e^{-\frac{h_q - A}{B}} * D_i}{r'} = 0$$

$$\Rightarrow h_{q;transition} = A - B * \ln\left(\frac{I_p * r'}{D_i}\right) \tag{7}$$

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, which is shown in Figure 2. Thus 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). Concluding the polder terminal is attractive for quay wall heights higher than the transitional height [$h_{q;transition}$] (m).

Figure 5 illustrates that for a quay wall height equal to the transitional quay wall height the total cost are constant, independent of the polder level (middle line). For quay wall heights higher than the transitional quay wall heights (bottom line) the total cost decrease with decreasing polder level, while for quay wall heights lower than the transitional quay wall heights (top line) the total cost increase with decreasing polder level. This demonstrates the linear influence of the polder level to the total cost. For quay wall heights higher than the transitional level the lowest possible polder level results in minimal total cost. There is however a boundary to the depth of the polder level, which is determined by requirements of stability of the quay wall flood defense and port logistics. This will be determined in the next section.

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 8–10. The solution of this equation is a Lambert function: an infinite row (exponent $[-(x-a)/b] = 1/x$). Such a function is solved numerically, through iterations. Thus after determining the boundary for the polder level the economic optimal quay wall height (higher than the transitional quay wall height) can be found by solving Equation 10 numerically.

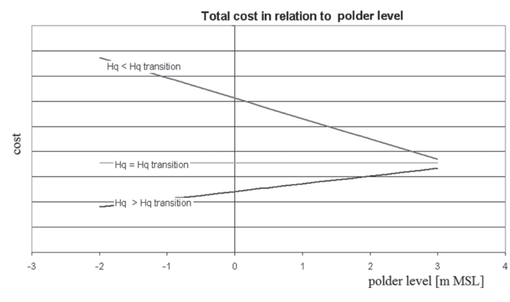

Figure 5. Total cost in relation to polder level for different quay wall heights.

$$\frac{\delta TC_{polder}}{\delta h_q} = 0 \tag{8}$$

$$I_q + \frac{e^{-\frac{h_q - A}{B}} D_i}{r'} - \frac{1}{B} \frac{e^{-\frac{h_q - A}{B}} \left[D_0 + D_i(h_q - h_p) + D_t(t_{flood}) \right]}{r'} = 0 \tag{9}$$

$$e^{-\frac{h_q - A}{B}} = \frac{I_q * r' * B}{\left[\left[D_0 + D_i(h_q - h_p) + D_t(t_{flood}) \right] - D_i * B \right]} \tag{10}$$

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. Finally, the optimal quay wall height is found numerically with Equation 10.

3.4.2 *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, these are illustrated in Figures 6–8 and explained in the next section.

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. Figures 6–8 show that, depending on the polder depth, the quay wall flood defense retains a resultant horizontal water pressure from the sea side (left) or a resultant horizontal soil pressure from the terminal side (right),

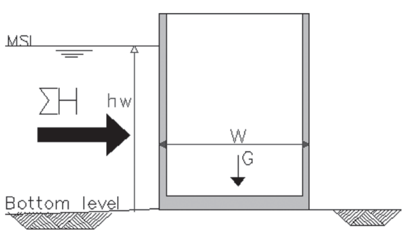

Figure 6. Resultant horizontal force in direction of terminal side of quay wall.

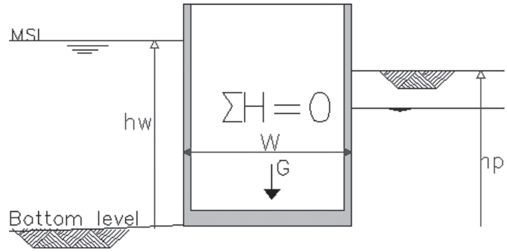

Figure 7. No resultant horizontal force on quay wall.

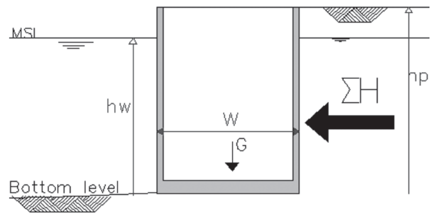

Figure 8. Resultant horizontal force in direction of por side of quay wall.

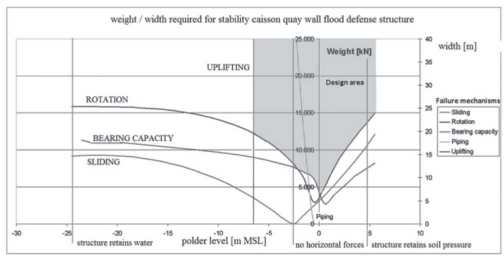

Figure 9. Required width of gravity structure related to the polder level (depth) for case study (4.1).

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 assured 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 width (and weight) to assure safety against these failure mechanisms depends on the polder depth as shown in Figure 9. The figure clearly shows that the structure requires minimal width at the location where the resultant horizontal force is zero (point B), this is the optimal polder depth.

The maximum polder depth 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 defense. 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 is found at the maximum polder depth, not the optimal polder depth. This is explained by the fact that the total costs are dominated by the reclamation cost (which are expensive order > 10 €/m^3), the quay wall cost only form a small percentage of the total 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 defense.

3.4.3 *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 $h_q = h_p$. The resulting investments are shown in Equation 11.

$$I_{conventional} = (I_q + I_p) * h_t \tag{11}$$

The probability of flooding is similar to the probability of flooding of the polder terminal (Equation 4 with $h_q = h_t$), the damage function consists of the summation of a constant level of damage [D_0] and the indirect damage [D_t] due to down time [t_{flood}] of the port (economic loss), Equation 12.

$$D_{conventional} = D_o + D_t * t_{flood} \tag{12}$$

The total cost of the conventional terminal [$TC_{conventional}$] is shown in Equation 13.

$$TC_{conventional} = (I_q + I_p) * h_t + P_f * D_{conventional}/r' \tag{13}$$

The optimal terminal level is found by minimizing the total cost function (Equation 13) to the variable terminal height, see Equation 15.

$$\frac{\delta TC_{conventional}}{\delta h_t} = (I_q + I_p) - \frac{1}{B}\frac{e^{-\frac{h_t - A}{B}} * D_{conventional}}{r'} = 0 \tag{14}$$

$$h_{t;optimal} = A - B * \ln\left[\frac{(I_q + I_p) * B * r'}{D_{conventional}}\right] \tag{15}$$

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: with a length of 4 kilometres and width of 0.8 kilometres. The polder terminal design is 5% larger than the conventional terminal design due to the required space for a water drainage and storage system. The subsoil consists of low permeable clayey layers and reclamation cost are expensive (order 20 €/m^3).

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 9.

To compare, the total cost of a conventional terminal with the same terminal height as the optimal polder terminal quay wall height is added as well as a polder terminal with terminal level at Mean Sea Level, see Table 3.

The following graph shows the results for a polder level at the uplifting boundary condition. By definition the conventional terminal and polder terminal have equal costs at the transitional quay

Table 1. Case study input parameters for Tuas Singapore.

Design parameter	Variable	Value
Current port depth [m MSL]	d	–25
Area conventional terminal [m^2]	A_c	3.0 * 10^6
Area polder terminal [m^2]	A_p	3.2 * 10^6
Quay wall cost [€/m^2]	I_q	1,700
Reclamation fill (sand is scarce) [€/m^3]	I_p	20
Exponential distribution water levels [–]	A, B	A = 2.87/ B = 0.15
Constant flood damage [€]	D_0	180 * 10^6
Direct flood damage [m]	D_i	360 * 10^6
Indirect flood damage [€/wk]	D_t	20 * 10^6
Reduced interest rate [–]	r'	0.05

Table 2. Total cost of optimal conventional and polder container terminals at Tuas Singapore.

	Conventional terminal	Polder terminal
Quay wall level [m MSL]	+3.8	+4.5
Terminal level [m MSL]	+3.8	–6.5
Investment [mln €]	2,090	1,585
Risk [mln €]	12	2
Total cost [mln €]	2,102	1,587
Total cost [€/m^2]	700	495
Difference [%]	0	–29

Table 3. Reference cases for comparison purposes of conventional and polder container terminal at Tuas Singapore.

	Conventional terminal	Polder terminal
Quay wall level [m MSL]	+4.5	+4.3
Polder level [m MSL]	+4.5	0
Investment [mln €]	2,130	1,950
Risk [mln €]	0.1	2.5
Total cost [mln €]	2,130	1,953
Total cost [€/m^2]	710	610
Difference [%]	+1	–13

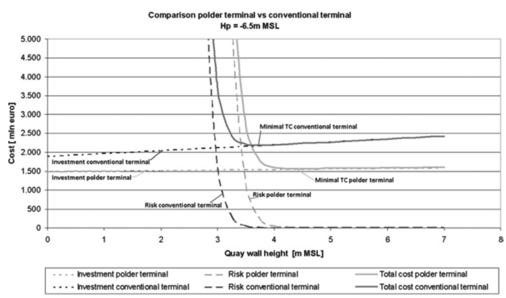

Figure 10. Comparison of total cost polder terminal vs conventional terminal (Reclamation = 20 €/m^3).

wall height of in this case +3.8 m MSL. For quay wall heights lower than the transitional height the conventional terminal is cheaper whereas for quay wall heights higher than the transitional level the polder terminal is cheaper.

5 DISCUSSION

From the optimization it can be concluded that a polder terminal could produce savings between 10 and 30%. As concluded earlier, the savings are largely dependent on the polder level (depth) which is bounded by uplifting of the polder. The percentage of reclamation saving as well as the risk prove to be independent of the total polder area, because both the reclamation cost and the 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 the 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 than 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 with a conservative design for drainage and storage capacities proves that the increase in cost is small (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 local extreme rainfall intensities.

6 CONCLUSIONS, LIMITATIONS AND FURTHER RESEARCH

In this paper the feasibility of the polder terminal is investigated through a risk based design of land reclamation. A risk framework approach is developed 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 defense level. In the new approach the investments and risk are determined by two variables: the flood defense 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 defense 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 project investments in dikes around the project are better or building the project on terps.

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 reduction of the reclamation cost proves to be larger than the increased risk of inundation and water storage/drainage cost of the polder terminal. 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 polder 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 such as dry bulk terminals. More research could provide useful 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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