SOCIO-ECONOMIC

LAND RECLAMATION:

THE POTENTIAL FOR SUBSURFACE FRESH WATER STORAGE

At present too little use is made of the opportunities that the design and construction of land reclamation offer for the underground storage and recovery of fresh water. The managed aquifer recharge systems in the coastal dunes of the Netherlands are a good example of successful subsurface water storage. And it is to be expected that the sandy deposits of land reclamations could serve a similar purpose. This in turn will contribute to a sustainable development of land reclamations.

Subsurface freshwater storage and recovery potentially increases the robustness of the water supply and the quality of life on land reclamations.

Fresh water is vital to accommodating an urban population in its residential, industrial and recreational needs. At land reclamations, fresh water cannot always be supplied from the mainland, simply because many coastal megacities already suffer from increasing freshwater shortages due to urbanisation and ongoing climate change. This leaves desalination as only alternative for the freshwater supply of most land reclamations, but this technique is expensive and highly energy consuming. Building freshwater storage capacity on the land reclamation is an alternative. Collecting rainwater, using treated wastewater or storing desalinated water are options. With a considerable storage, the land reclamation is made less dependent on supply from the mainland or on desalination. This is profoundly important in the light of sustainability and climate adaptation.

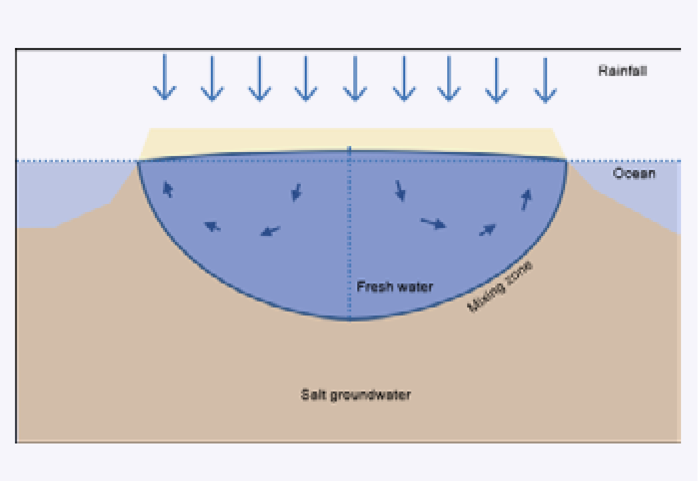


FIGURE 1

A freshwater lens in an oceanic island under natural conditions.

The possibilities for storage above ground are minimal, due to the high land prices and the high costs involved with aboveground storage tanks. Subsurface storage, on the other hand, has a minimal footprint above ground and utilizes the large space that is available in the subsurface of the land reclamation. Its conserving qualities both with respect to evaporation and water quality make subsurface storage of fresh water attractive compared to above ground storage. Moreover, fresh groundwater, if accessible to plants and trees, will immediately enhance the image of the new land in a natural way. All these benefits ensure that subsurface freshwater storage and recovery potentially increases the robustness of the water supply and the quality of life on land reclamations.

Groundwater in land reclamations is directly connected to the sea and is, therefore, saline. In oceanic islands and dune areas, a freshwater lens can develop in a natural way by the combination of the density difference between fresh and salt water, gravity and

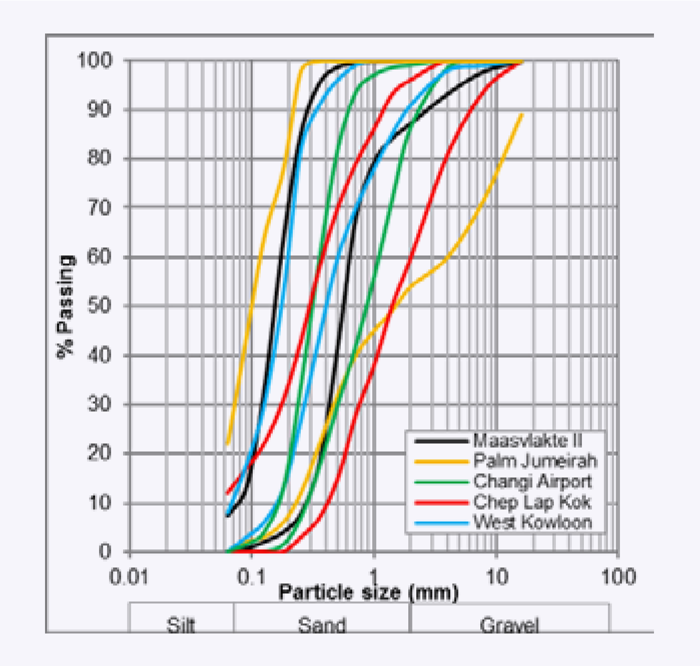


FIGURE 2

The minimum and maximum grainsize distribution curves of samples taken at land reclamations.

Darcy's Law. Badon Ghijben (1889) and Herzberg (1901) were the first to describe the physics of a freshwater lens (Figure 1). The natural development of freshwater lenses takes many decades and requires a constant flow of fresh water. Fresh water can also be infiltrated and recovered by means of groundwater wells. This technique is applied, for example, by the Dutch drinking water companies as well as by agri- and horticulturists in the western part of The Netherlands.

The feasibility of subsurface freshwater storage and recovery requires a high freshwater recovery efficiency, which is at risk because the injected water will inevitably come into contact with saline groundwater present in the subsurface of the land reclamation. The challenge is to prevent that freshwater recovery efficiency is impacted by mixing with salt water and by buoyancy caused by the density difference between fresh and salt water. In practice as well as in scientific literature, the freshwater recovery has always been controlled by operational factors, such as injected and recovered volume, location of wells, recharge rates and storage duration. However, the properties of the aquifer that also influence the recovery efficiency, such as porosity, hydraulic conductivity and aquifer thickness, have always been considered as fixed and site-specific. New for land reclamations compared to natural soils, is that these physical properties are part of the design of land reclamations and, therefore, this creates opportunities to better manage mixing and buoyancy to reach high recovery efficiencies from the freshwater lens.

Geotechnical data

This study investigates the hydraulic properties of five land reclamations that were constructed by a combination of bottom discharging, rainbowing and pipeline discharge to determine the feasibility for freshwater storage and recovery. Pumping tests are commonly applied to determine the hydraulic characteristics of the soil. However, pumping tests were not available for this study because land reclamations have hardly been studied for their hydraulic characteristics. The literature on land reclamations contains only geotechnical data related to bearing capacity, settlement and liquefaction. Therefore, the grainsize distribution curves and conepenetration tests from study area D2 in Maasvlakte II, the Netherlands were considered. These data were supplemented with the geotechnical data from the four other land reclamations that could be found in the literature. These are: Palm Jumeirah, Dubai, the United Arab Emirates, Changi Airport, Singapore, Malaysia and Chep Lap Kok and West Kowloon, both in Hong Kong, China.

Figure 2 presents the minimum and maximum grainsize distribution curves of the studied reclamations. These reclamations consist of fine to coarse sand. The corresponding porosity and hydraulic conductivity values are, therefore, likely to be moderate to high. At first sight, these conductivities seem to make these land reclamations suitable for the development of a freshwater lens.

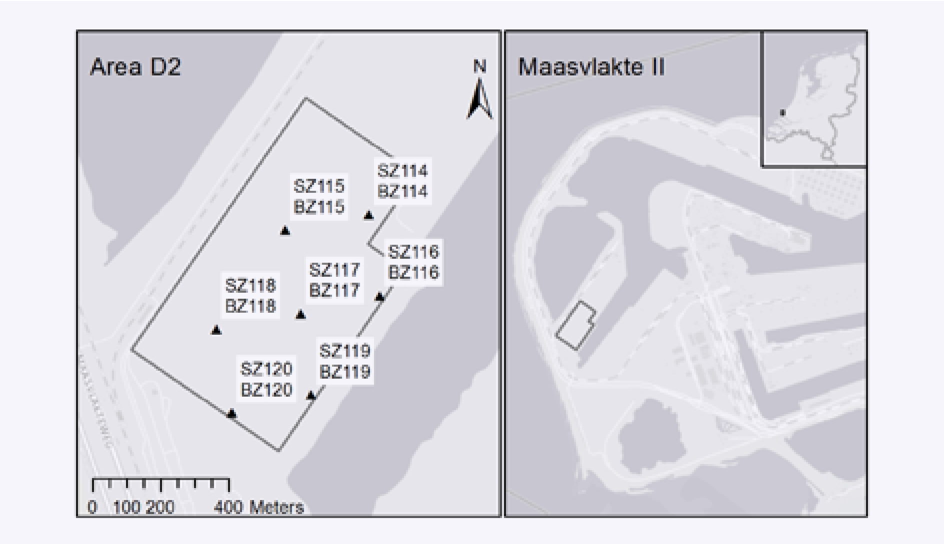


FIGURE 3

Location of study area D2 at Maasvlakte II, the Netherlands.

Data case study area D2 Maasvlakte II, the Netherlands

Figure 3 presents the location of study area D2 in the southern part of Maasvlakte II. Bottom discharging was applied until –7 m mean sea level (MSL), followed by rainbowing to bring the reclamation level up to MSL. Fill material above this level was placed by pipelines to achieve the final elevation of +5.35 m MSL.

The black lines in Figure 2 present the outer ranges of the grainsize distribution of study area D2. In study area D2 soil samples were taken at seven borehole locations, as presented in Figure 3. The soil samples were taken every 2 m depth, up to 10 m below ground level, and the sieve curves of the soil samples were determined. Figure 4 shows D_{10} and D_{50} of the soil samples and indicates which placement method was adopted at which depth.

Seven conepenetration tests (CPTs) were taken in the study area. Figure 5 shows the CPTs and indicates which placement method was adopted at which depth.

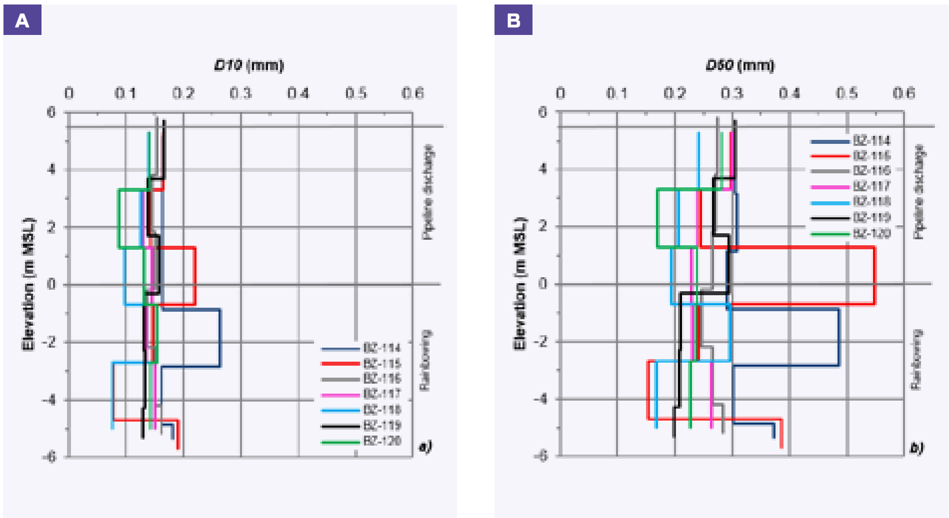


FIGURE 4

(A) D10 (mm) and (B) D50 (mm) over depth of the soil samples taken at Maasvlakte II study area D2.

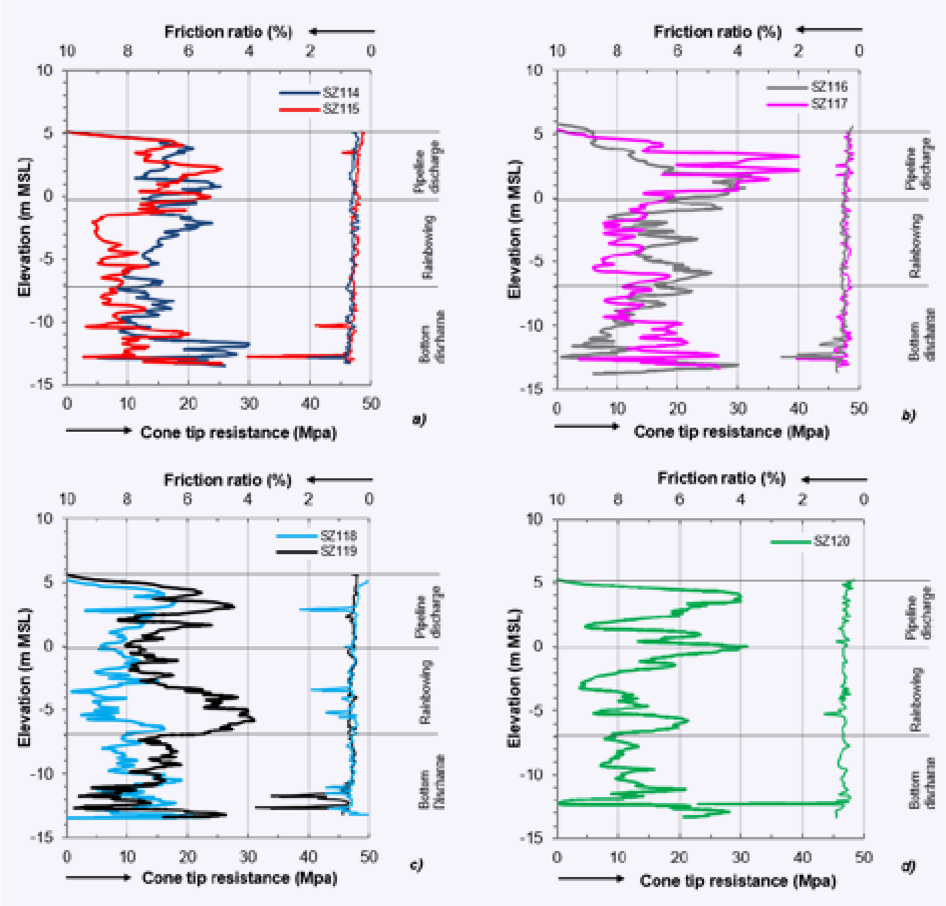


FIGURE 5

Conetip resistance (left lines) and friction ratio (right lines) at Maasvlakte II study area D2.

Data reference cases

Data of area D2 have been supplemented with the grainsize distribution curves and conepenetration tests that were previously presented in the work of Lees (et al., 2013), Chua (et al., 2007), Lee (2001) and Lee (et al., 1999). These land reclamations were also constructed by a combination of bottom discharging, rainbowing and pipeline discharge. The dimensions and construction details of these land reclamations can be found in the references.

Figure 2 presents the outer ranges of the grainsize distribution of the considered reference cases. Quartz sand of marine origin was used at Changi Airport (Chua et al., 2007), Chep Lap Kok (Lee, 2001) and West Kowloon (Lee et al., 1999). Shelly carbonate sand is used at Palm Jumeirah (Lees et al., 2013). Shells are angular and typically have a wider grainsize distribution than quartz grains (Lees et al., 2013). Figure 6 shows the CPTs of the reference cases and indicates which placement method was adopted at which depth.

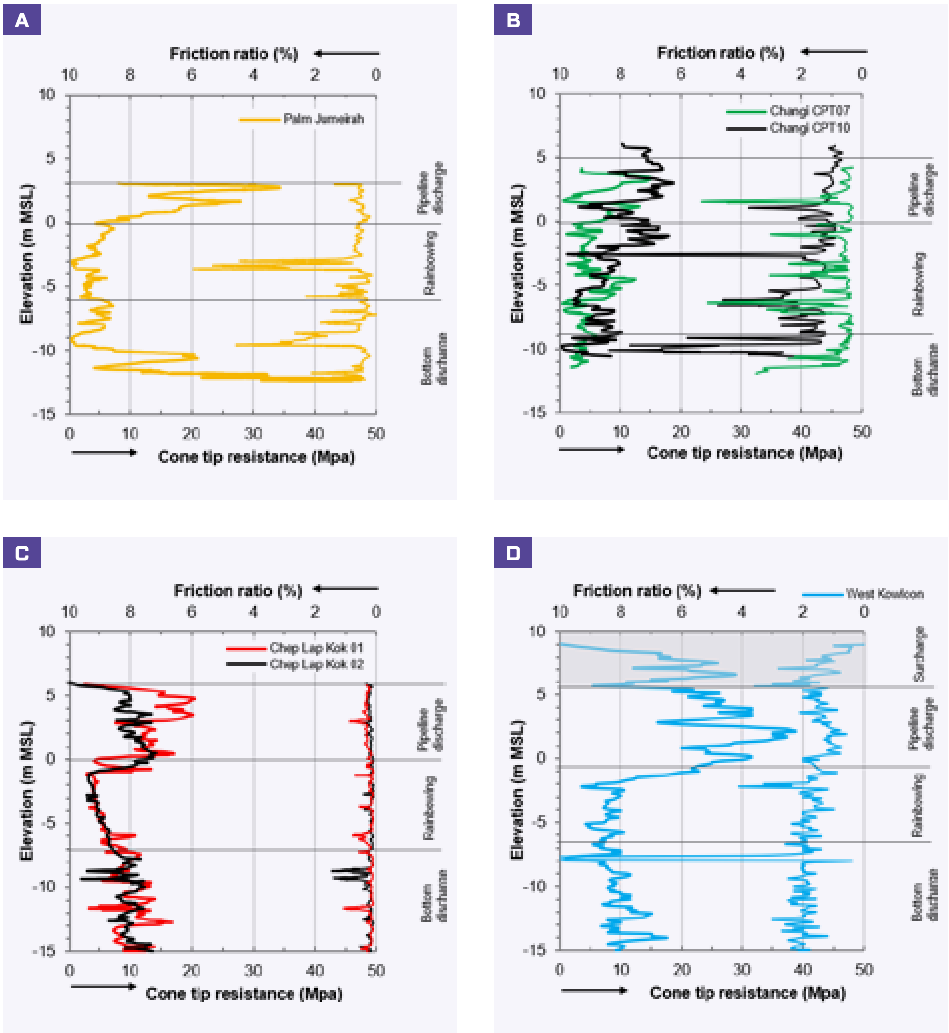


FIGURE 6

Conetip resistance (left lines) and friction ratio (right lines) at (A) Palm Jumeirah (Lees et al., 2013), (B) Changi Airport (Chua et al., 2007), (C) Chep Lap Kok (Lee, 2001) and (D) West Kowloon (Lee et al., 1999).

Method

Analysis of the sedimentation from a sandwater mixture for the three placement methods gives insight into grain sorting and how it varies from place to place in the reclamation. The structures of the porous media resulting from each placement method are presented. These structures are validated by comparison with semivariograms of conepenetration tests. A semivariogram provides insight in the spatial variance of a parameter and, therefore, into its degree of heterogeneity.

Sedimentation process bottom discharging

As presented by Van Rhee (2002) segregation of grain sizes has already developed during loading and transport inside the Trailing Suction Hopper Dredger (TSHD). Segregation also occurs within the settling sandwater mixture, with the larger grains tending to settle faster than the smaller grains, as explained by Stokes's Law.

The ambient seawater is, in principle, displaced sideways during the settling of the sandwater mixture, allowing the mixture to descend as a single mass (see Figure 7). However, some seawater will probably escape upward through irregularities in the sand-water mixture in the following manner: random 'volcanoes' of seawater will develop spontaneously in the sandwater mixture where seawater starts to flow through the mixture. The Reynolds number of the sand-water mixture is in the turbulent regime and turbulent eddies form around the mixture, keeping fine material in suspension. However, the bulk of the sandwater mixture will quickly fall upon the seafloor.

Complete segregation can only occur in infinitely deep water. However, land reclamations are typically constructed in the coastal zone where water depth is limited to a few tens of meters maximum, because of which it is unlikely that the mixture fully segregates. In addition, the settling velocity of the grains is hindered in accordance with the wellknown formula by Richardson and Zaki.

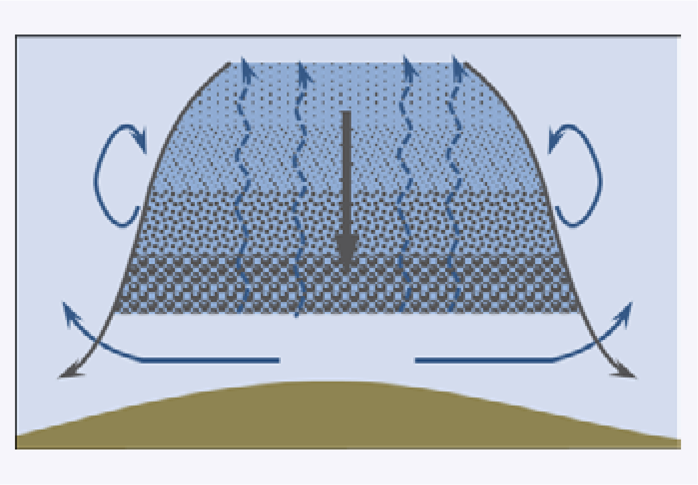


FIGURE 7

Illustration showing the settling sand-water mixture and how seawater is displaced.

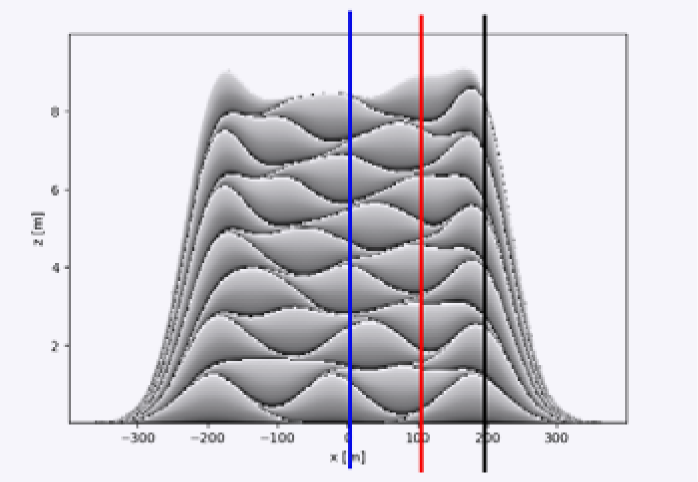


FIGURE 8

Crosssection of a bottom-discharged fill model in which the shading reflects the structure of the porous medium. A darker colour indicates a coarser grain size.

The sandwater mixture flows radially outward as soon as it hits the seafloor and its velocity decreases significantly due to the divergence of the flow lines. The turbulence in the sandwater mixture decreases accordingly, causing the mixture to come to an abrupt standstill causing sand to fall out of suspension. Redistribution takes place only when the angle of the bottom-discharged fill becomes more than the angle of repose, which cause sand slides along the slope.

A distinct segregation mark between two bottom-discharged layers can be observed in the typical cross-section of samples as presented in Lee (2001) and Shen and Lee (1995) taken from the bottom-discharged fill at Chep Lap Kok. Lee found that the grainsize distribution of the coarser grains corresponds closely to the upper bound of the possible range of the Chep Lap Kok sand. The grain-size distribution of the finer grains, on the other hand, is close to the lower bound of the Chep Lap Kok sand.

Lee (2001) represented the shape of each discharge dump as a trapezium and suggested that dumps are randomly distributed. Lee's model was slightly modified in this study. Figure 8 was made by assuming that each dump has the shape of the normal probability density function (PDF), which, therefore, reaches from $-\infty$ to $+\infty$. Its central location is the position of the TSHD and its volume equals that of the capacity of the vessel. The thickness of each dump at any location is, therefore, given by the pdf times the volume. In this study, the sieve curve of Maasvlakte II study area D2 is assumed to be completely segregated within each dump. Therefore, the grains in each dump are distributed upward from coarse to fine in accordance to the sieve curve. This is true at any *x*-coordinate for every dump. Subsequent dumps are added, so that the upper and lower boundary of each dump is according to the sequence of bottom discharging. It was assumed that the THSD is placed randomly across the reclamation site for the first dumps and later placed just above the point with the maximum distance between the elevation of the dumps and the target elevation. This fills the reclamation to a uniform height. Pure random discharging will never give the desired end shape.

As Figure 8 suggests for an ideal fully segregated dump, a bottom-discharged fill will consist of thin, elongated lenses of circa 1 to 2 m high and several tens of metres wide with a characteristic vertical grainsize distribution. The occurrence of such lenses may be investigated by means of semivariograms. The semivariance $\gamma(h)$ is half the average squared difference between points separated at a certain lag distance *h* (Matheron, 1963). Figure 9 presents the semivariograms of vertical crosssections through the bottom-discharged fill model at x=0, 100 and 200 m.

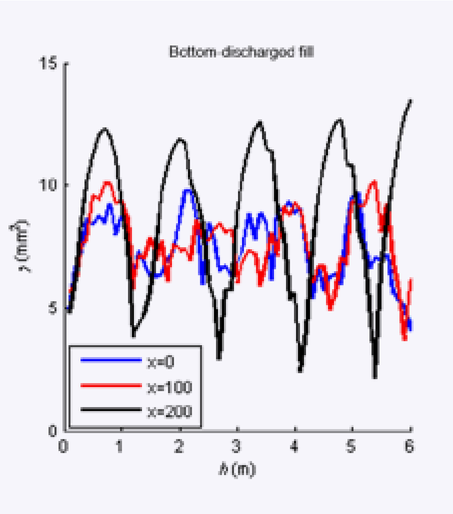


FIGURE 9

Semivariogram at the cross-sections of bottom-discharged fill model.

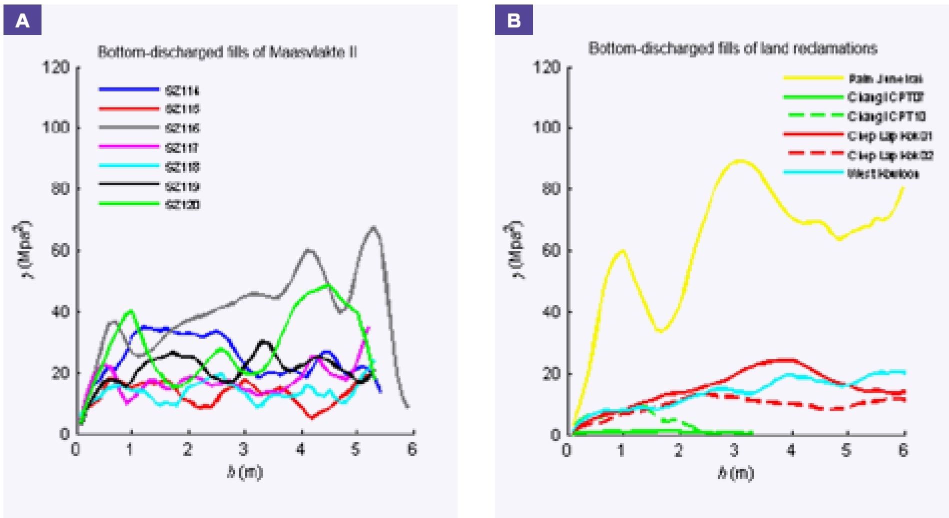


FIGURE 10

Semivariogram of CPTs of bottom-discharged fills, (A) Maasvlakte II study area D2, and (B) the other land reclamations.

The semivariance fluctuates periodically with lag distance. The periodic structure is most apparent at x=200 m, showing a sinusoidal semivariance with a period of 1.5 m lag distance. According to Pyrcz and Deutsch (2003), a periodic semivariance indicates regularly clustered lenses or strata of higher and lower grain size in the bottom-discharged fill. Figure 8 also shows that the characteristic distance between dumps at x=200 m repeats every 1.5 m. At x=0 and 100 m the periodic structure is more distorted because the stacking of the dumps is less uniform, as also appears from Figure 8.

Data analysis of bottom-discharged fills

The occurrence of lenses in bottom-discharged fills may be investigated with semivariograms of the conetip resistance measured with conepenetration tests (CPTs) done shortly after construction. Figure 10a and Figure 10b present the semivariograms of the bottom-discharged fills of the CPTs of Figure 5 and Figure 6. Similar to Figure 9, these semivariograms exhibit a periodic structure, which now indicates regularly clustered lenses or strata of higher and lower resistance of the conepenetration in the bottom-discharged fill.

How should these CPT readings be interpreted in terms of conductivities, while CPTs are known to reflect the relative density?

Several researchers, such as Baldi et al. (1986) and Lunne and Christofferson (1983), established correlations between the cone tip resistance q_c, the vertical effective stress σ'_v and the relative density D_r.

$$D_r = \frac{1}{C_2} ln\left(\frac{q_c}{C_0(\sigma'_v)^{C_1}}\right) \qquad (1)$$

Where C_0, C_1 and C_2 are parameters correlated in calibration chamber tests for specific sands. The relative density relates the *in situ* density to the minimum and maximum reference density values and these are inversely related to the minimum and maximum porosity n_{min} and n_{max} (Van 't Hoff and Van der Kolff, 2012):

$$D_r = \frac{\rho_d - \rho_{d,min}}{\rho_{d,max} - \rho_{d,min}} 100\% = \frac{n_{max} - n}{n_{max} - n_{min}} 100\% \qquad (2)$$

The semivariograms of the CPTs thus provide insight into the variation in porosity. A more uniform grain-size distribution and/or lower compaction will show a higher porosity. More uniform grain-size distributions in land reclamations consist of finer sediment because having come from the same borrow area, the coarse grains have been sorted out. Therefore, it is plausible that the peaks in the CPTs correlate with the better-mixed material at the bottom of each dump that consists of a mixture of coarser and finer grains. The relatively low values in the CPTs correlate with the more wellsorted, i.e. finer, material at the tops and slopes of dumps.

For the seven CPT readings done in the Maasvlakte II, the characteristic distance between lenses was found to be about 1.5 m. The semivariograms for West Kowloon and Palm Jumeirah for the bottom-discharged fills show a similar periodicity as Maasvlakte II. The much larger variance of Palm Jumeirah compared to the other land reclamations can be attributed to the larger gradation in grain-size caused by the broken shells that characterizes this fill material (Miedema and Ramsdell, 2011; Lees et al., 2013). The characteristic distance between lenses of the semivariograms of Chep Lap Kok 01 and 02 was found to be 2 m. This periodicity leads to the assumption that larger TSHDs were used to make this land reclamation. The bottom-discharged fill in Changi is not thick enough to register periodicity.

Sedimentation process of rainbowing

In the land reclamations considered in this study, rainbowed fill up to sea level was applied on top of the bottom-discharged fill. The sand-water mixture is fluidized and mixed on board the TSHD to obtain pumpability and the mixture sprayed through the nozzle is then well mixed, in contrast to bottom discharging. The velocity of the sandwater mixture is

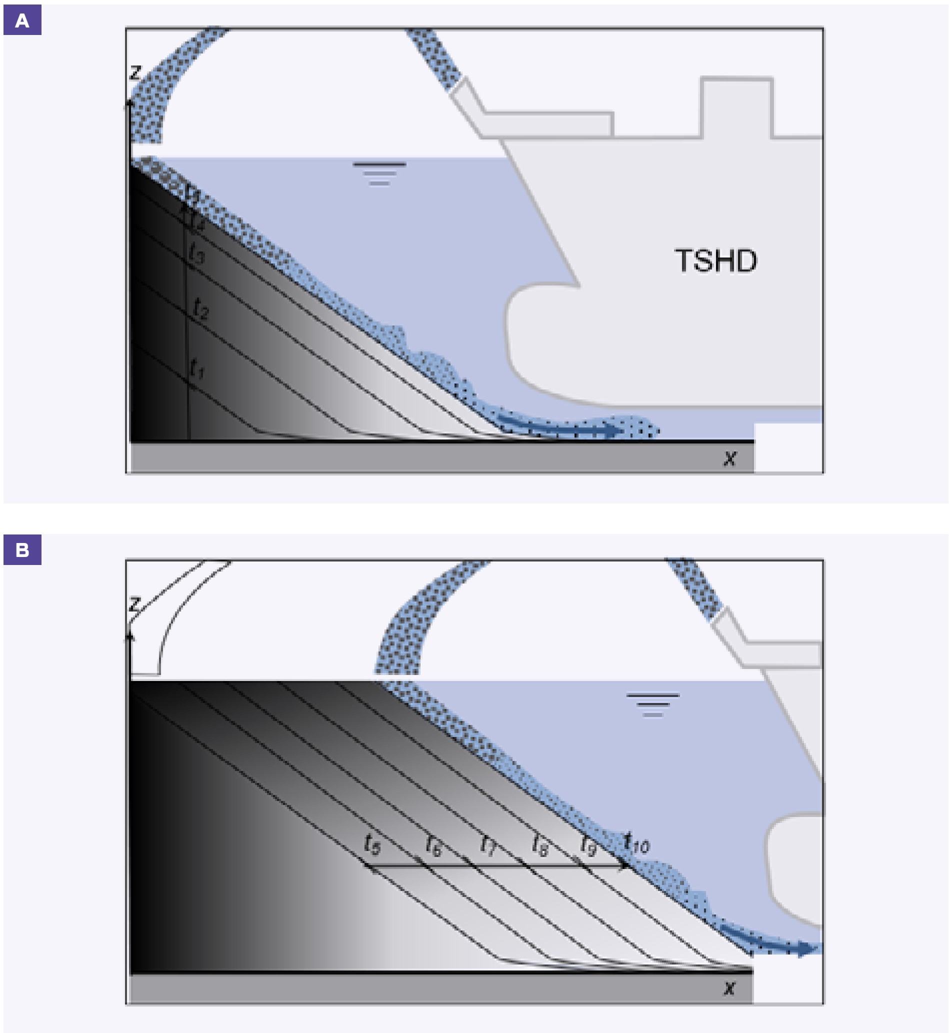


FIGURE 11

(A) cross-section of a rainbow-discharged fill over time (starting at t1 to t5) in which the shading reflects the structure of the porous medium and (B) the buildout over time (starting at t5 to t10). A darker colour indicates well-mixed material and a lighter colour indicates more well-sorted material dominated by finer grains.

immediately reduced upon reaching the sea surface. Some segregation will occur during settling. The rainbowed sandwater mixture builds up a fill as rainbowing continues at that location. As the fill grows, the sandwater mixture increasingly flows as a density current over its slopes. The slopes tend to maintain a certain angle of repose, so that the fill keeps the same shape while growing.

While rushing down the slope, turbulent eddies generated by the density current entrain surrounding seawater into the mixture (Huppert and Simpson, 1980; Hallworth et al., 1993). As the distance from the top increases, the density difference driving the current is reduced by dilution. Settling is most hindered near the top, where the concentration of sand in the density current is high. The result is a less segregated deposit along the upper part of the slope (Lowe, 1982). The mixture is more diluted further down, so settling is less hindered, resulting in a more segregated deposit.

Figure 11 shows the hypothetical structure of the porous medium resulting from rainbowing. The increased segregation downslope, results in a finer and more uniform particle-size distribution with distance from the top. Because the same processes operate during the total buildup of the fill, the grain size tends to remain constant for a fixed distance to the fill centre. This implies that the grainsize distribution is uniform in cylinders centred around the axis of the fill, i.e. constant along vertical lines.

Once the fill has reached sea level, the TSHD withdraws in seaward direction building the fill seaward (see Figure 11b). The grain size remains constant at the same distance from the top of the forward moving slope. This implies that the grain-size distribution will be constant horizontally, refining in downward direction. The finest grains will accumulate on the sea floor in front of the toe of the slope and are buried under the advancing slope. Fines still in suspension will settle after each interruption of the rainbowing process. This is expected to cause a few cm-thick layer of fines, marking the slope at interruptions in rainbowing. However, no evidence was found in the literature to support this hypothesis.

As the rainbow-discharged fill grows, the sandwater mixture increasingly flows as a density current over its slopes.

Data analysis of rainbow-discharged fills

Lee (2001) and Lee et al. (1999) concluded from the CPTs that the q_c profiles for rainbow-discharged fills are generally much smoother than for bottom-discharged and pipeline-discharged fills. This implies that rainbow-discharged fills are more homogenous. The increase in average q_c over depth is less than for bottom-discharged fills (Lee, 2001).

Figure 12 presents the semivariograms of the CPTs for the rainbow-discharged fills. The variance in Maasvlakte II study area D2 and West Kowloon is comparable to the variance for bottom-discharged fills, in contrast with the other rainbow-discharged fills, which show a lower variance than in Figure 10. Periodic structures are not apparent. It is assumed that the higher variance in Maasvlakte II study area D2 and West Kowloon compared to Chep Lap Kok and Changi Airport is caused by the larger amount of fine grains in these sands (see Figure 2) which caused more segregation during rainbowing and, moreover, more settling of finer material during interruptions in the rainbowing process. The relatively low variance in the rainbow-discharged fill at Palm Jumeirah can be attributed to the shells in the density

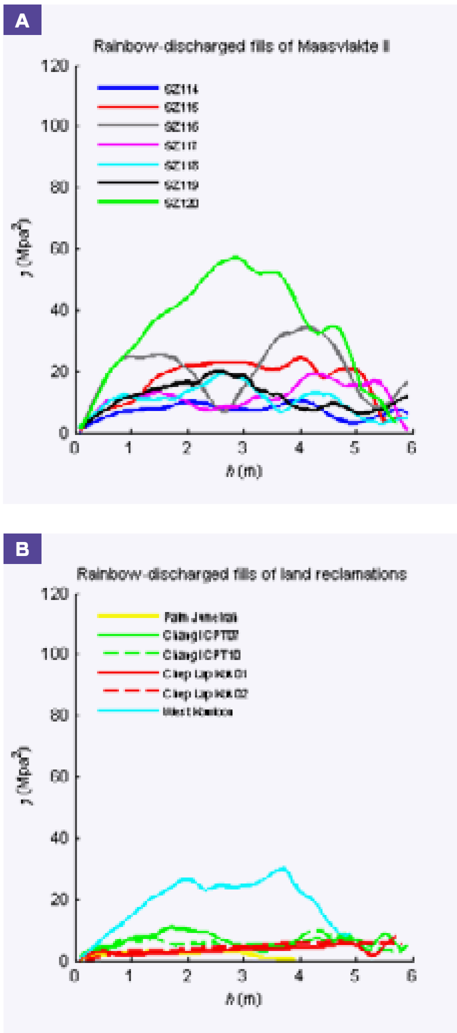


FIGURE 12

Semivariogram of CPTs of rainbow-discharged fills, (A) Maasvlakte II study area D2, and (B) the other land reclamations.

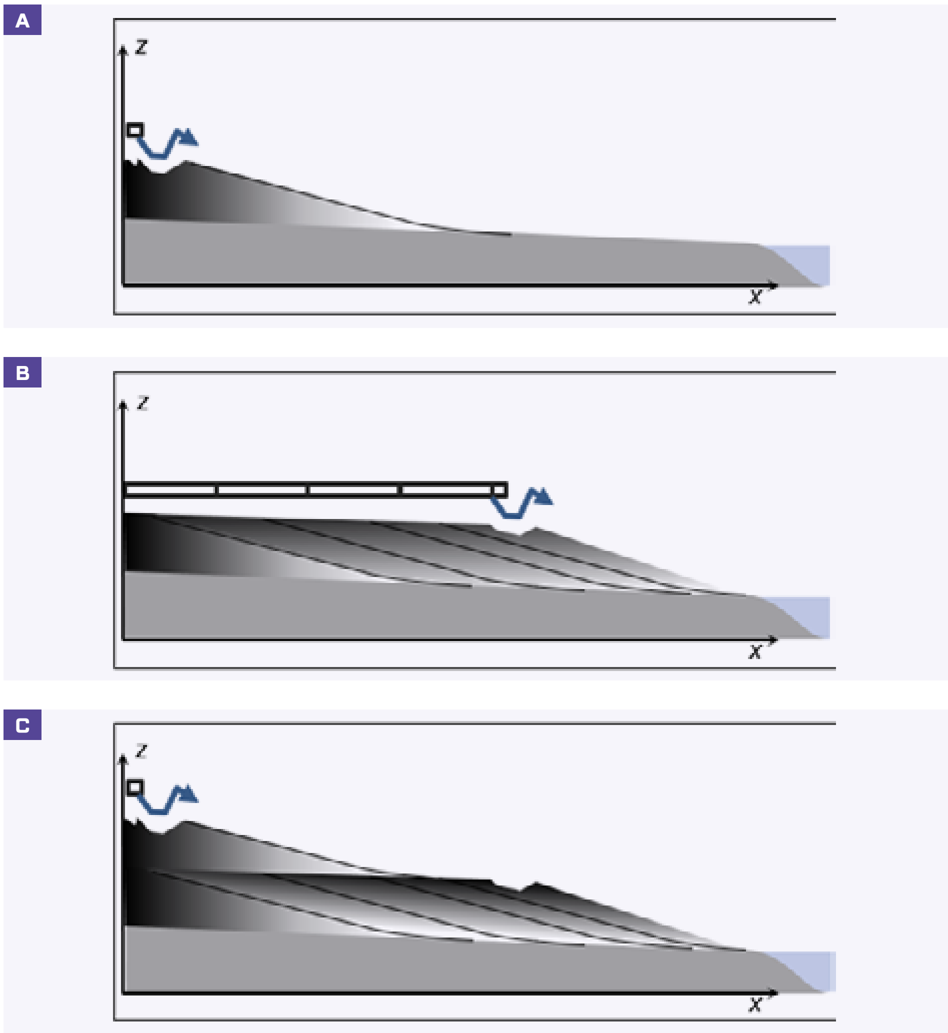


FIGURE 13

Cross-section of a pipeline-discharged fill above water in which the shading reflects the structure of the porous medium, (A) one section, (B) several sections that coincide with the extension of the pipeline, and (C) second stack. A darker colour indicates a coarser grain.

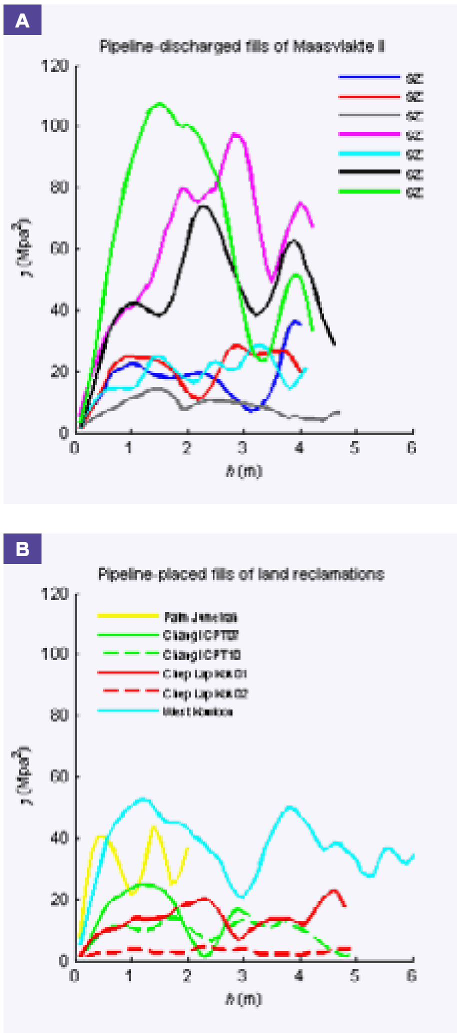


FIGURE 14

Semivariogram of CPTs of pipeline-discharged fills, (A) Maasvlakte II study area D2, and (B) the other land reclamations.

The structure of the porous medium of pipeline-discharged fills is similar to the parasequences of natural marine deposits.

current that cause more hindered settling due to which less segregation took place.

Sedimentation process of pipeline discharge

Above sea level, pipeline discharge was applied. Figure 13 shows the hypothetical structure of the porous medium resulting from pipeline discharge. At the pipeline outflow, the sandwater mixture forms a scour hole. The sandwater mixture flows over the edge of the scour hole. While the diameter of the pipeline is about the same as the diameter of the rainbow nozzle, the pumping rate is much lower. The degree of turbulence is so low that coarse grains settle directly near the pipeline (Mastbergen and Bezuijen, 1988). Finer grains are transported along the slope and the finest grains accumulate at the toe (see Figure 13a). Bulldozers level the area in front of the pipeline outflow and fill the scour hole.

After a certain elevation is reached, the next pipe section is connected and the filling process continues (see Figure 13b). The segregation of grains along the slope is similar to what happens under water during rainbowing. This implies that the grainsize distribution will be constant horizontally and will refine in a downward direction. As with rainbowing, the finest grains accumulate in front of the toe of the slope and are then buried as the slope advances (see Figure 13b). This creates a band of fine grains at the bottom. Fine material also accumulates before the bunds.

Once the end of the fill area is reached, the filling process may be repeated to create a following stack (see Figure 13c). As a result, the structure of the porous medium of a pipeline-discharged fill consists of stacks, which are similar to the so-called parasequences of natural marine deposits (Coe, 2002) in which each stack refines from top to bottom. These stacks may be recognised in a drilling by the band of fine material that vertically separates them, but these bands may be too thin to be recognized in a CPT.

Data analysis pipeline-discharged fills

The conetip resistance of sand fills formed above water is substantially higher than that of sand-fills formed by subaqueous placement. The compaction is further increased by the levelling operations of the bulldozers and the impact of other construction traffic. Figure 14 presents the semivariograms of the available CPTs of the pipeline-discharged fills. The variance is higher than that of the other placement methods shown in Figure 10 and Figure 12. All semivariograms of the pipeline-discharged fills exhibit a periodic structure. This periodicity strongly suggests that several stacks were applied; the periodicity is consistent with a general thickness of circa 1 to 2 m.

Consequences for the hydraulic conductivity of land reclamations

At the size of a representative elementary volume (Bear, 1972), i.e. circa 20 grain diameters, the conductivity is essentially expressed by the CarmanKozeny relation:

$$K = \frac{\rho g}{\mu} \frac{1}{CS_0^2} \frac{n^3}{(1-n)^2} D_{eff}^2 \qquad (3)$$

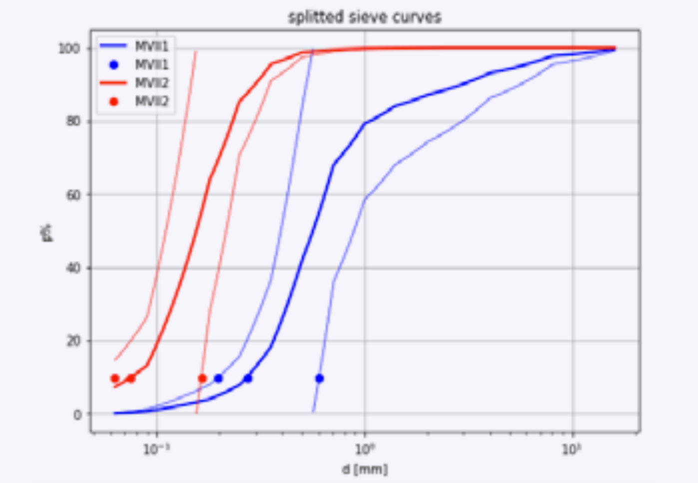
Where g/μ is the unit weight/viscosity of water, n [-] is porosity, D_{eff} [L] is the effective grain diameter usually taken to be equal to D_{10}, and S_o [1/L] is the specific surface. C is an empirical coefficient to correct for grain ordering and grain shape to match laboratory measurements for permeability with actual porosity and effective grain diameter. C is usually taken to be equal to 5.

With a given grain-size distribution, porosity is the only unknown in estimating conductivity. Porosity ranges from 35% to 40% in most unconsolidated sediments in the Netherlands (Olsthoorn, 1977), but could be higher in freshly reclaimed land, especially in places where the grainsize distribution is more uniform.

Based on equation 3 the difference in conductivity between sands with an equal grainsize distribution but a porosity of 35% and 40% respectively, is a factor of 1.75. However, the difference in conductivity due to different effective grain diameters of the two most extreme sieve curves from Figure 2 is about 4 in the Maasvlakte II study area D2, about 2 in Changi Airport and even more at the three other reclamations.

FIGURE 15

The two extreme sieve curves for Maasvlakte II original (thick line) and split in their lower and upper halves to illustrate the effect of segregation, which makes the curves steeper and shifts the effective diameter away from the original value (thick line).



In the equation of Carman-Kozeny the conductivity is proportional to the effective grain diameter squared, which indicates that the effect of the effective grain size by far outweighs that of porosity. This is also the case with the segregation of the grains, which can be illustrated by splitting the sieve curve into a lower part containing the finer grains and an upper part containing the denser ones (see Figure 15).

The segregation makes both sieve curves more uniform, i.e. steeper, but at the same time, the D_{10} of the lower curve is reduced relative to the original, and that of the upper curve has increased. According to Carman Kozeny, this implies that the conductivity of the lower curve is reduced and that of the upper curve in increased relative to the original mixture. It is likely that the more uniform fine sand will have highest porosity, but this porosity effect may only partly compensate its lower effective grain diameter.

The CPTs reveal zones of higher and lower relative density, i.e. of lower and higher porosity, rather than conductivity. However, the coarser sand will remain better mixed when placed and, therefore, has the highest relative density. Because the effective grain diameter has a more important effect on conductivity than porosity, the most plausible conclusion is that the higher CPT values correspond to a higher conductivity in land reclamations. Consequently, the grainsize distributions as illustrated in Figure 8, 11 and 13 mimic the conductivity.

It is noted that if the relative density of the fill mass after deposition and/or the underlying soil do not meet the required design criteria, ground improvement techniques can be applied to improve the properties of the fill and/or subsoil. Ground improvement was not taken into consideration in this study because the available data were without soil improvement.

Consequences for subsurface freshwater storage in land reclamations

Using the Carman-Kozeny equation, and taking the effective diameter of the actual soil samples of the rainbow-discharged part of the fill of Maasvlakte II study area D2, which are depicted in Figure 4, the conductivity would fluctuate between 2 and 24 m/day; an order of magnitude. This effect goes unseen if only average values are considered and is important for the subsurface storage and recovery of fresh water. The recovery efficiency of freshwater storage systems in land reclamations can be influenced by differences in dispersion and preferential flow resulting from the applied placement methods. The recovery efficiency is expected to be lowest for bottom-discharged fills in which the sand has a wide grainsize distribution. They show the largest grainsize variation on small vertical scales, because of the irregular stacking of lenses in each of which the grains coarsen downward. The recovery efficiency is expected to be highest in rainbow-discharged fills, because they are composed of wellmixed material where the grain size smoothly increases upward over the total depth of the fill.

Despite the small variations in grain-size distribution, the porosity and hydraulic conductivity of land reclamations that are constructed of sand by bottom discharge, rainbowing and pipeline discharge are comparable to natural dunes and the heterogeneity is more predictable than that of natural soils. Disturbances, such as clay layers, do not occur, because only sand is used for the construction of the land reclamation. Moreover, the content of fine material in land reclamations is usually lower than in the socalled borrow areas, which is due to the overflowing water during loading of the TSHD carrying along fines, and because fines are partly transported beyond the reclamation site during placement. In conclusion, land reclamations that are constructed of sand by bottom discharge, rainbowing and pipeline discharge are suitable for subsurface storage and recovering fresh water.

The degree of segregation caused by a specific placement method still depends on sitespecific circumstances, such as settling depth, grainsize distribution and angularity resulting from grain type. It is impossible to separate these three parameters with a single CPT. Therefore, to verify the hydraulic properties in a specific land reclamation in which the exact placements are not known, (undisturbed) soil samples and pumping tests at different depths and places are indispensable. To advance the development of water storage in land reclamations, field experiments in the form of pumping tests and infiltration tests are helpful. Not only to show the potential but also to research and further develop technologies and operational and management concepts.

Since land reclamations are typically constructed in coastal zones of limited depth of at most a few dozen meters, the potential storage zone is restricted, unless the sea floor itself is highly conductive. The thickness of the potential storage zone may be further restricted where land reclamations are constructed by a sequence of placement methods, because a layer of finer grains is expected to be present at the bottom of the rainbow-discharged fill and at the bottom of the pipeline-discharged fill. Moreover, a band of fines will be present along the edges of pipeline-placed fills wherever closing bunds were applied. Such bundformed elongated bands of fine material may be advantageous for the formation of a freshwater lens. On the other hand, parallel bunds bounding strips of land that mark phases in the construction of the reclamation, will likely result in some degree of compartmentation.

The time required to fill the storage volume to its design capacity depends on the available water resources and the capacity of the infiltration facilities. In tropical and moderate climates with considerable precipitation, the potential growth of the freshwater volume is likely greatest during the construction phase when the reclamation is still unpaved. Smart inclusion of the development of the freshwater storage in the planning and design of the land reclamation is therefore required. The growing capacity of the groundwater storage and recovery system can then be aligned with the growing water demand of the developing area. Another advantage is that gravel packs around wells and under infiltration facilities can be far more easily realised during construction works of the land reclamation. This also applies to the construction of the infiltration facilities, i.e. the infiltration basements, infiltration ponds, storm water attenuation and infiltration crates and wadis.

Disclaimer

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Summary

The sandy deposits of land reclamations provide opportunities to create underground freshwater storage capacity. This freshwater can later be recovered and used, contribution to a sustainable management of water on the newly reclaimed land. The structures of the porous media are derived of reclaimed lands constructed by a combination of bottom discharging, rainbowing and pipeline discharge. These are validated by comparison with semivariograms of cone penetration tests of five land reclamations. The consequences for the hydraulic conductivity of different hydraulic filling methods and the feasibility of hydraulically filled reclamations for underground freshwater storage are determined.

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Marloes obtained her MSc in Civil Engineering at Delft University of Technology in 2007. From 2008 to present, she has been working as a water resources consultant at Royal HaskoningDHV. While working on the drainage design of a land reclamation project off the coast of Lagos, Nigeria, Marloes became fascinated by the opportunities that the construction of new lands could offer to optimize their subsurface for freshwater storage. She obtained her PhD in 2019; her PhD thesis 'Design of the subsurface of land reclamations for freshwater storage and recovery, a new view on land reclamations' is available at TU Delft repository.

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