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Distribution of grain size and resulting hydraulic conductivity in land reclamations constructed by bottom dumping, rainbowing and pipeline discharge

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Abstract
Spatially constant porosity and hydraulic conductivity are usually applied in hydrological studies related to land reclamations. However, the grain sorting and the degree of compaction within land reclamations differ per placement method. A study area at Maasvlakte II, the Netherlands, and the four other land reclamations that could be found in the literature are considered that were constructed by a combination of bottom dumping, rainbowing and discharging the sand-water mixture by pipeline. The structures of the porous media are derived for each placement method and validated by comparison with semi-variograms of cone-penetration tests. It is found that all placement methods lead to some degree of heterogeneity, so that the hydraulic conductivity in these land reclamations is not constant. This is due to the degree of segregation of the grain sizes that differs between placement methods. Segregation even varies within a specific placement method because of its characteristics and site-specific circumstances such as settling depth, grain-size distribution and angularity resulting from grain type. If land reclamations are considered for aquifer storage and recovery for freshwater supply, it should be considered that the recovery efficiency will be affected by both the properties of the material in the borrow area and by the placement methods including their spatial configuration as applied during construction of the reclamation.

Keywords Water resources · Artificial recharge · Land reclamations · Hydraulic properties · Coastal aquifers

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1 Introduction

Urban expansions in seaward direction by means of land reclamations occur worldwide in highly urbanised coastal areas for residential, industrial and recreational development, and for ports and airports. Fresh water often already is a critical resource in these coastal areas, because of overexploitation due to urbanisation, economic development and climate change (e.g., Loucks 2017; Koop and van Leeuwen, 2017). Fresh water from the mainland is, therefore, often not available for urban development on the reclamation. Hence, it is important to arrange freshwater supply on the new land by means of desalination or rainwater collection, storage and reuse. Van Ginkel (2015) pointed out that land reclamations have potential for the managed storage of fresh water in the subsurface of the reclamation for later recovery and use analogous to a freshwater lens, as can be found under natural islands in the ocean (e.g., Stoeckl et al. 2016). Such systems are otherwise known as Aquifer Storage Recovery (ASR; Pyne, 2005) and can provide a robust, effective and cost-efficient solution to manage freshwater resources (e.g., Zuurbier et al., 2017).

Fig. 1 presents the minimum and maximum grain-size distribution curves of reclamations constructed in the Netherlands, the United Arab Emirates, Malaysia, and China. 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 natural freshwater lens or ASR.

In the literature, the hydraulic conductivity in land reclamations is generally considered fairly homogeneous compared to natural soils in which layering, and anisotropy are

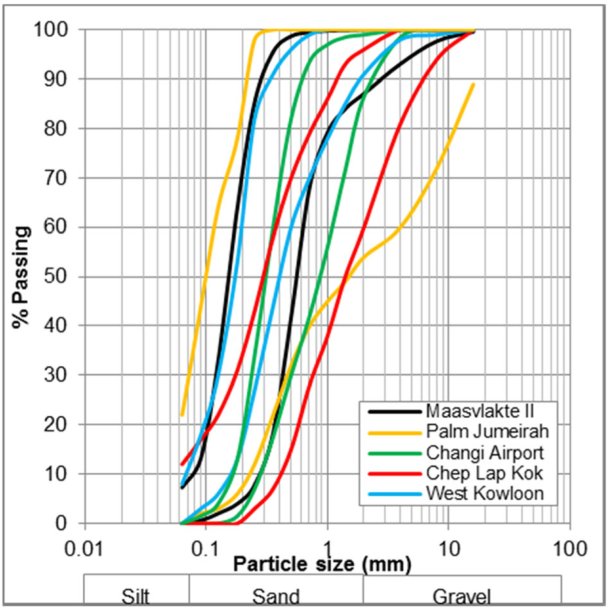

Fig. 1 The minimum and maximum grain-size distribution curves of samples taken from the Maasvlakte II, Rotterdam, the Netherlands, Palm Jumeirah, Dubai, the United Arab Emirates (Lees et al. 2013), Changi Airport, Singapore, Malaysia (Chua et al. 2007), Chep Lap Kok, Hong Kong, China (Lee 2001), West Kowloon, Hong Kong, China (Lee et al. 1999)

ubiquitous. Jiao et al. (2001, 2006) and Huizer et al. (2017), for instance, applied a constant porosity and conductivity for the land reclamation when they studied the increase of the freshwater volume under adjacent old land caused by land reclamations in Hong Kong, China and along the Dutch North Sea coast, respectively.

However, several geotechnical scientists, including Sladen and Hewitt (1989), Lee et al. (1999), Lee (2001), Chang et al. (2006) and Chua et al. (2007), analysed the results of cone-penetration tests taken on land reclamations that were constructed using different placement methods. They concluded that the grain sorting and the degree of compaction differed per placement method. Since each land reclamation is constructed with material originating from a single source area, these differences are attributed to the sedimentation characteristics pertaining to each placement method. Which implies that different placement methods also cause different hydraulic properties within land reclamations. This is because porosity is determined by the degree of sorting and compaction. Hydraulic conductivity also depends on grain characteristics (Bear 1972) which more profoundly determines the difference in hydraulic properties between land reclamations because of different source areas.

Chua et al. (2007), in Singapore, obtained different values for hydraulic conductivity and groundwater flow velocity at different depths within a land reclamation that was constructed by bottom dumping, rainbowing and pipeline discharge. Hydraulic conductivity values between 10 and 94 m/d were obtained with slug tests, a repacked sand column test, a step-drawdown test and grain-size analyses. No other studies that specifically address hydraulic properties of land reclamations were found in the literature.

Average conductivity values may be sufficient to determine external hydrological effects of land reclamations. However, more detailed information is required if land reclamations are to be considered for water storage as part of their freshwater supply (Van Ginkel 2015). The objective of this paper, therefore, is to investigate the distribution of grain size and the resulting hydraulic conductivity of land reclamations that are constructed by the most commonly applied placement methods, which are bottom dumping, rainbowing and discharging the sand-water mixture by pipeline.

Pumping tests are commonly applied to determine the hydraulic characteristics of the subsurface. However, pumping tests were not available for this study, because land reclamations have been barely studied hydraulically. The land-reclamation literature contains only geotechnical data related to bearing capacity, settlement and liquefaction. Therefore, the grain-size distribution curves and cone-penetration tests were considered of study area D2 in Maasvlakte II, the Netherlands. These data are supplemented with the geotechnical data of the four other land reclamations that could be found in the literature. Analysis of the sedimentation from a sand-water mixture for the three placement methods provides insight into grain sorting as it varies from place to place in the reclamation. The structures of the porous media are presented resulting from each placement method. These structures are validated by comparison with semi-variograms of cone-penetration tests. A semi-variogram provides insight in the spatial variance of a parameter and, therefore, in its degree of heterogeneity. The hydraulic conductivity and the degree of heterogeneity inside land reclamations are derived.

1.1 Placement methods used in the construction of land reclamations

The construction of land reclamations involves a number of consecutive phases (Van t Hoff and Van der Kolff, 2012). Firstly, the fill material is dredged, secondly, this material is transported to the reclamation site, thirdly, the fill material is placed, and lastly, if necessary, ground improvement of the fill material is applied. Land reclamations are often constructed using so-called Trailing Suction Hopper Dredgers (TSHD), which are vessels equipped with devices to loosen sand at the seabed, mix it with process water and suck the sand-water mixture into the vessel. Process water is spilled overboard to allow filling the TSHD to its maximum capacity. Because the overflowing water caries along fines, the content of fines in the TSHD is lower than at the borrow area (Van Rhee 2002). Once filled, the TSHD sails to the reclamation site and discharges the sand-water mixture by bottom dumping, rainbowing or via floating pipelines. The hopper capacity of TSHDs varies between 4000 m^3 and 35.000 m^3 of which the larger ones are used for land reclamations (Van t Hoff and Van der Kolff, 2012). Table 1 lists the characteristics of TSHDs currently operated by the Dutch dredging companies Van Oord (2018) and Boskalis (2018).

The placement methods, namely bottom dumping, rainbowing and discharging by floating pipelines, are often executed in sequence. Bottom dumping is the quickest placement method but can only be applied when there is sufficient water depth (Fig. 2a). The sand-water mixture falls through the water column by opening the bottom doors or splitting the hull of the TSHD. A TSHD with a typical capacity of 20.000 m^3 can unload by bottom dumping in approximately 5 min. Dumps are deposited in a random pattern until the water depth becomes too shallow for the TSHD.

Rainbowing consists of high-velocity pumping of the sand-water mixture above seawater level, which is done from a nozzle on board of the TSHD onto the reclamation site (Fig. 2b). This method is usually applied until the reclamation rises above sea level. A 20.000 m^3 TSHD can unload by rainbowing in approximately 60 min. Above sea level, the sand-water mixture is discharged to the reclamation site by floating pipelines, where bulldozers guide the flow of the sand-water mixture by setting up bunds (Fig. 2c). In this process, the bulldozers also compact the sand.

According to Morgenstern and Kupper (1988), these are the most commonly applied placement methods for hydraulic filling. Other placement methods are known (Van t Hoff and Van der Kolff, 2012). One of them is pumping through a spreader or diffuser which is often used to attain an equal spreading on top of a soft seafloor. However, no data could be found of land reclamations constructed by those other placement methods, so these were not included in this study.

1.2 Data case study Area D2 Maasvlakte II, the Netherlands

Maasvlakte II is a large-scale, 2000 ha, expansion of the port of Rotterdam in the Netherlands that was constructed from 2008 to 2013. Fig. 3 presents the location of Maasvlakte II in the Netherlands and study area D2 in the southern part of Maasvlakte II. The placement methods and depths as applied in study area D2 are essentially the same as elsewhere in the Maasvlakte II. Bottom dumping 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.

Table 1 Characteristics of Trailing Suction Hopper Dredgers

Hopper capacity	4.000–35.000 m^3
Draught	7–14 m
Length over all	100–230 m
Breadth	20–32 m
Discharge pipeline diameter	1 m

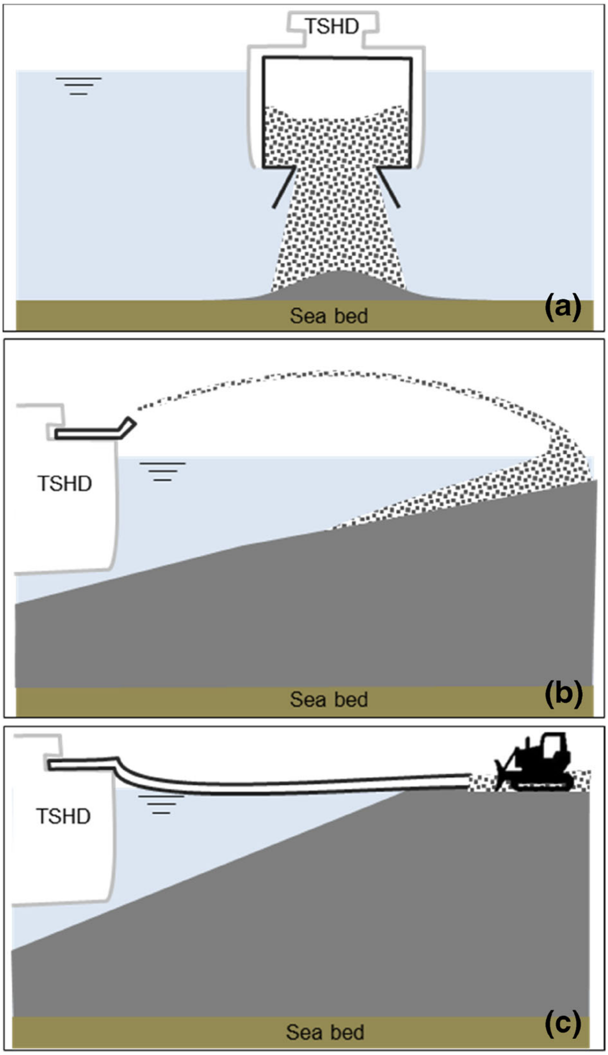

Fig. 2 Placement methods: **a)** bottom dumping, **b)** rainbowing, and **c)** pipeline discharge

Maasvlakte II is constructed of quartz sand of marine origin (Vessies 2012). The black lines in Fig. 1 present the outer ranges of the grain-size distribution of study area D2. In study area D2 soil samples were taken at a total of seven borehole locations, as presented in Fig. 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. Fig. 4 shows D_{10} and D_{50} of the soil samples and indicates which placement method was adopted at which depth.

Seven cone-penetration tests (CPTs) were taken in the study area. Fig. 5 shows the CPTs and indicates which placement method was adopted at which depth. The cone-penetration resistance, q_c, varies from 5 to 25 MPa in sands under MSL (Robertson 1989). A low penetration resistance in combination with a high friction ratio indicates finer sand, and a higher penetration resistance indicates coarser sand. The CPTs show the composition of the sand across the depth in more detail than the sieve curves, because

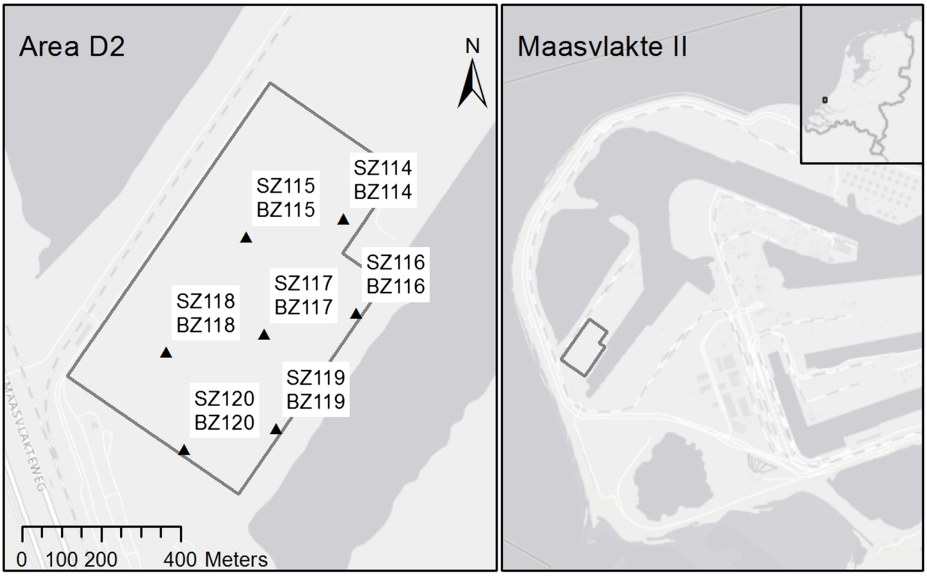

Fig. 3 Location of study area D2 atMaasvlakte II, the Netherlands

the soil samples are disturbed. The CPTs, therefore, provide a more detailed picture of the grain-size distribution than the soil samples.

1.3 Data reference cases

Data of Maasvlakte II-study area D2 has been supplemented with the grain-size distribution curves and cone-penetration tests that were previously presented in the work of Lees et al. (2013), Chua et al. (2007), Lee (2001) and Lee et al. (1999). They studied land reclamations that were constructed in the United Arab Emirates, Malaysia, and China, respectively. These land reclamations were also constructed by a combination of bottom dumping, rainbowing and pipeline discharge. Dimensions and construction details of these land reclamations can be

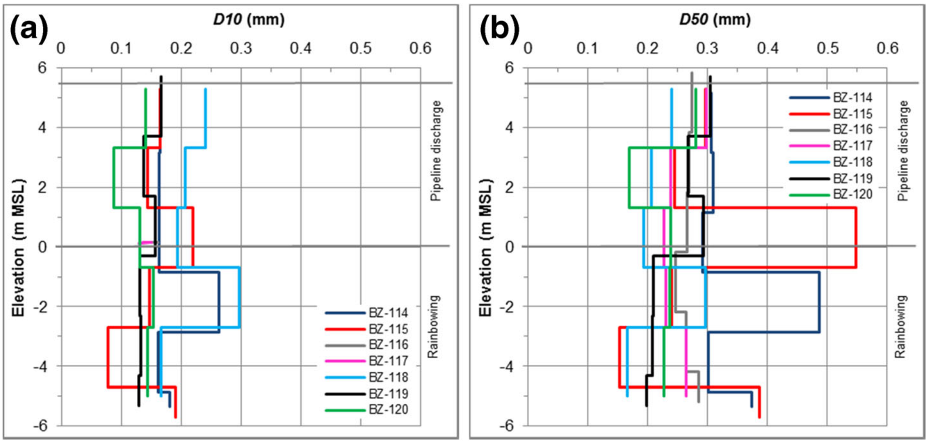

Fig. 4 **a)** D_{10} (mm) and **b)** D_{50} (mm) over depth of the soil samples taken at Maasvlakte II-study area D2

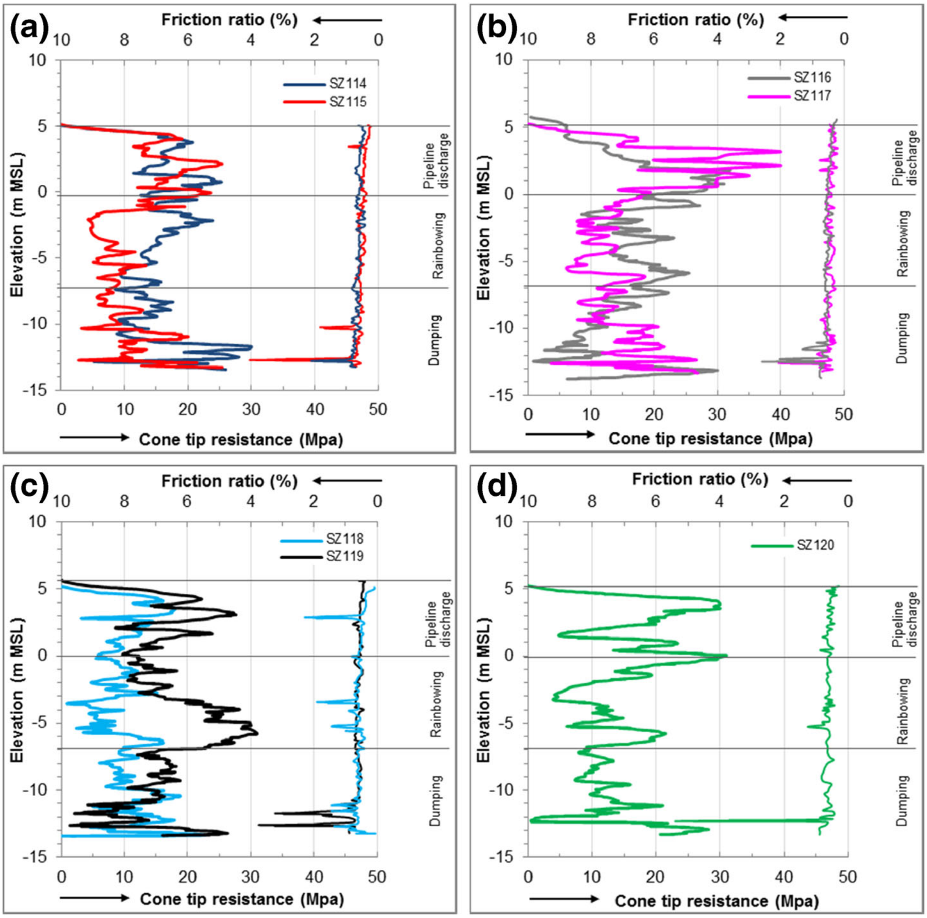

Fig. 5 Cone-tip resistance (left lines) and friction ratio (right lines) at Maasvlakte II-study area D2

found in the references. To the authors' knowledge, no other geotechnical data on land reclamations is available in the literature. The available studies all investigated the details and data of one land reclamation; this paper, however, considers all these site-specific details and data in combination.

Fig. 1 presents the outer ranges of the grain-size 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 very angular and typically have a wider grain-size distribution than quartz grains, which is mainly due to crushing during construction (Lees et al. 2013). Fig. 6 shows the CPTs of the reference cases and indicates which placement method was adopted at which depth.

1.4 Bottom dumping

Stokes's law expresses the terminal settling velocity of a single grain in a fluid (e.g., Selley 2000; Van Rhee 2002):

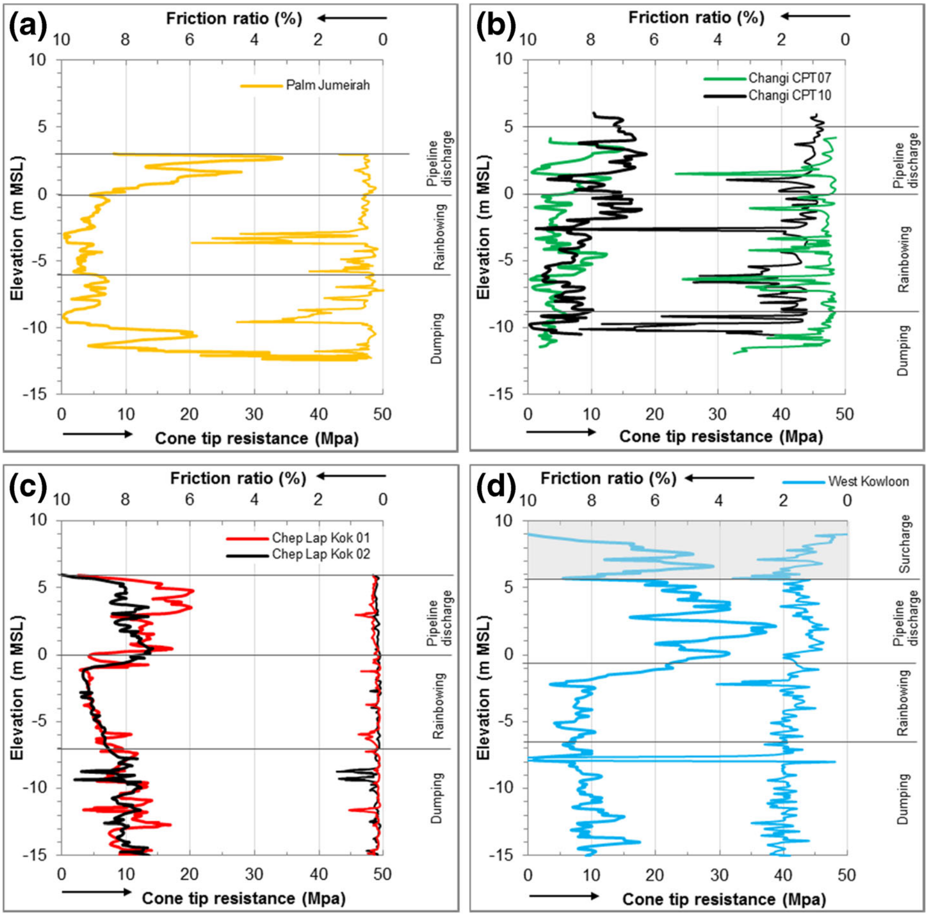

Fig. 6 Cone-tip resistance (left lines) and friction ratio (right lines) at **a)** Palm Jumeirah (Lees et al. 2013), **b)** Changi Airport (Chua et al. 2007), **c)** Chep Lap Kok (Lee 2001) and **d)** West Kowloon (Lee et al. 1999)

$$w_0 = \sqrt{\frac{4g\Delta D}{3C_D}} \tag{1}$$

Where w_o [L/T] is the terminal settling velocity of a single grain, D [L] is the diameter of the grain, g [L/T^2] is the gravitational acceleration, Δ is the specific density defined as $\Delta = (\rho_g - \rho_f)/\rho_f$, where ρ_g and ρ_f [M/L^3] are the density of the grain and fluid respectively, and C_D [−] is the drag coefficient. The drag coefficient depends on the Reynolds number Re [−]:

$$Re = wD\rho_f/\mu \tag{2}$$

Where μ [M/LT] is the dynamic viscosity of the fluid. In the laminar flow regime, where $Re < 1$, the drag coefficient is $C_D = 24/Re$ which leads to an explicit relation for the terminal velocity:

$$w_0 = \frac{\Delta g}{18\nu} D^2 \tag{3}$$

For the transitional regime, where $1 < Re < 2000$, the drag coefficient is $C_D = 24/Re + 3/\sqrt{Re} + 0.34$ and the terminal settling velocity can be computed by iteration of C_D with Eq. 1. For turbulent flow, where $Re > 2000$, the drag coefficient is $C_D = 0.4$ and the terminal velocity is:

$$w_0 = 1.8\sqrt{\Delta g D} \tag{4}$$

The ambient seawater is, in principle, displaced sideways during settling of the sand-water mixture, allowing the mixture to descent as a single mass (Fig. 7). However, some seawater will probably escape upward through irregularities in the sand-water mixture; random volcanos of seawater will likely develop spontaneously in the sand-water mixture where seawater starts to flow through the mixture. The Reynolds number of the sand-water mixture lies in the turbulent regime. Turbulent eddies occur around the mixture keeping fine material in suspension. However, the bulk of the sand-water mixture will quickly arrive at the seafloor.

Segregation has already developed during loading and transportation inside the TSHD. Research on sedimentation in TSHDs has been carried out by Van Rhee (2002). Based on measurements of the particle-size distribution, the concentration and the velocity in the TSHD, Van Rhee deduces that the incoming sand-water mixture flows towards the bottom of the TSHD while forming an erosion crater and a density current. Sedimentation takes place from this current from which the largest grains settle first. This leads to a segregated sand bed in the TSHD, with the coarsest grains at the bottom and the finest material remaining in suspension and flowing overboard.

Segregation of the grains also occurs within the settling sand-water mixture, where the larger grains tend to settle faster than the smaller grains according to Stokes's law. Complete segregation can only occur in infinite 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 according to a well-known formula by Richardson and Zaki (1954):

$$w_s = w_0(1-C)^{\alpha} \tag{5}$$

Where w_s[L/T] is the settling velocity of grains, the concentration $C = (\rho_m - \rho_f)/(\rho_g - \rho_f)$, where ρ_m [kg/m^3] is the density of the sand-water mixture, $\alpha = 4$.

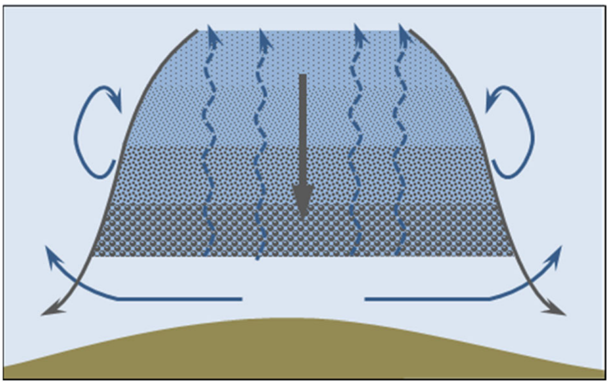

Fig. 7 Settling sand-water mixture and displacement of ambient seawater

The computed hindered-settling velocity as function of the grain diameter is shown in Fig. 8 for a sand-water mixture concentration of 0, 35 and 50%. The concentrations of 35 and 50% correspond to a density of the sand-water mixture of 1600 and 1800 kg/m^3, respectively. These mixture densities are practical values. Hindered settling is caused by a) the return flow created by the settling grains, b) the increased mixture density which reduces the driving buoyancy force, c) the increased viscosity of the fluid, and d) collision between particles (De Wit 2015). The initial concentration is reduced by entrainment of ambient water during the settling process, which reduces the hindered-settling effect.

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

A distinct segregation mark between two bottom-dumped layers can be observed in the typical section of a vibrocore sample as presented in Lee (2001) and Shen and Lee (1995) taken from the bottom-dumped fill at Chep Lap Kok. Based on examination of the sample, Lee found that the grain-size distribution of the coarser grains corresponds closely to the upper bound of the possible range of the Chep Lap Kok sand, whereas that of the finer grains is close to the lower bound of the Chep Lap Kok sand.

Lee (2001) represented the shape of each dump as a trapezium and suggested that dumps are randomly distributed. The model of Lee was slightly modified in this study. Fig. 9 was made by assuming that each dump has the shape of the normal probability density function (pdf), which, therefore, reaches from -∞ to +∞. Its central location is the position of the TSHD and its volume equals that of the vessel. The thickness of each dump at any location is, therefore, given by the pdf times the volume. In this model, the sieve curve of Maasvlakte II-study area D2 is assumed to be segregated completely within each dump. Therefore, the grains in each dump are distributed upward from course to fine in accordance with 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 dumping. The THSD is placed randomly across the reclamation site for the first dumps. And later, the TSHD is placed just above the location with the maximum distance between the elevation of the dump and the

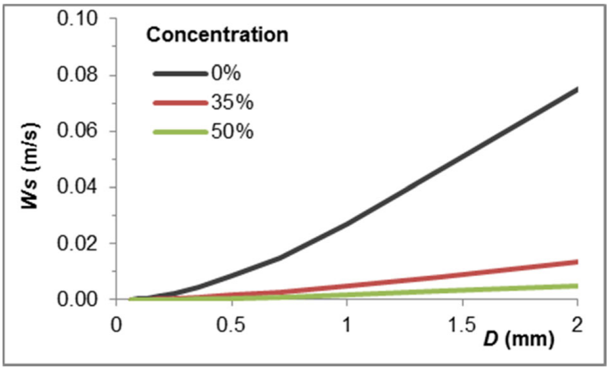

Fig. 8 Hindered-settling velocity w_s in a sand-water mixture (viscosity $13\cdot10^{-3}$ kg/ms) as function of the grain diameter D for 0, 35 and 50% concentration

target elevation. This fills the reclamation to a uniform height. Pure random dumping will never give the desired end shape.

As Fig. 9 suggests for an ideal fully-segregated dump, a bottom-dumped fill will consist of thin, elongated lenses of circa 1 to 2 m height and several tens of meters wide with a characteristic vertical grain-size distribution. The occurrence of such lenses may be investigated by means of semi-variograms. The semi-variance $\gamma(h)$ is half the average squared difference between points separated at a certain lag distance h (Matheron 1963). Fig. 10 presents the semi-variograms of vertical cross-sections through the bottom-dumped fill model at x = 0, 100 and 200 m.

The semi-variance fluctuates periodically with lag distance. The periodic structure is most apparent at x = 200 m, showing a sinusoidal semi-variance with a period of 1,5 m lag distance. According to Pyrcz and Deutsch (2003), a periodic semi-variance indicates regularly clustered lenses or strata of higher and lower grain size in the bottom-dumped fill. Fig. 9 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 Fig. 9.

1.5 Data analysis of bottom-dumped fills

The occurrence of lenses in existing bottom-dumped fills may be investigated by means of semi-variograms of the cone-tip resistance registered by cone-penetration tests (CPTs) done shortly after construction. Fig. 11a and Fig. 11b present the semi-variograms of the bottom-dumped fills of the CPTs of Fig. 5 and Fig. 6. Similar to Fig. 9, these semi-variograms exhibit a periodic structure which now indicates regularly clustered lenses or strata of higher and lower resistance of the cone-penetration in the bottom-dumped fill.

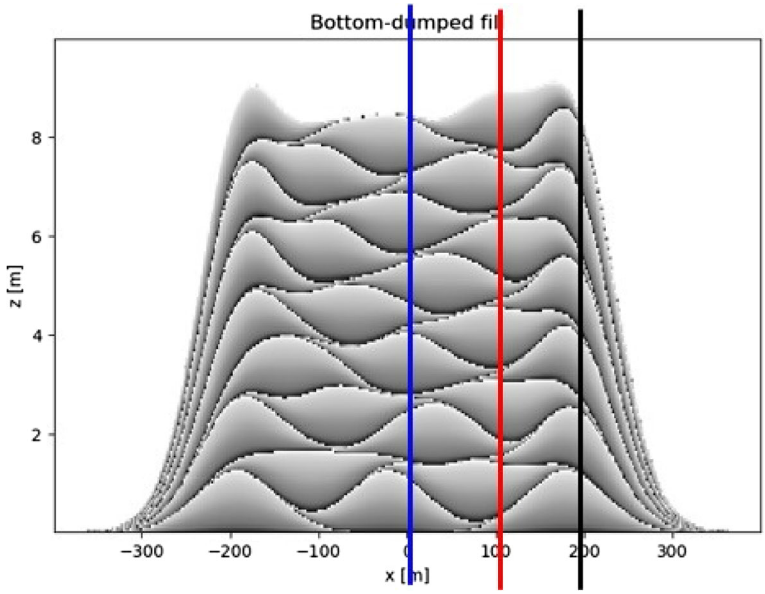

Fig. 9 Cross-section of a bottom-dumped fill model in which the shading reflects the structure of the porous medium. A darker colour indicates a coarser grain size

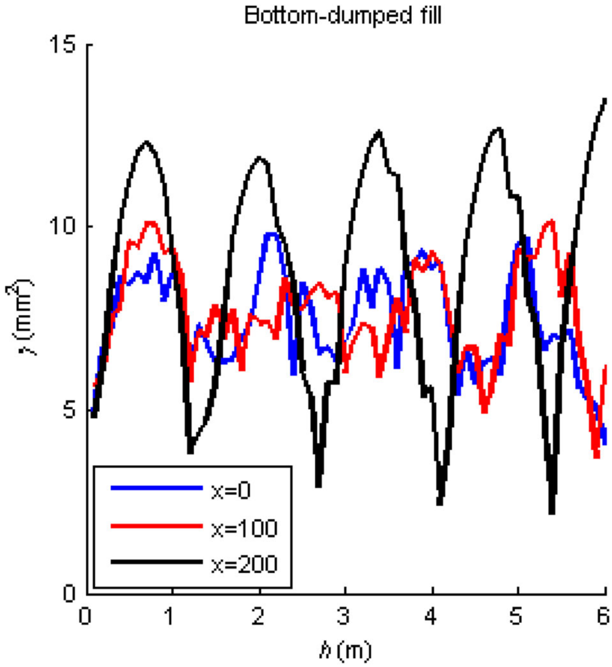

Fig. 10 Semi-variogram of bottom-dumped fill model

For the seven CPTs of the Maasvlakte II, the characteristic distance between lenses is about 1.5 m. The semi-variograms for West Kowloon and Palm Jumeirah for the bottom-dumped fills showa similar periodicity. 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 periodicity of the semi-variograms of Chep Lap Kok 01 and 02 is approximately

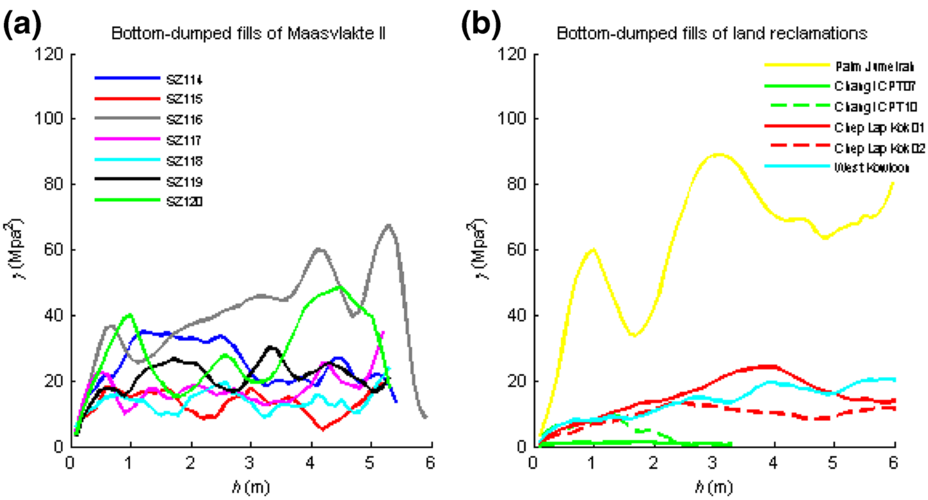

Fig. 11 Semi-variogram of CPTs of bottom-dumped fills, **a)** Maasvlakte II-study area D2, and **b)** the other land reclamations

2 m. Based on this periodicity, it is assumed that larger TSHDs were used for this land reclamation. The bottom-dumped fill in Changi is not thick enough to recognise periodicity.

1.6 Rainbowing

In the land reclamations considered in this study, rainbowing up to sea level was applied on top of the bottom-dumped fill. The sand-water mixture is fluidized and mixed on board the TSHD to obtain pumpability. The sand-water mixture that is then sprayed through the nozzle is well mixed, in contrast to dumping. The diameter of the nozzle is up to 1 m. The sand-water mixture flies through the air as a compact jet up to 150 m distance (Van ‘t Hoff and Van der Kolff 2012). The composition of the mixture hardly changes in the air and its diameter is enlarged by air entrainment (Vessies 2012).

The velocity of the sand-water mixture is immediately reduced upon reaching the sea surface. Some segregation will occur during settling. The sand-water mixture starts building up a fill which grows as rainbowing continues at the same location. As the fill grows, the sand-water mixture flows more and moreas 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. The density current, equally called turbidity current, is driven by gravity, i.e. the density difference between the sand-water mixture and seawater (Middleton 1993). Density currents can transport material over large distances; in 1929 for example, a 7.2-magnitude earthquake-induced turbidity current running off the continental shelf near Newfoundland, Canada, broke 12 trans-Atlantic cables 1000 km out into the abyssal plain (Heezing and Ewing 1952).

While rushing down the slope, turbulent eddies generated by the density current entrain seawater into the mixture (Huppert and Simpson 1980, Hallworth et al. 1993). With increasing distance from the top, the driving density difference is thus reduced by dilution. Near the top, where the sand concentration in the density current is high, settling is most hindered, which results in 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.

Fig. 12 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 of the fill. Because the same processes operate during the total build-up of the fill, the grain size tends to remain constant for a fixed distance to the fill centre. This implies that the grain-size distribution is uniform in cylinders centred around the axis of the fill, i.e. constant along vertical lines.

The impact of the plunging jet will, of course, scour a depression in the top of the fill when it approaches sea level within a few meters. However, the amount of material that is thus spread out over the slopes is small and is, therefore, further neglected. Once the fill has reached sea level, the TSHD withdraws in seaward direction. The fill then builds out seaward (Fig. 12b). 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 always accumulate at 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 up to a few cm-thick layer of finer material marking the slope at rainbowing interruptions, however, no evidence could be found in the literature.

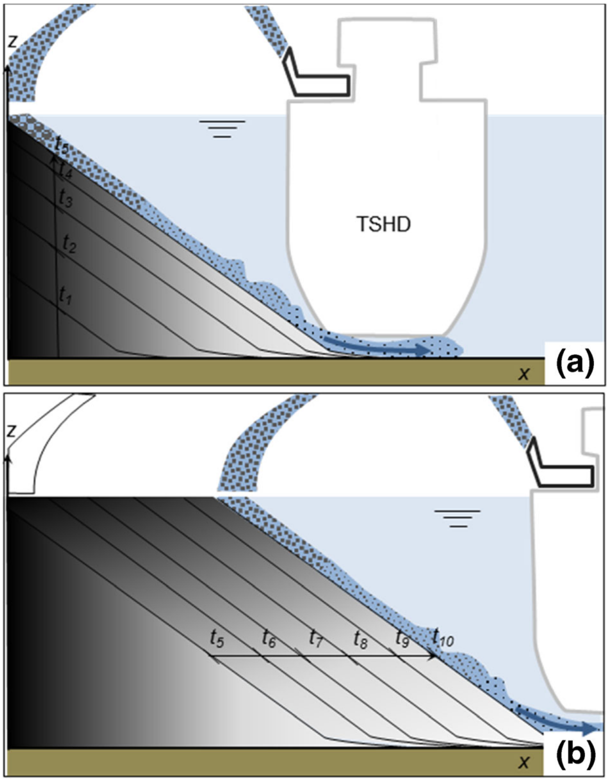

Fig. 12 **a)** Cross-section of a rainbow-discharged fill over time (starting at t_1 to t_5) in which the shading reflects the structure of the porous medium and **b)** the build-out over time (starting at t_5 to t_{10}). A darker colour indicates a coarser grain size

1.7 Data analysis rainbow-discharged fills

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

Fig. 13 presents the semi-variograms 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-dumped fills, in contrast to the other rainbow-discharged fills which show a lower variance than in Fig. 11. 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 higher amount of fine grains in these sands (Fig. 1); 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 current that cause more hindered settling due to which less segregation took place.

1.8 Pipeline discharge

The part of the land reclamations above sea level is generally placed by pipeline. The fluidized sand-water mixture is pumped through floating pipelines to the reclamation site. Bulldozers first construct small containment bunds at a certain mutual distance. These bunds guide the flow of the sand-water mixture as the space between these bunds is filled by the pipeline discharge. While constructing the bunds, the bulldozers also compact the sand.

Fig. 14 shows the hypothetical structure of the porous medium resulting from pipeline discharge. At the pipeline outflow, the sand-water mixture forms a scour hole. The sand-water 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 (Fig. 14a). Bulldozers level the area in front of the pipeline outflow and fill the scour hole.

After a certain elevation is reached, the next (circa 12 m) pipe section is connected and the filling process is continued (Fig. 14b). The segregation of grains along the slope is similar to that happening under water during rainbowing. This implies that the grain-size distribution will be constant horizontally and will refine in downward direction. As is the case with rainbowing, the finest grains accumulate in front of the toe of the slope and are then buried as the slope advances. 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 lift (Fig. 14c). When the required elevation level is reached, the pipeline is moved to the next strip. As a result, the structure of the porous medium of a pipeline-discharged fill consists of stacked lifts which are similar to the so-called para-sequences of natural marine deposits (Coe 2002) in which each lift refines from top to bottom. These lifts 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.

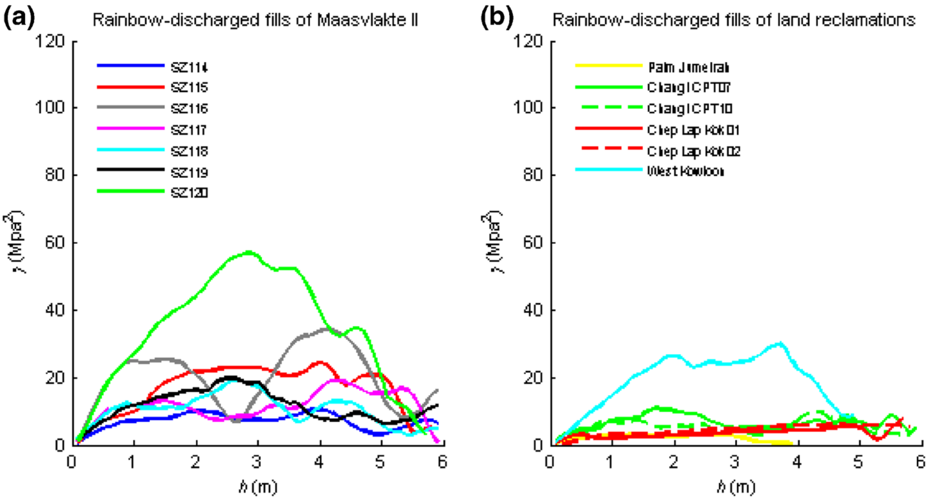

Fig. 13 Semi-variogram of CPTs of rainbow-discharged fills, **a)** Maasvlakte II-study area D2, and **b)** the other land reclamations

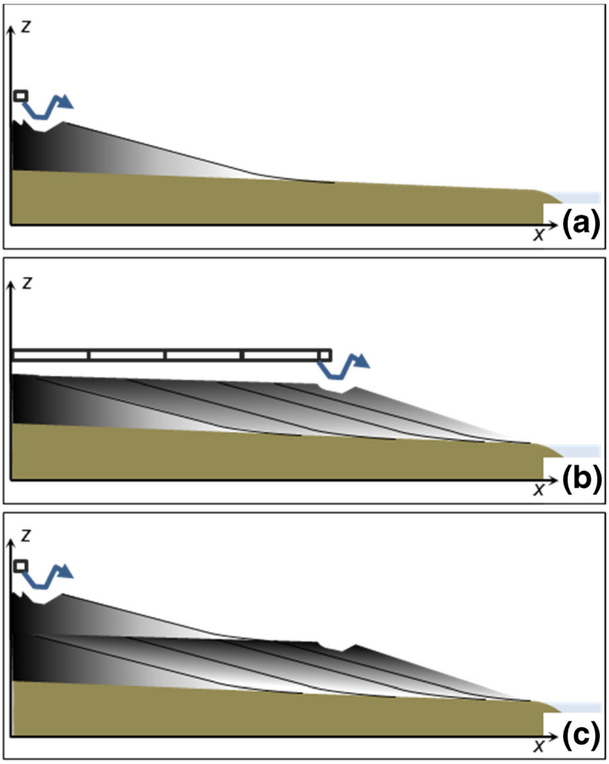

Fig. 14 Cross-section of a pipeline-discharged fill above water in which the shading reflects the structure of the porous medium, **a)** one section, **b)** several sections that coincide with the extension of the pipeline, and **c)** second lift. A darker colour indicates a coarser grain size

1.9 Data analysis pipeline-discharged fills

Lee et al. (1999), Lee (2001) and Lees et al. (2013) concluded that the cone-tip resistance of sand fills formed by subaerial-placement methods (i.e. above water, as defined by Morgenstern and Kupper (1988)) is substantially higher than that of sand fills formed by subaqueous placement. They explain this higher compaction of subaerial placements by noting that a sand fill above water is subjected to downward seepage, which results in a void ratio lower than that of subaqueous deposition. The compaction is further increased by the levelling operations of the bulldozers and the impact of other construction traffic.

Fig. 15 presents the semi-variograms of the available CPTs of the pipeline-discharged fills. The variance is higher than that of the other placement methods shown in Fig. 11 and Fig. 13. All semi-variograms of the pipeline-discharged fills exhibit a periodic structure. This periodicity strongly suggests that several lifts were applied; the periodicity is consistent with a general lift thickness of circa 1 to 2 m.

1.10 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 Carman-Kozeny relation:

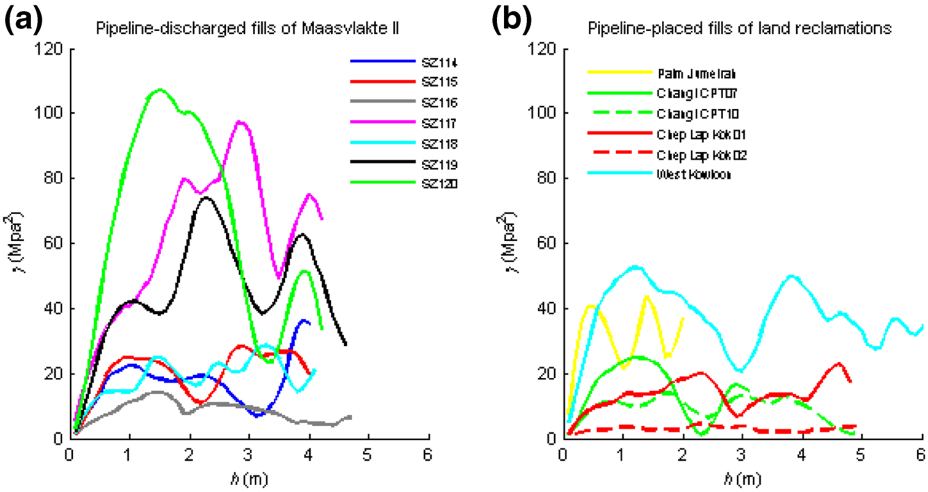

Fig. 15 Semi-variogram of CPTs of pipeline-discharged fills, **a)** Maasvlakte II-study area D2, and **b)** the other land reclamations

$$K = \frac{\rho g}{\mu} \frac{1}{CS_0^2} \frac{n^3}{(1-n)^2} D_{eff}^2 \tag{6}$$

Where $\rho g/\mu$ is the unit weight/viscosity of water, n [−] is porosity, D_{eff} [L] is the effective grain diameter, 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.

The only unknown is porosity. The effect of the ratio of porosity of 35% over 40% yields a ratio of conductivities of 1.75 for the same effective grain diameter. While the effect of the ratio of D_{50} over D_{10} for the grain-size distributions of Fig. 1, however, yields a ratio of conductivities of 3.5 for the minimum sieve curve of the Maasvlakte II to 36.0 for the maximum sieve curve of Palm Jumeirah. In other words, although porosity affects hydraulic conductivity, the effective grain size is decisive. Consequently, the grain-size distributions as illustrated in Fig. 9, Fig. 12 and Fig. 14 mimic the conductivity.

Using Eq. 6, and taking D_{10} based on Fig. 1 (0.20 mm) as the effective grain size, and a porosity of 35%, the expected conductivity of Maasvlakte II-study area D2 is 15 m/d. However, taking the D_{10} of the actual soil samples of the rainbow-discharged part of the fill of study area D2, which are depicted in Fig. 4a, the conductivity would fluctuate between 2 and 24 m/d, which is an order of magnitude, an effect that goes unseen if only average values are considered and which is important for the subsurface storage and recovery of fresh water.

2 Conclusions

The structures of the porous media were investigated resulting from three placement methods, i.e. bottom dumping, rainbowing and discharging the sand-water mixture by pipeline. The results were compared with the data of a study area at Maasvlakte II, the Netherlands, and four other land reclamations. It was found that all placement methods result in some degree of heterogeneity in the structure of the porous medium. Therefore, the hydraulic conductivity in a land reclamation is not constant, even though 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 lower than in the so-called 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.

This study showed that a bottom-dumped fill consists of a random distribution of stacked thin, elongated lenses that are about 1 to 2 m high and several tens of meters wide, in which the resulting hydraulic conductivity must decrease from the centre of the lens to its outer edges because of the obtained grain-size distribution. The resulting hydraulic conductivity in a rainbow-discharged fill must increase from the bottom to the top of the fill for the same reason. A rainbow-discharged fill will be interspersed with sloping layers of low conductivity caused by interruptions of the rainbowing process. A pipeline-discharged fill consists of stacked lifts of about 1 m thickness, in which the hydraulic conductivity should likewise increase from the bottom to the top.

This study also showed that the degree of segregation caused by a specific placement method still depends on site-specific circumstances, such as settling depth, grain-size distribution and angularity resulting from grain type. It is impossible to separate these three parameters from 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 deemed indispensable.

The outcomes of this study imply that, if land reclamations are considered for Aquifer Storage Recovery (ASR), the recovery efficiency of these systems can be impacted by differences in dispersion and preferential flows resulting from the applied placement methods. As such, the recovery efficiency is expected to be lowest for bottom-dumped fills in which the sand has a wide grain-size distribution. They show the largest grain-size variation on small vertical scales, because of the irregular stacking of lenses in each of which the grain size coarsens upward. The recovery efficiency is expected to be highest in rainbow-discharged fills, because they have a grain size that smoothly coarsens upward over the total thickness of the fill.

Land reclamations are typically constructed in coastal zones of limited depth of at most a few tens of meters. The potential storage zone is, therefore, 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. It is also noted that a band of fine material will be present along the edges of pipeline-placed fills wherever closing bunds were applied. Such bund-formed elongated bands of fine material may have an advantage 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, result in some degree of compartmentation. The location of these bunds may be derived from the documentations regarding the phasing of the construction of the land reclamation.

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Compliance with ethical standards

Conflict of Interest None.

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