CREST
CLIMATE RESILIENT COAST

TAKE HOME MESSAGES

1. Coping with long-term climate change involves many uncertainties. Several climate scenarios have been updated to support policies.

2. Over the past thirty years, it appears that a net natural supply of sediment from the sea to the Belgian west and east coasts has taken place, which has contributed to the soft coastal defence.

3. The technology to follow evolutions in beach morphology is available.

4. Providing sufficient sand on the beaches not only strengthens the beach itself, but also contributes to strengthening the dunes.

5. After a storm, our beaches recover at least partially, and this within a period of barely a few months.

6. Taking fundamental processes better into account is a good basis for understanding and simulating the patterns of coastal sediment transport.

7. The FLIAT model developed under CREST provides a solid basis for hinterland flood risk calculations.

8. Wider beaches reduce the impact of waves on the dikes.

AGENTSCHAP INNOVEREN & ONDERNEMEN
Vlaanderen is ondernemen

THEME 1: CLIMATE CHANGE INCLUDING MORPHOLOGICAL EVOLUTION ON LONG TIME SCALE (DECADES) FOR THE BELGIAN COAST AS A WHOLE.

1. In concertation with Complex Project Coastal Vision, climate change scenarios for Belgium were agreed upon.
2. Although according to projected changes in the climate extreme waves conditions and storm surges are not expected to change much, sea level rise will increase the impact at the Belgian coast unless the level of coastal protection can grow at equal pace.
3. A sea level rise of 2.4 mm per year for the last decades has been confirmed. A temperature increase in the order of 0.1 degree Celsius per decade in Belgian waters has been observed.
4. Sea level rise will cause higher high tides and lower low tides.
5. During the last four centuries, the Flemish coast straightened under the combined influence of human activity and natural evolution, advancing in the southwest area, retreating in the central area and both advancing and retreating in the northeast area.
6. In the past 30 years, the natural sediment supply in the active zone of the Belgian coast was of the same order of magnitude (0.5 million cubic meter per year) as the artificial supply by means of nourishments. The natural supply is the result of cross-shore transport from the offshore towards the coastline. Detailed understanding in the driving mechanisms is still lacking.
7. In the past 30 years, the natural sea defences at the western and eastern parts of the Belgian coast have heightened more (10 to 30 mm per year) than sea level rise (2 to 3 mm per year), while the central part naturally loses sand (loss of 2 to 8 mm per year). The western and eastern parts thus show a certain natural resilience to sea level rise contributing to the soft coastal defence. Climate change induced coastline retreat can be partly compensated by natural feeding.
8. One-off events, like a storm, show little or no impact in the decadal beach volume morphological time series. Although not seen over the last decades, this does not exclude that extreme events could have a devastating impact.
9. The increased replenishment efforts of the past years have realised permanently wider beaches on nourishment locations. Like with all beach nourishments, erosion rates increase initially, yet after a few years return to the long-term average. The wider beaches enhance the coastal safety level, the touristic use and resilience with respect to sea level rise.
10. Over 50 historical elevation maps and over 500 beach profiles of Belgian coast were digitized and made available within CREST project. These have already proven valuable to study the difference in response of different types of beaches to sea level rise and storminess over more than 30 years.
11. Your data and research methodology might be invaluable for future researchers, document them well.
12. The uncertainty on the bathymetric surveys has a large impact on the accuracy of the observations. It can be reduced by performing independent terrestrial control measurements of the low-tide area immediately following echo sounding.
13. The human interventions (dredging in navigation channels, beach nourishments and local interventions by municipalities) should be kept in a well-structured database in relation to the morphological monitoring.
14. In order to study the morphological relationship between the off-shore and the active coastal zone, the surveyed area should be extended seaward.

THEME 2: MORPHODYNAMICS ON TIME SCALE OF DAYS (STORMS) TO YEARS (LIFETIME OF NOURISHMENTS) FOR THE TWO PILOT AREAS MARIAKERKE AND KOKSIJDE

During four years intensive monitoring was performed at two locations along the Belgian coastline. At Mariakerke the coastal defence exists of a dike and beach, whereas in Koksijde a dune and beach protect the hinterland from storm impacts. Investigating both hard and soft coastal protection measures in situ give better insight in their interaction and efficiency.

1. Permanent static terrestrial laser scanning of the dry and intertidal beach yields vertical accuracies < 2 cm and permits very time intensive scanning.
2. A special purpose mobile LiDAR vehicle with RTK-GNSS and IMU was developed and gave an absolute accuracy and precision as good as 2 cm, making it a highly accurate and precise technique for topographic monitoring of the intertidal zone at a hyperspatial resolution.
3. A one-year series of time intensive PLS measurements were acquired at Mariakerke-Beach and during a longer time span of 3 years, incidental mobile LiDAR scans and UAV photogrammetric measurements at both Mariakerke and Koksijde were acquired, in addition to numerous ground-based survey techniques.
4. The intertidal zone in Belgium is not only shaped by waves, but equally by tidal currents and, to a lesser extent, by natural variations in sediment supply.
5. A unique data set, consisting of wind conditions and aeolian sand transport rates, has been obtained through field experiments in Belgium on the natural beach of Koksijde and the developed beach of Mariakerke. Between 2016 and 2018, 40 datasets on aeolian sand transport (20 in Koksijde and 20 in Mariakerke) were obtained during moderate to strong wind conditions. Although sand transport by wind is easily observable, reliable and accurate data sets of sand transport rates are still scarcely available due to measuring difficulties. This accurate field data set has an added value in understanding how coastal environments (managed or natural) respond to wind forces over short to long-term timescales.
6. On short-time scales (hours to days), saturated aeolian sediment transport rate is cubic related with wind speed by a new modified Bagnold model. This model is validated by our own field data set and other international field data sets. The modified Bagnold model performs reasonably well in predicting sand transport.
7. On decadal timescales, the Belgian coastal dunes grow linear in time with a constant rate. Dune growth varies between 0 and 12.3 cubic metre per metre per year with an average dune growth of 6.2 cubic metre per metre per year, featuring large variations in longshore direction. Dune growth is primarily caused by aeolian sediment input from the beach during west to southwest wind conditions.
8. Based on the modified Bagnold model, onshore potential aeolian sediment transport ranges to maximum 9 m^3/m/year, while longshore potential aeolian sediment transport could reach up to 20 m^3/m/ year towards the Netherlands.
9. There is strong correlation between observed and predicted dune growth on decadal timescales (long-term). Most of the predicted data are within a factor 2 of the measured value. It suggests that annual differences in forcing and transport limiting conditions (wind and moisture) only have a slight effect on the overall variability of dune volume trends.
10. Aeolian sand from the foreshore is deposited at the foot of the steep cliff due to a decrease in shear velocity. Large shear velocities are measured at the berm lip due to compression and acceleration of the flow field. Onshore aeolian sand transport starts at the berm lip and

increases rapidly towards a maximum downwind until it decreases to a lower equilibrium. The deposition at the foot of the cliff and erosion at the berm lip causes the cliff to change to an equilibrium profile.

11. The steep cliff in front of the human-constructed coastal berm of Mariakerke is very sensitive to erosion. Sand being eroded from the berm lip is deposited in front of the dyke and in the trench. This specific beach topography is a general good solution to minimize sand transport to the hinterland, but only serves temporally.
12. Further research should focus on better quantifying aeolian sediment transport processes by more innovative monitoring techniques, especially when long-term monitoring is required. A camera-system to monitor the overall weather and wave conditions, bar welding, beach morphology, and the frequency and magnitude of erosional events could be useful. The images could be used to extract moisture maps, beach dimensions, fetch distances and vegetation cover. It would be also of interest to introduce a self-rotating vertical sand trap that measures the whole transport column from surface to a certain distance above the surface to get information of the entire flux profile. A change in decadal dune behaviour due to climate change is also very relevant to study. A changing wind field could cause the dunes to erode instead of the current growth.
13. Morphological features of the intertidal bars, embryonic dunes and backshore berm play an important role in beach recovery.
14. Developed beaches in urban areas can retain some natural ability to rebuild after the storm. In the test sections 98-104 (Mariakerke) up to one third of the eroded volume due to Storm Dieter was recovered within 5 months.

THEME 3: PHYSICAL PROCESSES AND INNOVATION IN MODELLING

1. The widely used Longuet-Higgins & Stewart (1960) method for wave run-up calculations overestimates the long wave energy for a sloping bottom. Therefore, a correction factor has been designed based on parametrizations from semi-analytical solutions that significantly improves the prediction for large normalized bed slopes.
2. Sheet flow modifies the hydrodynamics under waves because it leads to more significant wave dissipation than skin friction.
3. Turbulence modelling in 3D computational fluid dynamics with standard linear interpolations and refined grids are incompatible with standard bottom boundary conditions. An alternative boundary treatment procedure has been designed to overcome these limitations.
4. Modelling of particle-turbulence interactions remains a key issue in highly concentrated sediment transport modelling. A physics-based turbulence closure is essential for modelling energy dissipation due to sediment motion.
5. A good basis for long-term simulation of mixed sediment transport is present in the 2D TELEMAC-TOMAWAC-SISYPHE coastal models. This is good news for management considerations that require large scale and long-term simulation of complex scenarios in reasonable time.
6. The road to efficient and accurate design of the optimised coastal defence systems of tomorrow – Coupling numerical models enables complex modelling only where necessary: advantages of each model are preserved without suffering their individual downsides.
7. Lack of public awareness equals lack of motivation among people to support, or even protest, changes in necessary landscape measures to improve coastal safety. Therefore, there is demand for a good visualisation and communication tool in Flanders that quickly conveys strong messages, condenses complex information, and engages the community in issues of environmental change.
8. In order to make well-informed decisions, and because time is key during a flood disaster, tools that collect all relevant information to determine the extent of the flood event and its damage as quickly and accurately as possible must be available ahead of time.
9. A cloud-based flood risk assessment tool with an object-relational approach, FLIAT, is developed, to improve the accuracy, calculation speed, ease of use, and possibilities for further development of the flood risk and damage assessment methodology in Flanders.
10. If a predicted storm is more severe than anticipated, evacuation is necessary. In case available evacuation time is short, a vertical evacuation is preferred above the classical evacuation outside the flood area.

THEME 4: PREDICTION OF WAVE IMPACT (OVERTOPPING AND LOADS) ON THE DIKE DURING STORMS

1. Hidden in plain sight: imperceptible to the naked eye, very long waves are unexpected adversaries for our coastal defence protection against flooding during violent storms.
2. Shallow beaches are essential in our hybrid soft-hard coastal defence system – Size matters in the protection against violent storms: wider beaches reduce the wave impact on the dike.
3. Complexity begets complexity: the complex shape of our coastal defence system leads to complex hydrodynamics – Accurate prediction of the wave impact on the dike and buildings requires state of the art numerical modelling to avoid over-conservative design
4. Using the more detailed insight in physical processes and the validated numerical tools acquired in the CREST project, the complete calculation methodology for safety assessments and risk calculations can be improved.
5. Large-scale experiments on overtopping wave loads (WALOWA project) suggest that the impact force acting on dike mounted vertical walls with shallow foreshores can be estimated using a hydrostatic pressure assumption.
6. A new experimental dataset is available of 2D wave flume physical modelling of (individual) wave overtopping and impacts on dikes with very shallow foreshores (very relevant to the Belgian coast). The dataset also includes high spatial resolution measurements of surface elevations along the foreshore slope, allowing a more detailed study of long waves.
7. A new experimental dataset is available of 3D wave basin physical modelling of (individual) wave overtopping and impacts on dikes with very shallow foreshores (very relevant to the Belgian coast). This dataset includes long-crested, obliquely incident long-crested and short-crested wave tests, allowing the study of 3D effects at the dike and directional spreading of the waves.
8. The spectral wave period at the toe of the dike, $T_{m-1,0,t}$ is used in all overtopping and wave impact prediction formulas. An existing semi-empirical formula for $T_{m-1,0,t}$ was validated using data from mildly sloping shallow foreshores, but returns an overestimated value for the case of steep shallow foreshore slopes. A modification of the formula has been carried out, making it applicable and more accurate for use in cases with steeper shallow foreshore slopes.
9. A significant effect of the foreshore slope angle and the dike geometry (promenade length, inclusion of storm wall,…) on the wave overtopping and wave impact force is discovered. A modification of the existing prediction formulas is ongoing.
10. Long waves (or infragravity waves) significantly affect the wave-induced structural response (overtopping, wave impact) of dikes for the case of very shallow foreshores. However, very little is actually known about these long waves in the nearshore region during storm conditions, especially along the Belgian coast. Dedicated field measurements are strongly recommended.
11. Long waves feature strong reflection from a dike with shallow foreshore, while they might break on mildly sloping beaches in the surf zone and reflect much less from the shoreline in case no dike is present. The presence of the dike therefore affects long wave reflection on mildly sloping beaches. Further research into the role of the dike in this process, might lead to further insight into changes in the hydrodynamics and their influence on the surf zone morphodynamics during storm conditions.
12. Active wave absorption in physical models should be tuned to include both reflected long waves and seiches (if the wave paddle stroke length allows it) when testing coastal structures

with a very shallow foreshore. Otherwise, build-up of long wave energy will significantly affect the measurements of wave-induced structural response.

13. Measured experimental wave impact forces have a low repeatability, because of a high dependence on small changes in environmental conditions. On the other hand, repeatability is important to reduce uncertainty in prediction formulas derived from experiments and for validation of deterministic numerical models. Low-pass filtering of the measured signal of the impact forces in the post-processing step, effectively removing mostly the stochastic part of the dynamic impact types, improves repeatability.
14. Smaller elements of buildings, such as windows and doors, usually have a higher natural frequency than the recommended low-pass filter for experimentally measured impact forces and are affected by the stochastic part of the dynamic impact types. Therefore, a dynamic impact force safety factor should be applied to a calculated maximum force (determined from low-pass filtered force measurements) for the design of such elements.
15. Directional spreading, expressing the degree of short crestedness of real sea waves, is an essential parameter in the design of beach nourishments and structures for coastal safety. The higher its value, the lower the long wave height is at the dike toe, leading to lower overtopping and impact force. Modification of existing prediction formulas is ongoing. However, there is little known about the amount of directional spreading actually occurring nearshore during storm conditions along the Belgian coast. More analysis of existing field measurements is strongly recommended, in addition to continued and more dedicated field measurements.
16. First order wave generation at the offshore boundary in nearshore experimental and numerical models introduces spurious, non-physical long waves, which affect the maximum individual overtopping volume and the mean wave overtopping discharge. This is especially true for mean overtopping discharge values in the order of 10 l/m/s and lower. Second order wave generation prevents such spurious long waves and is therefore recommended.
17. The numerical model SWASH is able to provide an accurate estimation of the maximum force per impact event on dike-mounted vertical walls, by assuming hydrostatic pressure only for the calculation of the force on the vertical wall. Including non-hydrostatic pressure effects might improve results further, particularly for dynamic wave impacts. However, spurious pressure/force oscillations are observed when including the non-hydrostatic pressure. No explanation for this numerical effect has been found yet.
18. The numerical model SWASH significantly underestimates the impulse of the force per wave impact event on a dike-mounted vertical wall in shallow foreshore conditions, indicating that the wave impact flow is not modelled correctly. More detailed Navier-Stokes models such as OpenFOAM and DualSPHysics are necessary for a more accurate flow modelling along the vertical wall, leading to a better estimation of the duration of wave impact forces.
19. Maximum individual wave overtopping and impact is affected by the wave generation method (seed effect). This effect was tested for a mean overtopping discharge, q, of about 15 l/m/s, and is expected to increase even more for smaller mean overtopping discharges (e.g. $q \approx 1$ l/m/s, currently the limit used in the safety assessment). Additional in-depth research into this issue is necessary.
20. Modelling beach morphodynamics during a storm is a key aspect in understanding and accurately predicting wave overtopping. The sand transport along the beach profile during a storm (beach morphodynamics) triggers profile changes which need to be included in the modelling of wave overtopping over a dike with a very shallow foreshore (very relevant to the Belgian coast).

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