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Design Process of a Sandy Convex Shaped Beach Layout

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Abstract: The planned Colombo Port City (CPC) development, shown in Figure 1, comprises 450 acres of reclaimed land, 3 km of offshore breakwater, two additional breakwater revetments and a central canal. In its final stage, the reclamation will be closed off by a sandy beach at the seaward side. This beach will be partly sheltered by the offshore breakwater and lagoon in front of it. The beach layout is convex, implying that all beach angles are offshore directed. This layout with respect to erodibility, poses multiple design complexities. These problems will be tackled by a converging design approach, focusing on reduction of risks and increasing knowledge (from measurements and modelling) at the one hand and a highly adaptable design at the other hand. This engineering management approach is described in the present paper.

Sediment transport along the beach is influenced by the complex hydraulic climate in the lagoon area: the combination of wave overtopping and transmission through the breakwater, waves diffracting around the breakwater heads, local waves and residual currents. The anticipated sensitivity to beach erosion should not negatively affect the development. Therefore, to quantify the beach stability, the hydraulic climate inside the breakwater has been assessed by numerical modelling to form a basis for the spatially distributed sediment transport computations. To acquire a reliable translation from the offshore wave and current climate to the climate within the lagoon area, extensive physical and numerical model studies have been performed.

The preliminary beach stability analysis indicates that mitigation measures will most probably be required. This requirement, as well as assessment of the type of mitigation measures, is key to the adaptive engineering approach that has been adopted here. The adaptive approach aims at arriving at a practical design for the beach to secure the functional (public) requirements within economical (maintenance) and practical (constructability) boundaries. A groyne scheme is a relative simple and adaptive way to stabilize an unstable beach, whilst providing flexibility as it can be implemented in a phased way and be adapted rather simply when required. Along with the design, we focused on optimization of the construction strategy and sustainable material usage.

The present paper presents the numerical analysis part of the iterative design process, which has not yet been completed. As such, this paper is the launching paper regarding the CPC beach stability, providing a baseline for the design, and will be followed up by further paper(s) at a later stage of the design and construction.

Keywords: Beach Protection, Colombo Port City, Convex layout, Erosion, Sediment transport.

1. Introduction

The Government of Sri Lanka together with the Project Company has initiated the development of a high- end urban development on newly reclaimed land near the port of Colombo: the Colombo Port City (CPC) Project. CPC Project will be constructed against the existing Colombo South Port in the North and against the Galle Face in the East. The development comprises 450 acres of reclaimed land, 3 km of offshore breakwater, two additional breakwater revetments and a central canal. The primary protection of the development is a semi-circular shaped offshore breakwater which obtains a calm wave climate along the reclaimed area to facilitate amongst others the construction of an ocean facing beach. Between the offshore breakwater and the beach a 300m wide so called “lagoon” will be created. The beach layout is convex-shaped and serves as secondary protection for the development. In principle such a beach layout is considered morphologically unfavourable. However, due to the anticipated relatively mild wave and current conditions caused by the sheltering effect of the offshore breakwater, as well as by the expected large sediment grain size on the beaches, the beach stability has been considered as potentially feasibly during the first design stage.

Figure 1: Artist impression of Colombo Port City

This paper elaborates further on the anticipated beach stability and the adopted engineering management cycle to arrive at a practical beach design. The emphasis of the design is on integration of functional and safety requirements. It is the responsibility of the developer to combine these aspects within an integrated design, which favors the development and the people of Colombo. Due to the large number of uncertainties and functional requirements of the beach, the engineering cycle is a highly iterative process.

The beach design has not yet been finalized and is still continuously subject to progressive insights from increasing data and information on prevailing hydraulic conditions. The complexity of the design of the convex-shaped beach demands the use of state-of-the-art models and latest scientific view-points and inputs. Therefore, this paper is the launching paper regarding the CPC beach stability, providing a baseline for the design, and will be followed up by further paper(s) at a later stage of the design and construction.

2. Engineering design process

2.1 Requirements

One of the most recent designs of the CPC development can be seen in Figure 2 with the beach indicated in yellow. The beach area needs to fulfil a number of functions:

- The beach is a major landscaping element in the spatial city environment that connects the water and urban environment.
- The beach is part of the land revetment, minimizing wave overtopping and forming the foundation for the retaining wall / staircase as land revetment.
- The beach will facilitate leisure activities, such as: strolling, sun-bathing, swimming, boating and wind-surfing.
- The beach enhances an attractive water front development (e.g. restaurants, beach apartments, sites with attractions), and can be equipped with an attractive boardwalk.

The convex-shaped beach layout as currently designed, however, is also a highly challenging element as regards the vulnerability for sand losses in the anticipated exposed situation with waves coming from one predominant direction. Major requirements, connected to the above functions are:

- The beach should sufficiently protect the land revetment.
- The beach should facilitate leisure activities at minimum risk.
- The beach in itself should be sufficiently maintainable to fulfil its safety and recreational functions at acceptable costs and efforts.

Protective function

The beach should maintain a minimum width and volume to fulfil its function as protection of the land revetment to prevent overtopping of the revetment crest or flooding of the reclaimed land in case of extreme events.

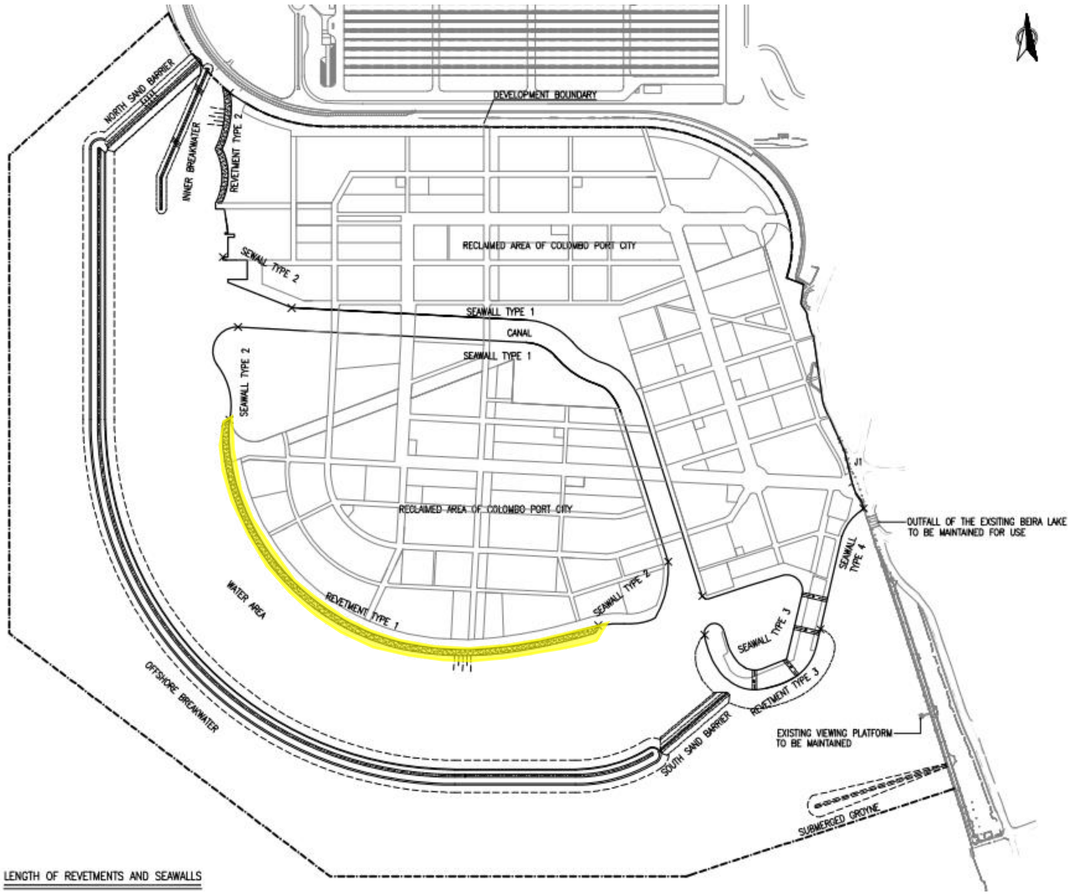

Figure 2: Layout design Colombo Port City with main beach indicated in yellow

Risk for people

People that are near or in the water at the beach zone should be safe at all times, as far as they cannot be held responsible for their own safety. A gentle and relative flat beach profile, to be maintained over a sufficient area, will reduce the danger considerably. This also increases the safety for swimmers.

Maintenance

The fully unprotected beach will experience cross-shore and long-shore adaptation of the beach profile in order to naturally adjust to the prevailing hydraulic conditions. The degree of protection by the offshore breakwater and potential additional beach stabilizing measures will determine the remaining morphological activity. Hence, the sand volume fluxes should be considered carefully in relation to the sand volume available within the beach area, to arrive at a feasible and acceptable maintenance.

2.2 Integrated design

Keeping the functional requirements as indicated above in mind, the risk can mainly be expressed as function of the anticipated morphological changes, governed by the wave and current action in the lagoon. A potentially feasible and flexible solution to improve the stability of the beach, if required, is by means of a groyne system. For an optimized design of the arrangement of the groyne system, the morpho dynamics of the beach has to be known in detail. However, accurate prediction of the morphological changes in the design stage is highly challenging because of:

- Uncertainties in the wave transmission / overtopping parameters of the offshore breakwater.
- Uncertainties in the 3D hydraulic effects within the lagoon.
- Uncertainties in the properties of the beach sand.
- Lack of information and data on the beach system, or similar systems.

For these reasons 2D and 3D physical modelling as well as numerical wave modelling studies are performed to obtain more insight in the erosive and wave propagation processes. This paper only focusses on the numerical study on the sand stability, in a later stage results of the numerical and physical modelling study will be combined to obtain a clearer and broader picture of the occurring processes.

As a consequence, a flexible and dynamic design approach is applied with ‘no regret’ measures where required and flexibility where allowed. A basic idea is to let nature shape the beach first in the different seasons during the construction period to obtain more (reliable) knowledge. Subsequently, in order to meet the functional requirements best, an optimum design can be obtained with the least amount of stabilizing measures. This approach may be maintained until progressive insight proves otherwise.

2.2 Uncertainties

Although a groyne field will significantly improve the stability of the beach, uncertainties in spatial distribution of the erosion and sedimentation patterns require intensified monitoring, even when such a groyne field has been designed properly. The maintenance requirements of the beach are dependent on the spatially and temporal distributed sand loss volumes in time. Accurate assessment of these losses will allow for an optimum beach maintenance program. Improving insight on the behaviour of the beach system during early stages of construction will accelerate the iterative design process. The iterative design process is characterized by the continuous decrease of uncertainties due to the increasing amount of data and information on the morphology which will be obtained through (amongst others) surveys. The best results can therefore be met by ‘learning by doing’ through observation, monitoring and (re-)calibration of modelling, which is characteristic for such a unique design.

At this point in time, the sand body of already reclaimed land is fully exposed to the incoming wave and current climate (see Figures 3 and 4). The offshore breakwater has not yet been constructed. The morphological activity around the reclaimed land is monitored regularly. With the known information (ref [1]) on the behaviour of the pre-construction conditions and situation (Figure 5), the changes in the morpho dynamic system can be identified, which in turn will improve the knowledge base.

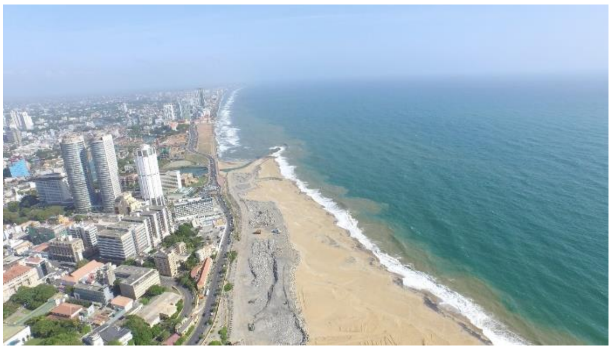

Figure 3: Sediment transport around the CPC development (photo September 2015)

Figure 4: Development of the beach profile of the newly reclaimed land (photo April 2015)

Figure 5: Base scenario along Galle Face

3. Beach design

The design of the beach will be obtained through the following steps:

1. Hydraulic data analysis and determination of governing hydraulic conditions (not part of this paper);
2. Beach stability analysis for the unprotected (= without groyne field) beach;
3. Design recommendations for the beach area.

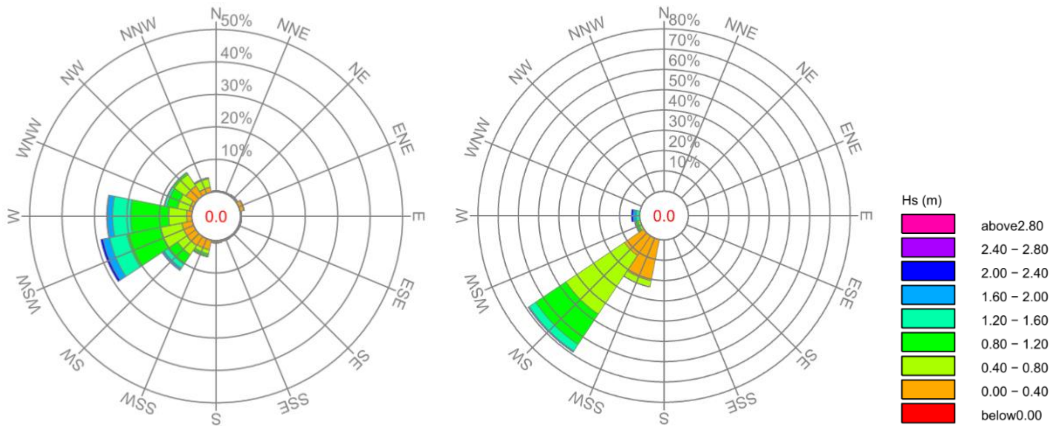

Figure 6: Average annual wave climate offshore the CPC development. Left: sea waves. Right: swell waves

3.1 Hydraulic conditions

Sediment transport along the convex shaped beach layout is mainly governed by the wave climate inside the lagoon. The hydraulic conditions inside the lagoon are obtained through numerical model simulations using the input of wave and wind statistics and 2D physical model test results, providing reliable data on wave overtopping and transmission of the offshore breakwater. The wave climate is a translation of the offshore wave climate disturbed by:

- i) wave penetration through the northern and southern openings;
- ii) wave transmission through the offshore breakwater;
- iii) wave overtopping over the offshore breakwater and;
- iv) locally generated waves inside the lagoon due to local winds.

The tidal currents (0.02 – 0.05 m/s), wind-driven currents (up to 0.2 m/s for normal conditions) and wave-driven currents (up to 0.2 m/s) are relative limited in the breaker zone of the beach area. Moreover, the currents will also be strongly varying over time and will have opposing directions. In spite of the moderate currents, practice shows that they may play a significant role in the transport of sediment (which is stirred up mainly by the wave action and transported along the beach by the currents). Due to the large timely and spatial variation of the currents and the moderate intensities, accurate assessment of the currents and their effect on the sediment transport is not practically attainable. Hence, this should be left to practice and monitoring after construction of the beach.

Figure 6 shows the governing sea wave conditions (left) and swell wave conditions (right). Sea waves are dominating from the WSW and W directions whereas swell waves are dominating from SW and show a more narrow sector of incidence. The governing overall direction of both sea waves and swell waves is within the sector W to SSW. The highest occurring waves also come from these directions. In addition, the NE monsoon from about October till April induces waves from NW direction with (generally) lower waves.

Upon reaching the offshore breakwater, the incoming wave energy will partly be absorbed, partly be reflected and partly be transmitted. The transmitted wave energy will subsequently propagate through the lagoon and reach the beach and the waves will have a different character there: the wave energy will be redistributed, resulting e.g. in a change in significant wave height. The quantification of the wave redistribution in the lagoon and actual wave transmission was a major subject of the 2D physical model tests (Figure 8). In addition to the wave energy deformation, the wave direction will change. For the predominant SW waves, the offshore breakwater will act as a "magnifying glass" and will cause the wave energy to converge, see Figure 7. Such a shift in wave angle has also been identified in literature studies (ref. [2])

To assess the wave climate in the lagoon in a 3D environment, the numerical wave model SWAN has been applied. This wave model enables to compute the wave energy through the openings into the lagoon with sufficient accuracy and uses the wave transmission relations through the breakwater as measured in the 2D physical model tests. Wave energy through the openings was also computed by a more accurate time-domain model, however such model cannot compute wave

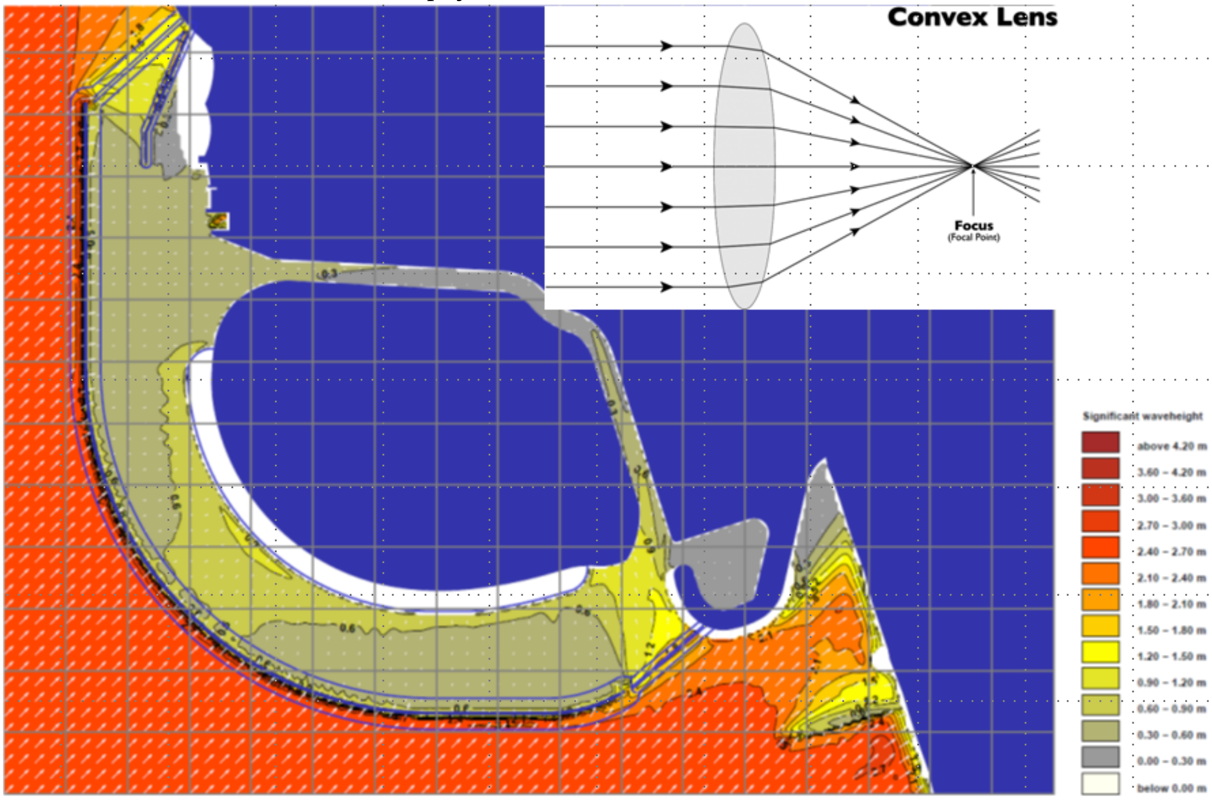

Figure 7: Model results of 'magnifying glass' principle of waves that overtop the Offshore breakwater.

transmission and computational times are very high. Although the spatial variation of the wave penetration was different between both models, the actual wave energy was very similar and for this reason the SWAN model provides sufficient accuracy. The computed change of wave direction follow the available theories in general and is in line with the theoretical expectations (Figure 7). Using this numerical wave model, the full offshore time series have been translated to a number of locations (12) along the beach profile within the lagoon area, which are further used in the beach stability analyses. The uncertainty within this modelling approach are known and considered in further analysis of the results, including sensitivity analysis of the morphological model,

From the 2D physical model tests the wave transmission – crest height correlation functions of the breakwater have been determined for the whole range of wave heights and periods (see Figure 9). These correlation functions have been used as main input parameters in the numerical modelling to determine the wave climate inside the lagoon area. For higher water levels (or lower relative crest levels) the wave transmission through the breakwater increases significantly, the future situation with respect to sea level rise should thus be taken into consideration. A high variability of the water level (e.g. by seasonal influence and uncertainties in sea level rise) makes it complex to accurately and reliably predict the wave climate. By taking different wave climates and different crest heights (i.e. water levels), uncertainties can be reduced as well as the sensitivity for the height of the breakwater and climate change effect on the water level can be accounted for.

In addition to the above, the following interesting and informative outcomes can be summarized from these wave transmission results:

- Measured wave transmission coefficients go up to 0.3 for high wave conditions (low relative crest height);
- Higher water levels (or lower relative crest heights) cause significant higher wave transmission, which will negatively affect wave disturbance and beach stability for future situations (including sea level rise or seasonal variations);

- For a relative high crest level the transmission coefficient is limited, but not negligible. This means that even for lower wave heights, a portion of the wave energy will constantly penetrate into the Lagoon area, always giving some waves at the beach;

Figure 8: Set up of 2D physical model test to determine the characteristics of the offshore breakwater

For longer wave periods (wave steepness = 0.005) the transmission is higher. This means that a minimum of approximately 20% of the swell wave height penetrates into the Lagoon. For sea waves this minimum is in between 5 to 10%.

3.2 Uncertainties

Particle size distribution

The exact sand characteristics of the available sand for the beach fill are yet uncertain. Also due to spatial variation in the borrow area and during and after construction of the beach, the particle size distribution along the beach may vary. Sieve curves from the currently constructed area of the CPC Project showed particle sizes ranging from 600 µm to 800 µm. To be on the safe side, a homogeneous particle size distribution with a mean particle diameter of 600 µm has been assumed for the stability analysis. To determine a band-width for the expected sediment transport, 300 µm and 900 µm particle size are investigated as well. In numerical modelling, the roughness factor to be applied normally is a calibration factor. As no calibration data is available here, based on similar studies this parameter is taken as k = 5 m, with a lower and upper limit of k = 2.5 m and k = 10 m.

Hydraulic Conditions

The beach stability analysis is performed for yearly average conditions. The impact of extreme storm conditions is not considered yet and should be included in a final design phase. Based on the computed annual average wave climate, a conservative and less conservative wave climate has been applied in the sediment transport computations.

Also the incoming wave direction at the beach has uncertainty as the change of wave direction in the numerical model cannot be affected. Although the results look similar to the available theories (ref. [2]), the local wave directions cannot be considered highly accurate. For this reason also the effect of the incoming wave direction on the beach stability is investigated by a sensitivity analysis.

Cross Shore Profile

In the sediment transport computation a constant beach slope of 1:20 is applied. This slope is considered stable according to generally accepted empirical slope stability formulae (refs 0, 0 and 0). Steeper slopes can be applied at depths beyond the depth of closure (refs. 0 and 0)where sediment in not influenced by waves and currents.

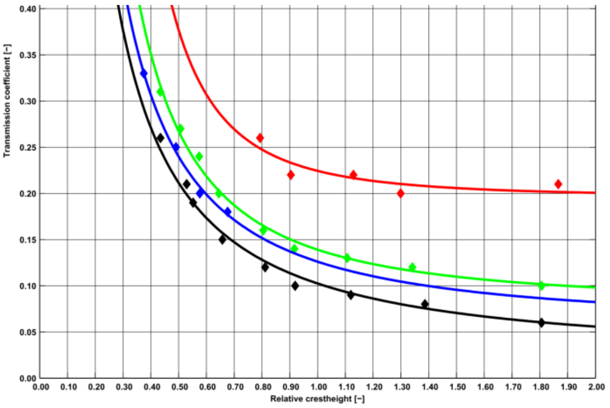

Figure 9: Transmission coefficient a function of the relative crest height as measured in the 2D physical model tests

3.3Beach stability

Wave-induced cross-shore redistribution of sediment will tend to shape the beach profile towards its own 'natural equilibrium'. Although the cross-shore beach stability may be important for safety reasons, and the cross-shore profile is relative stable, this paper focuses on long shore sediment transport, since the gradients of such transport are expected to be dominant for beach erosion and hence beach stability. The net sediment transport along the sand beach is computed while taking uncertainties in bathymetry, particle size distribution and wave climate into account. In the first design phase, an initial assessment is compared to the numerical model results.

The beach stability is done for an unprotected beach, viz. no additional beach stabilizing measures in addition to the offshore breakwater. Structural beach erosion is generated by long shore sediment transport gradients which require quantification to determine potential beach instability. Numerical modelling of long shore sediment transport and coastline evolution is carried out by using the LITPACK module of the MIKE21 software package from DHI (ref. 0). LITPACK is suitable for quasi-uniform (relative straight) coastlines or beaches. As the CPC beach-layout is in a strongly curved convex shape, the model results towards the edges of the beach (where curvature is strongest) should be considered cautiously. The model results are compared with generally accepted long shore sediment transport formulas as CERC (ref. 0) and Kamphuis (ref. 0). Model results are qualitatively in good comparison with the transport formulas. Sediment transport rates have been computed at 12 locations along the convex shaped beach layout.

Based on the transport gradient, the qualitative results of the sediment transport computations are shown in Figure 10 for the unprotected beach. The following conclusions are obtained:

- Points 578 and 584 are close to their own equilibrium (best estimate transport around 0), For the other points the order of magnitude does not change significantly for varying incoming wave directions;
- Along the west beach, a significant N directed sediment transport gradient is present (points 576 and 577). Depending on the detailed location of the beach end in the west, sediment transport toward the channel might occur. The channels are considered as sediment traps which may suffer from siltation if left unprotected;
- The overall computed sediment transport over the beach area is SE to E directed, transporting sand towards the SE canal/marine entrance/exit. This will potentially lead to structural erosion of the S beach and will cause siltation of the channel;
- The design orientation of the coastline at the W beach seems to be far from the equilibrium coastline orientation, which will lead on the long term to a significant reorientation of the W beach coastline, the extend of this effect also depends on the design of the transition between the beach and the canal boundaries;
- The design orientation of the coastline at the South beach is closer to its equilibrium orientation, which may lead on the long term to a minor reorientation of the S beach coastline;
- In terms of magnitude, sediment transport rates [m^3/yr] at the S beach are an order of magnitude smaller than the transport capacities of the W beach.

An example of the generated output at location 584 of a LITDRIFT (annual sediment drift) computation is presented in Figure 11. This location was selected as there was a clear sediment transport in both directions here, despite that the net transport is relative limited. This means that even when the net transport is relative low, it does not mean the total sand transport along the beach is low at all times. Especially near the canal entrances this may induce sand losses instead of sand being able to be transported back and forth in both directions along the coast.

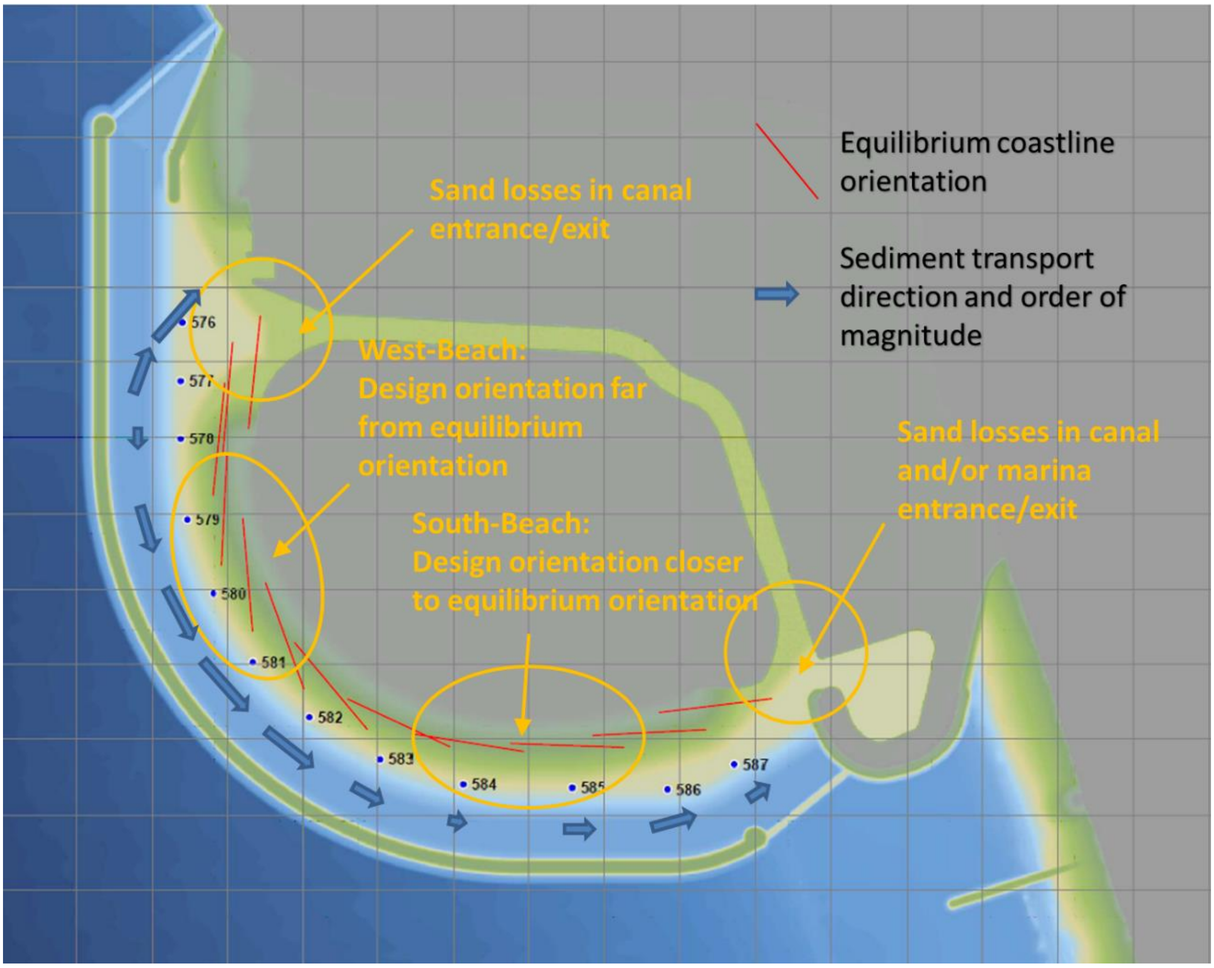

Figure 10: Qualitative transport directions and equilibrium orientation per output location

Results from the sensitivity analysis have shown the large impact of small changes in input parameters and lead to the following conclusions:

- The incoming wave height has a very large influence on the occurring sediment drift. This reveals that the actual magnitude of sediment transport is very complex to predict accurately and can strongly vary throughout the years. Also, sediment transport may increase further in the future due to sea level rise;
- The bed roughness has a pronounced influence on the occurring sediment drift. This confirms the uncertainty of sediment transport modelling, hence interpretation of computed values should be done with care;
- The grain size is important for the actual occurring sediment transport. If a larger grain size is used, the sediment drift can decrease by a factor 2. For this reason it is important to apply suitable larger grain sizes for construction of the beach;
- Overall, there is a large bandwidth in the actual sediment transport; the expected erosion volumes or meters coastline retreat thus indicate an uncertainty with factor 3 to 5. It is however clear that significant transport will be occurring, which will probably require beach stabilization measures if maintenance has to remain at practical levels.

Taking the model outputs into account, erosion rates in the range of 4-10 meters per year might occur. Without beach stabilization measures the required maintenance is in the order of 20,000 – 40,000 m^3/year. Averaged over time, erosion is expected at both the northern and eastern end and accretion in between locations 581 and 584 as shown in Figure 12. Temporary variations, e.g. due to storms, may change this pattern of erosion or accretion

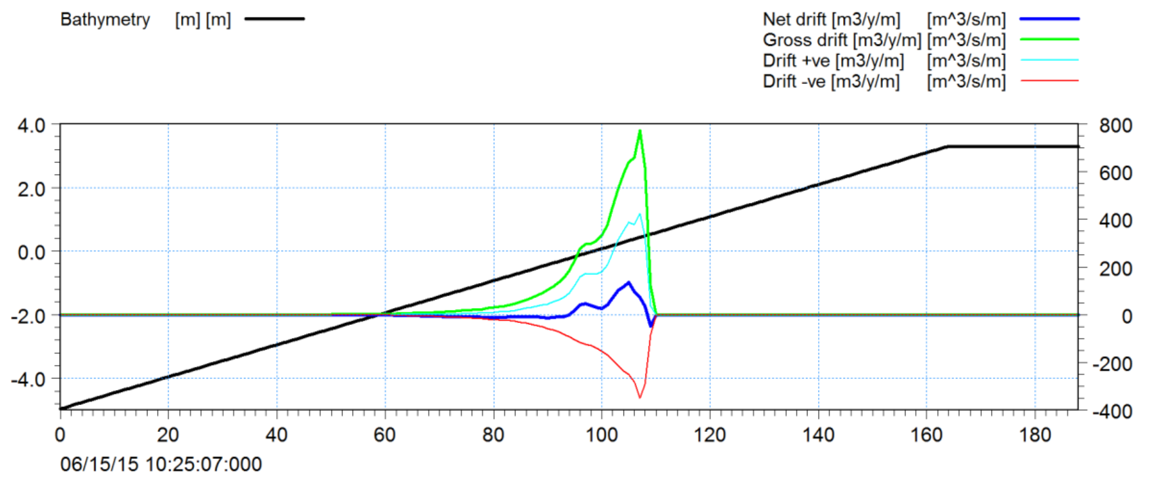

Figure 11: Computed net and gross transport along the south stretch of the beach profile

3.4 Design

Based on the preliminary model outcomes, we think it is highly advisable to install coastline stabilizing measures in order to reduce the long shore sediment transport capacity. As a feasible type of measures this stability can be improved by the construction of a well-tailored groyne field. The groyne field can be adjusted in such a way that it regulates or blocks the sediment drift. Per beach section, the groynes may be different. For adequate detailed design, more information on the hydrodynamic and morphologic system is required. Therefore, depending on the overall planning of the project, monitoring of the sediment transport processes and hydraulic regimes will lead to progressive insight into the expected beach stability. Moreover, with this information, the simulation models can be (re-)calibrated and updated. As an example: already during the construction of the offshore breakwater, the transmission parameters as used in the numerical model can be verified.

Depending on the design, adaptation of the cross-sectional beach profile towards a dynamic equilibrium profile will mostly take place in a relatively short period after completion of the beach. To take this adaptation into account, it is common practise to use a ‘buffer’ quantity of sand in the higher part of the beach, which may move downwards due to the initial changes or erode, ensuring that the minimum required width of the beach will remain over a certain (predetermined) period.

As a general approach, the best evidence for the performance (and thus for the design) of a groyne scheme may be sought in observation of similar groyne schemes in similar environments elsewhere. However, here it should be noted that this strongly convex-shaped beach design is unusual, so no similar artificial beach designs are present to use as reference. Therefore, all design considerations have to be based on the investigations carried out (physical and mathematical) and on experience. The accuracy of the numerical morphological modelling is a reflection of the accuracy of the input parameters, hence a large bandwidth in modelling results occurs. Results should thus be interpreted with care and require to be updated with progressive insight during design and construction. This is an important aspect of the engineering management process described in this paper. For this reason a flexible, costs efficient but effective design is proposed with the groyne field design.

The groyne scheme as designed based on the model calculations, consists of at 2 terminal groynes near the N and E beach boundary to prevent sediment losses into the canal. For the time being we foresee 8 intermediate relatively short groynes. The terminal groynes could be installed as rubble mound structure since they are of permanent character. For the intermediate groynes, impermeable wooden structures may be more suitable. The recommended preliminary layout design is presented in figure 14. The reason for choosing for the relatively short intermediate groynes is to remain as close as possible to the natural system. Advantage is e.g. that strong saw-tooth effects will be mitigated, as well as rip currents which are dangerous for bathing people. Further detailing of the beach stabilizing methods will follow from progressive insight. The groynes as indicated here, are considered no-regret and can be extended or adapted in future upon the increase of progressive knowledge, e.g. by monitoring and update simulation modelling. The detailed design should maximally allow for such extension or adaptation.

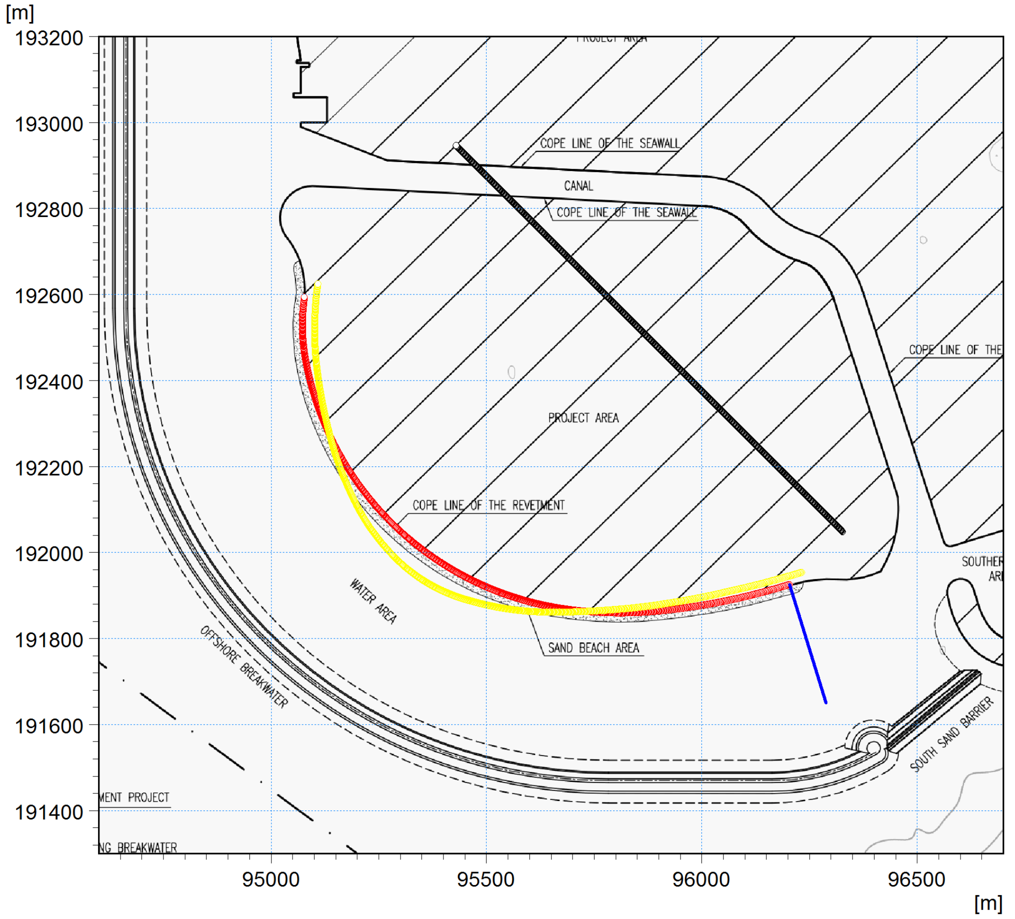

Figure 12: Model result: computed coastline evolution over 20 years (yellow line)

4. Conclusions and recommendations

4.1 Conclusions

The present paper illustrates the complex and iterative design process for the convex-shaped Colombo Port City (CPC) beach layout. To solve the complex problems involved, the sediment transport distribution along the beach has been determined for annual average wave conditions based on a 20 year time series. The hydraulic boundary conditions within the lagoon were determined by making use of the numerical wave model SWAN, in which wave transmission outcomes from 2D physical model testing have been used as input to determine the wave heights inside the lagoon area. Despite the use of state-of-the-art physical and numerical models, uncertainties remain. The model results are subject to uncertainties due to e.g. wave climate, offshore breakwater characteristics, beach profiles and sand properties.

We think that the largest uncertainty from this wave study is the prediction of the wave climate inside the lagoon, for which no tailor made combination of wave theories (transmission, reflection, diffraction, penetration) and calibration data are available. The complex layout of the development and the modelling assumptions lead to uncertainties in the output of the numerical wave models applied. Also for the main beach section, the input parameters for sediment transport computations (bed roughness, particle diameter) lead to uncertainties in the output results. Therefore, a sensitivity analysis has been carried out to determine the range of uncertainties in the computed sediment transport rates. In the sensitivity analysis the individual influence of i) particle size ii) bed roughness iii) wave climate and iv) coastline orientation on the sediment transport rates has been determined.

The modelling results indicate that without any beach stabilizing measures, the present convex beach layout could significantly erode due to gradients in the long shore sediment drift. The required maintenance is estimated to be in the order of 20,000 – 40,000 m^3/yr, however due to the uncertainties this estimation may vary up to a factor 3. In the SW area (middle area of the beach), the beach sand will start to accumulate. The source of this sand responsible for the accumulation are the N to S stretch in the W part of the beach and, to a lesser extent, the E to W stretch in the S part of the beach. Furthermore, sand may well be transported towards the canal entrances / exits near the end of the beaches and thus be 'lost'. The W and S parts of the beach are therefore subjected to structural erosion. The erosion rates at the N and S stretches of the W part of the beach may initially be around 10m per year and at the E to W stretches of the S part of the beach approximately 3m per year.

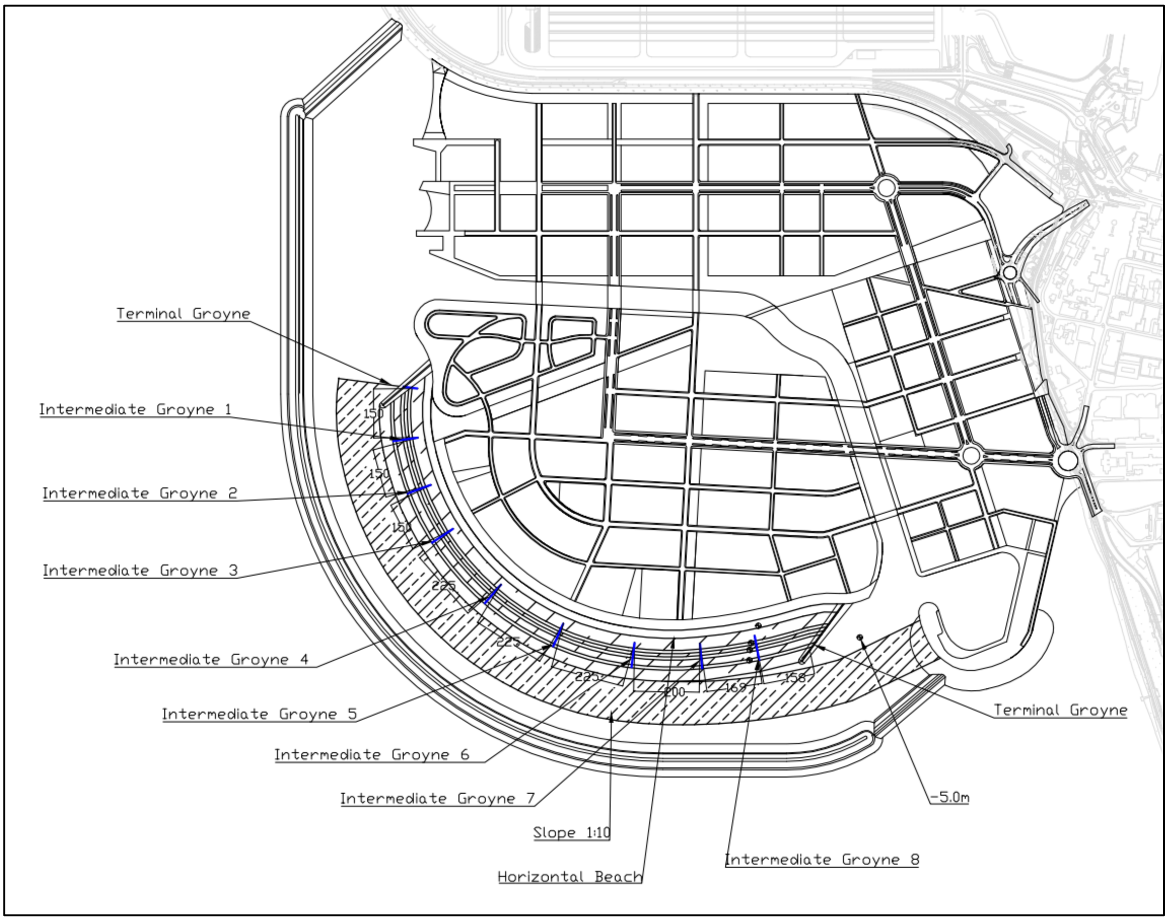

Figure 13: Layout groyne field with 2 terminal groynes and 8 intermediate groynes

The most NW tip of the main beach appears to be relative well sheltered by a protruding piece of land N of the main beach. This area is therefore less subjected to northerly directed sediment transport into the canal entrance. This is in contrast to the most SE tip of the main beach where there is a nett E directed sediment transport. On the long run this will results in erosion of the S main beach and accumulation of sand in the S Canal Entrance. This effect will be less in the N, but over time sand may bypass the land protrusion and be transported into the canal entrance there. Moreover, the overall sediment transport picture as shown in the above is an averaged picture. Individual periods (seasonality, storms) may give other distributions, so the sediment transport at the extremities will have to be arrested anyhow.

4.2 Recommendations

The sediment transport analysis along the beach of the CPC development indicates that at some locations significant erosion of the beach is likely to happen and that at other locations sedimentation may occur. If this would really occur and required maintenance is considered too high, the situation can be mitigated by a properly designed groyne system. At the other hand, we think that the uncertainties in the predicted erosion rates do not yet justify to propose a final solution at this stage of the project.

Instead, we propose to maximally utilize progressive insight on the breakwater characteristics, wave climate and particle size in next iterative design rounds. We therefore also recommend to start a monitoring program on hydraulics and the morphological behaviour of the beach and volumes of local erosion and accretion during construction. This may further indicate the necessity of the (interstitial) groynes. If such a groyne scheme is strongly indicated then, the monitoring results and subsequent increased knowledge on the local morphological behaviour of the beach can be used for the final design of the (initial) groyne field.

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