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An Extreme Event as a Game Changer in Coastal Erosion Management

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ABSTRACT

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The construction of hard protection measures along the northeast coast of Sealand, Denmark, has gradually led to profile steepening, loss of beaches, and increased storm erosion. Although the problem has been addressed for decades no common solutions have been implemented yet. However, the impact of cyclone Xaver in December 2013 with severe coastal erosion led to collaboration between the involved municipalities to work on a coherent solution for the entire coastline that involves sand nourishments, renovation and optimization of hard protection structures, and the restoration of recreational values. We present a concept of 'erosion pressure' as a simple method to estimate potential chronic (longshore) and acute (cross-shore) erosion on protected coasts. The erosion pressure estimates are reliable at the investigated coast and the concept has proved useful for dissemination to stakeholders about coastal dynamics.

ADDITIONAL INDEX WORDS: *Extreme events, sand nourishments, long-term strategy, natural erosion.*

INTRODUCTION

Major coastal erosion events challenge coastal engineers in opting for the best management solutions. Current scientific knowledge and our predictive abilities about the nature of extremes and of shoreline processes may be sufficient to respond. Factors like legislation and governance, politics, economy, ecology, history, as well as a potential complexity in landowners and their organizational form, opinions and needs must also be accounted for, however. The dissemination about coastal dynamics to all stakeholders is an everlasting task, too.

A large part of the northeast coast of the island of Sealand, Denmark, experiences cliff and beach erosion. The story is classic: The construction of hard (passive) protection measures transfers the erosion to neighboring stretches and leads to more constructions *etc.* and gradually diminishes the natural cliff erosion and depletes the coastal profile of sand. The problem has been obvious for decades but with very few counteractive achievements despite several efforts to advocate for sand nourishments and beach restoration over the past 35 years. On the contrary, specific storm events have led to an urge from landowners for more hard structures and to the abolishment of any long-term strategy for larger stretches of coast. Coastal protection in Denmark works on a "those who benefit must pay" principle. Individual house owners, or, small house owner associations are in charge of and must pay for protection and discussions have been on economy rather than on methods.

Perhaps the game is about to change in favor of more sound management practices due to severe erosion along the Sealand coastline from cyclone Xaver on 5-6th December 2013. We present an 'erosion pressure' model used for evaluating shoreline challenges and dissemination to the public. We also provide a brief overview of and discuss the shift towards more active protection solutions and visions for the entire coastline across municipality borders.

Background

The approximately 65 km long coast of NE Sealand (Figure 1) predominantly consists of soft cliffs with higher parts (up to 40 m) in glacial deposits varying with low postglacial cliffs, beach ridges and dunes. Accordingly, sections of wide abrasion platforms in glaciogenic sediments, often covered with only a thin veneer of sand, interchange with marine, sandy sections with more pronounced offshore bars (FU, 1978). The coast is

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moderately exposed towards W and NW. Storms may push water in from the North Sea and raise the general Kattegat water level.

Figure 1. Denmark (inserted) and the northeast Sealand coast with towns, *municipalities*, and positions for wave hindcasts (35, 36), wave (ADCP) and water level measurements (TG) referred to in the text.

Tidal range is 0.2-0.4 m and annual exceedance water level is 1.08 m DVR90 at Hornbaek (0 DVR90 ≈ MSL in 1990).

Large parts of the coast experienced Aeolian sand drift in the 16-18th centuries. Around 1880 almost all larger stones were removed from the coastal area for construction works elsewhere which increased the wave impact and erosion rates (Bech, 1909). Harbors and offshore breakwaters were built at several locations from 1912 onwards and led to leeside erosion and to the construction of groins. As the coastline became increasingly more popular from the 1920s onwards, holiday houses and permanent residences were built at vulnerable clifftop locations and were accompanied by passive protection measures in the form of groins, T-groins, seawalls *etc.* (FU, 1978). In many places this practice has continued until today (Figure 2).

Some protection measures in the mid-20th century were designed by the Danish Coastal Authority (DCA) and by engineering companies according to the standards, but many were erected by individual landowners. By the end of the 1970s the coast and beaches were 'in a miserable condition' (FU, 1978), and the coastal municipalities and the former county (Figure 3) initiated efforts to coordinate and reorganize the entire strategy for coastal protection (FU, 1978; FU, 1984). An ambitious 10 year plan to renovate and optimize existing coastal protection together with sand nourishment schemes was presented in 1989 which also included a financial plan (FU, 1989; FC, 1991). A few successful projects were carried out, but budgets were cut and the plan lost momentum (FC, 2001).

In 2007, the newly established Gribskov Municipality made an effort to revitalize a common strategy along the coast, but the two other municipalities were reluctant to participate. A plan for the Gribskov Municipality coastline (COWI, 2009) that included financial contributions from landowners up to 1 km inland was rejected by the politicians in 2011 following a public vote. A national coastal protection strategy (DCA, 2011) and guidelines for coastal climate adaptation (Sorensen and Sorensen, 2012) address the need for more holistic and optimized coastal management solutions. DCA has been restrictive in permitting passive measures and has continuously argued in favor of sand nourishments along the coast of NE Sealand.

Figure 2. NE Sealand coastline with older as well as and new houses on the clifftop (Photo: DCA/Hunderup Aerial Photo).

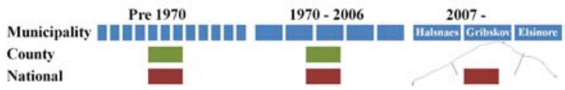

Figure 3. Governance structure. The change in composition of local, regional and national bodies over time along the NE Sealand coast.

METHODS

Historic shoreline changes, *e.g.* along the NE Sealand coast (FU, 1984; Kabuth, Kroon & Pedersen, 2014), do not reflect the autonomous erosion due to the large number of hard structures. An 'erosion pressure' (EP) concept is developed to describe and map the potential erosion rather than calculating the actual erosion rates and sediment loss. The focus is on simple and easily applicable methods and rough estimates rather than on detailed numerical solutions. EP is divided into potential 'chronic' and 'acute' erosion, respectively.

Chronic erosion accounts for the continuous alongshore loss (or gain) of sand in the profile due to waves and littoral currents. A longshore transport equation index is derived from coastline orientation and wave conditions using DHI's Littoral Drift model (Fredsoe and Deigaard, 1992) and scaled to reflect the expected transport (DHI, 2013 p.8). Hourly time series of offshore wave conditions (significant wave height and period, and direction) at selected points are simulated from wind data (1994-2011, 18 years) in MIKE 21SW (DHI, 2012). For a stretch of coast two sets of data area are used in a weighed form. Calculations of the observed transport from shoreline changes are used for validation in this study.

Acute erosion describes the cross-shore transport from the inner profile to the outer during storm events. It acknowledges that cliff erosion from waves and extreme water levels may be infrequent. The cross-shore transport is generally more difficult to calculate and it is estimated from the correlation between the simulated wave heights and measured water levels from tide gauges. Here, the cumulative frequency of correlations in the directional spectra of incoming waves and water levels (in 45° intervals) is used to scale the acute EP (DHI, 2013).

Tide gauge records from Hornbaek, 1890-2014 (DMI, 2014) and recorded offshore waves at 7 m depth off the coast (ADCP – 2 hour intervals) are included to describe wave and water level conditions during Xaver. An update of the current extreme water level statistics to include Xaver water levels is calculated based on Sorensen, Madsen and Knudsen (2013).

RESULTS

In the calculations of chronic erosion, the coastline is divided into two sections; Hundested-Gilleleje (Figure 4) and Gilleleje-Elsinore (not shown). Based on the wave hindcasts and coastline orientation a point of zero potential longshore transport is identified immediately east of Hundested. An overall trend of increasing potential longshore transport is observed towards Gilleleje due to the coastline orientation and a more severe wave climate. Local shifts in coastline orientation cause deviations from the trend. Coastline advances are related to harbor and offshore seawall constructions and large erosion rates are often found on the downdrift side of these. A good correlation to the observed longshore transport based on the 1890-2005 shoreline changes is found and provides a good opportunity to scale the transport index, q_*, to reflect the expected transport rates; refer below.

A strong correlation exists between wave heights and water levels at Gilleleje (Figure 5). Due to the relatively harsh wave climate the acute erosion potential is classified as 'large'. As the erosion pressure model is designed for use along the entire Danish coastline both the chronic and the acute erosion pressure potential have been scaled and categorized to reflect national conditions (Figure 6). Here, the yearly 12 hour maximum wave height (H_s_12) is used to separate categories of acute erosion. Also shown are the scaled potential and observed transport rates.

Some 'jumps' in transport rates are observed and may partly be due to limitations in the applied methods. The erosion is up to 30 m^3/m/y and the potential longshore transport is calculated to a maximum of 65.000 m^3/y. Simple sketches are produced to assist the dissemination of the acute and chronic erosion pressure concept and the causes of erosion (DHI and Hasloev & Kjaersgaard, 2015), Figure 7.

The water level during Xaver reached 1.96 m DVR90 at Hornbaek which is the highest recorded (1890-2015) and corresponds to a 1000 year event according to Sorensen, Madsen and Knudsen (2013). An update that includes Xaver increases a 100 year return level from 1.68 to 1.76 m DVR90 (de-trended). Furthermore, the water level exceeded 1.5 m for more than 18 hours, Figure 8. Not since 1922 has the coast experienced any comparable event in terms of water level and duration. Unfortunately there are no registrations around the peak of the 18 December 1921 event. The tide gauge record also lack data from a 26 December 1902 storm where extreme water levels were measured (*e.g.* 3rd ranked water level in Copenhagen, 1890-2014) and widespread erosion was reported (Bech, 1909). Peak significant wave heights in excess of 3 m and peak wave periods of 10 s (not shown) were recorded off the coast during Xaver. This corresponds well to the modeled numbers for extreme conditions.

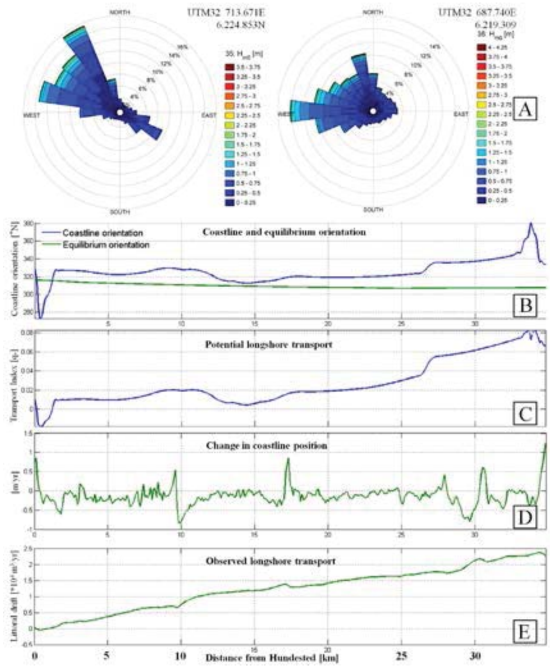

Figure 4. Modeled wave conditions off the coast (refer Figure 1 for positions) (A), coastline orientation and equilibrium orientation (B), calculated potential longshore transport (C), rate of change in coastline position (c. 1890-2005) (D), and observed longshore transport (E) for the Hundested to Gilleleje coastline.

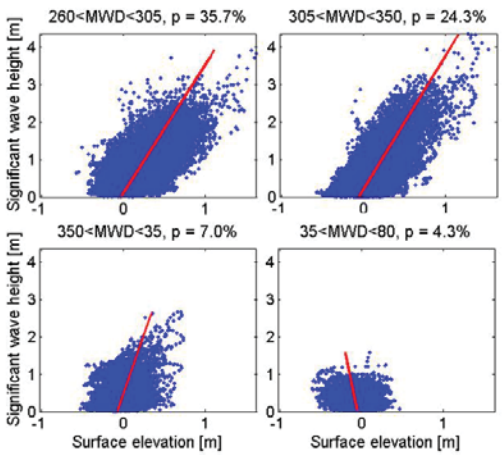

Figure 5. Correlation between water levels (measured) and significant wave heights (simulated) in 45° intervals off Gilleleje used to assess acute erosion pressure.

DISCUSSION

The concept of erosion pressure is a little hypothetical, but it serves an important purpose in the sense that it describes how much pressure there is on the protected stretches. This information may be useful in situations where consideration is given to change a coastal protection strategy, *e.g.* by replacing the hard sea defenses with sand nourishments, and it provides a framework for addressing the potential erosion along a coast. The erosion pressure model may be developed further by including more and updated wave climate and water level data to better resolve and predict the spatial variation.

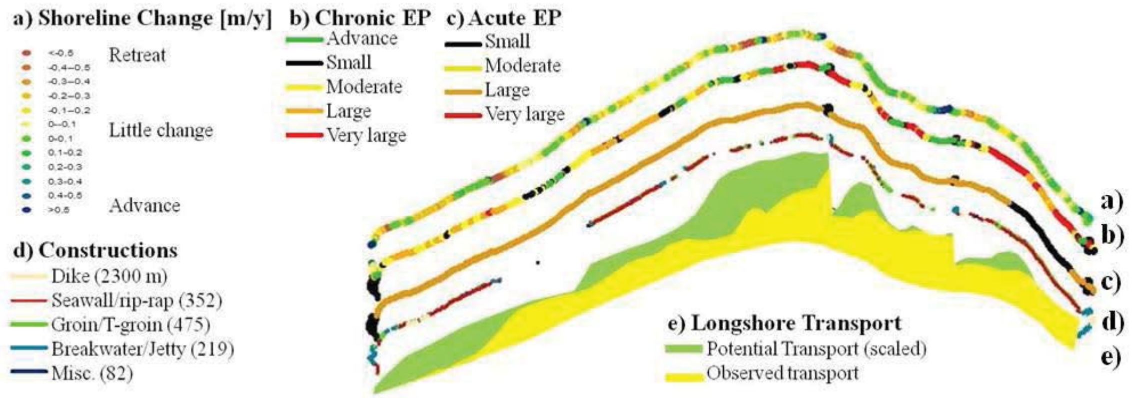

Figure 6. Shoreline change (a), chronic (b) and acute (c) erosion pressure; hard protection measures with number of constructions shown in legend (d), and a sketch of the observed versus the scaled potential longshore transport (e) for the NE Sealand coast, Denmark.

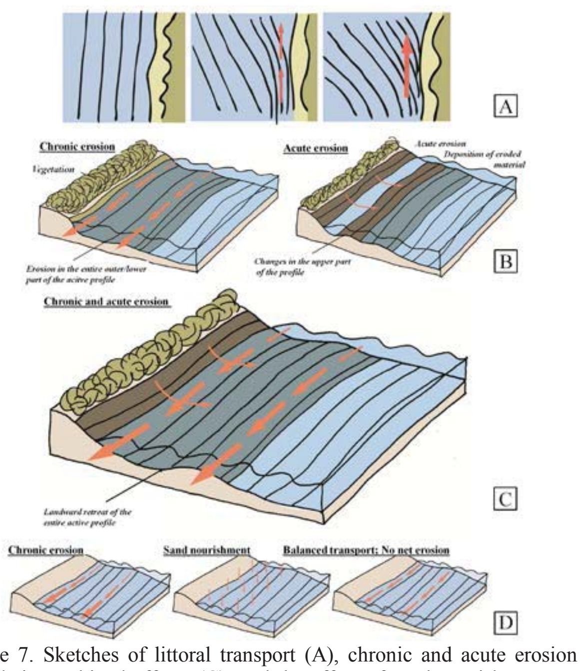

Figure 7. Sketches of littoral transport (A), chronic and acute erosion (B), their combined effects (C), and the effect of sand nourishments to balance out chronic erosion (D) used for stakeholder dissemination.

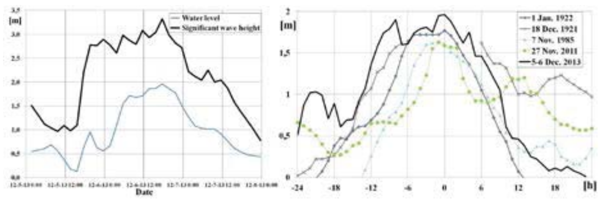

Figure 8. Measured significant wave heights and water levels at 7 m water depth during Xaver (A) and water levels (peak at 0 hrs.) at Hornbaek (solid black) (B) together with 'top-4' extreme water levels previous to this event.

Although the acute and chronic erosion are combined over time their different causes are fairly easy to disseminate. The cumulative deficit of sand in the profile over the past 30-40 years due to chronic erosion can be communicated. The acute erosion is the visible erosion from storm events. Acute erosion was experienced along the entire coastline from Xaver and at some locations it exceeded the total erosion in the past 100 years. In some locations there is no need of passive protection measures as no properties are in imminent danger, whereas at other locations the pressure is critical regarding both the acute and chronic erosion, respectively. Along the stretches with the highest erosion pressure a combination of passive and active measures is needed. For the NE Sealand coast the methods provide realistic results, and the erosion pressure concept is included in the current conceptual project design for the coast (DHI and Hasloev & Kjaersgaard, 2015; Hasloev & Kjaersgaard, 2014).

It is the lack of natural sources for sediment supply and the numerous hard structures along the coast that is a problem and not natural erosion itself. This lack of resilience towards erosion was very clearly exposed during Xaver. Contrary to past events the widespread erosion yielded the opportunity to forward long-term visions for coastal management and to bring in arguments for sound solutions and more resilient coasts. Here, the erosion pressure concept proved useful to address in a very simple manner that the economic impact from erosion will only increase in the future if no coordinated measures are implemented. The event has been a game changer inasmuch as the three municipalities now are working together to implement and co-finance a common solution for the NE Sealand coast (Municipality Mayors, 2015). Naturally, landowners away from the coast have been reluctant to financially support passive solutions where the only result is that beaches are lost. On the other hand, the municipalities and the coastal landowners with passive (and often massive) protection measures must acknowledge the cumulated sand deficit and that very large initial (> 1 million m^3) and repeated sand nourishments are needed to restore the sediment balance. This also includes a reassurance to landowners that in longer time perspective sand nourishments (in some places in combination with passive measures and cliff slope stabilization) will safeguard their real estate values. Arguments for the municipality engagement lie not solely within protection against storms and climate impact but have become integrated in the overall economic development visions and planning for the future. This includes restoration of natural values to boost tourism and attract citizens, and it requires involvement and input from various municipal departments, private companies, and the public to bring out all potential synergies. The visionary but very concrete prospect for the future (Hasloev & Kjaersgaard, 2014) acknowledges previous efforts to protect the NE Sealand coast. Hopefully this time the municipalities, the landowners, and other stakeholders will succeed in the implementation of a sound management concept *anno* 2016. Xaver may thus also become a game changer in bringing in science and interdisciplinary approaches to the Danish coastal erosion management.

The Danish Coastal Protection Act has proven unsuccessful in promoting and implementing active solutions to deal with chronic erosion but the law may be up for revision. An ongoing coastal analysis will by 2016 provide a national overview of present and potential future erosion and flooding challenges, and it will also address financial issues regarding coastal protection. This hopefully will lead to a political debate of how we as a society proceed with coastal challenges that involves the future national engagement. Discussions about retreat strategies in some areas to allow for natural sediment supply may also be relevant to include.

CONCLUSIONS

The concept of erosion pressure and a division into potential chronic and potential acute erosion is a simple method to estimate the erosion pressure on a coast protected with hard structures. Dissemination of the concept has proven successful in promoting sand nourishments along the northeast coast of Sealand, Denmark. After many years of more or less unsuccessful attempts, the impact of cyclone Xaver in December 2013 have led to collaboration across municipality borders to implement a coherent solution for the entire coastline that involves sand nourishments, optimization and renovation of existing passive protection measures, and restoration of recreational values.

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