Scour and erosion: common ground between hydraulics and geotechnics

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Traditionally, hydraulics and geotechnics are considered as separate disciplines that have not much in common. We think this is a mistake: there are many overlap areas where the two can strengthen each other. Flood risk management is one example, bank/dune erosion is another, local scour near structures a third. In all these cases, geotechnical failure mechanisms are just as important as hydrodynamic and sediment transport processes.

I. INTRODUCTION

Geotechnics and hydraulics have always played an important role in The Netherlands, in its fight to protect the low-lying land from flooding, in its efforts to set up a robust and efficient water management system, in its strive to maintain itself as a modern industrialised country amidst water, soft soil and swamp, and in its need for sustainable development in this densely populated delta area.

Dikes, for instance, have been built since over a thousand years to protect communities and their land against flooding. The effectiveness of those dikes is not only a matter of geotechnical stability, but also of adequate estimates of the design hydrodynamic load (water level, wave attack, overtopping, ice jamming). Borders between land and water are hardly ever stable: they erode and accrete all the time, which leads to phenomena such as dune formation and erosion on the coast, bank erosion and channel migration in rivers, channel and shoal formation in estuaries and coastal lagoons, and downwind extension of lakes.

The problem of local scour exists since man has started building structures (e.g. bridge piers, groins) in water that moves over a bed consisting of loose sediments. However, water and soil interact at a much wider range of scale levels, smaller as well as larger than that of a bridge pier or a groin.

Despite these practical connections, hydraulics and geotechnics have developed into rather independent disciplines. In this paper we will show how a closer collaboration between the two can be beneficial to the solution of a number of important practical problems and what role numerical and physical modelling can play therein.

II. MICRO-SCALE INTERACTIONS

Grain-to-grain interactions play a role in a variety of phenomena that are traditionally considered as belonging to both disciplines hydraulics and geotechnics. The focus in hydraulics is on superficial grain interaction and external shear stress loading, whereas in geotechnics it is on granular fabric, local pore pressures and corresponding internal stresses dominated by soil self weight. Because grain-to-grain interactions at micros-scale are not fully understood, both disciplines use primarily empirical methods for practical application.

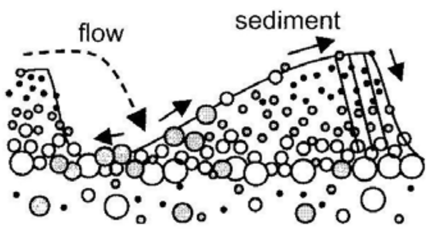

Figure 1. Intergranular processes at the lee side of river bedforms lead to vertical segregation of coarse and fine sediment

An obvious example is the behaviour of bedforms (ripples, dunes) on a mobile riverbed (Fig.1). The lee face of such a bedform propagates via an alternating and intermittent process of build-up and collapse of its slope. Since it influences the size and the shape of the bedforms as well as the grainsize stratification in the bed [5], it determines to a large extent the flow resistance and minimum navigable water depth, and it influences the river's long-term morphological evolution. Therefore, understanding these processes is an important issue in flood protection, river navigability and sustainable river management.

So far, this phenomenon is included in numerical models via empirical modules. Its numerical simulation is still in its infancy and requires sophisticated 3-D eddy-resolving flow modelling, combined with a dynamic model of grain motion that includes grain-to-grain interactions.

Another example is wave-induced sheetflow: under strong wave action, the top layer of a beach may fluidise during part of the wave cycle, thus behaving totally different from a sand bed where individual grains move now and then. Since this phenomenon is strongest during storms, when much sediment is in motion, it is of major importance to beach and dune stability.

Generally, downhill gravitational effects on sediment grains sliding or jumping over the bed play a key role in morphology, in rivers, estuaries, coastal waters and shallow shelf seas. Here, too, empirical submodels are the state of the art. There is a definite need to further improve and underpin them via detailed numerical model simulations combined with well-controlled laboratory experiments.

Alternating pressures influence the bed response to turbulence and waves. Pore pressure variations may penetrate relatively far into the bed [3], causing additional alternating groundwater flows and accompanying buoyancy near the surface. The interplay of hydraulic and geotechnical forces and processes at the water-sediment interface is evident, but complex and not well understood.

Dredgers know from hard experience what a small percentage of cohesive sediment can do to the strength of the bed [8]. Consequently, erosion of consolidated beds of cohesive sediment is as much a matter of geotechnics as of hydrodynamics. The implementation of the latest insights at this point into numerical models is on its way, but still not available.

Intertidal flat and saltmarsh formation in estuaries and tidal lagoons have a lot to do with the interaction of water motion, sediment transport, soil mechanics, vegetation and benthic organisms. The presence of millions of the latter per square metre greatly influences the bed composition and the bed erodibility. One of the many interesting issues in this area is the pattern formation at the edge of a saltmarsh, with cliff-erosion and tussock formation as a result of a complex interaction process between vegetation, soil properties and hydrodynamic forcing [19].

Figure 2. Smartsoils©: bacterial activities produce a bond between individual grains (see http://www.geodelft.nl)

Apart from natural phenomena, there is new scope for engineering, viz. pore-space engineering, at this micro-scale level. Recent developments in biochemical modification of soil properties may create a breakthrough in scour protection and erosion control (Fig. 2). Several so-called smartsoil concepts control with success permeability changes up to a hundred fold and/or strength of granular materials up to a 5 fold. One can turn loose sand into sandstone within weeks!

At a larger scale, creating a negative pore pressure via beach drainage may lead to better beach stability (for instance, see http://cozone.org.uk/wll/11hs.pdf). Soil formation, a key process to combat delta subsidence, e.g. [7], can be artificially stimulated, for instance by stabilising newly formed soil. As yet, numerical modelling in support of this kind of applications is restricted to parametric or empirical effect modelling at a larger scale.

III. MESO-SCALE EFFECTS

A. Local scour near structures

Flow around structures may create local scour, which may jeopardize structure's integrity. Therefore, this scour has to be taken into account in the design, e.g. of the foundation. In natural flows, the depth of scour will vary with time, depending on the flow conditions and the bed geometry in the vicinity of the structure. In such situations, a probabilistic analysis of the scour depth may be necessary.

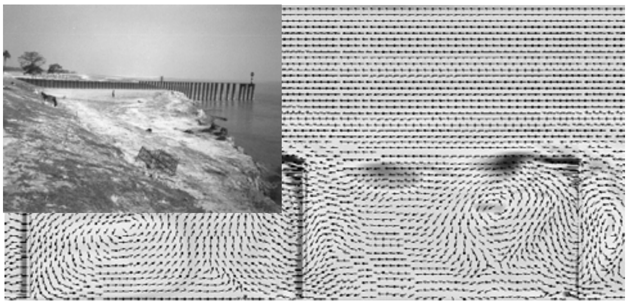

Figure 3. A computed instantaneous velocity field in case of a permeable groin

Numerical modelling of this type of phenomena is coming within reach as far as the flow pattern is concerned (Fig. 3; see [20]). Modelling 3-D scour processes, however, is not entirely trivial, primarily because the relationship between the sediment transport rate and the bed shear stress is probably different from that in uniform rectilinear shear flow. Yet, the latter is the basis of most empirical transport capacity formulae.

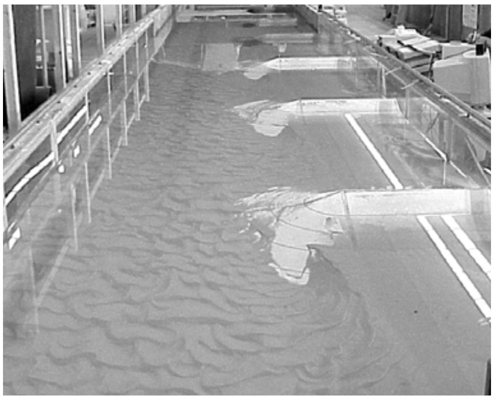

Figure 4. Local scour near groyne heads [22]

Examples of engineering structures giving rise to scour that may jeopardize their own stability are bridge piers, groins (Fig. 4) and training walls in rivers and estuaries, breakwaters and seawalls on the shore [22], and oilrigs, pipelines and windmill parks in shallow shelf seas. The accuracy of prediction of the maximum scour depth – and in some cases also the range of bed level variation – is strongly correlated to the risk of failure, hence the construction and maintenance costs.

Scour also plays a role in the burial (an later possibly unburial) of objects, such as pollutant containers, or war gear, into loose-sediment beds. Mine burial (e.g. http://www.onr.navy.mil/sci_tech/32/321/docs/cg/04/cgfo ster.pdf or http://cumin.ceegs.ohio-state.edu/~khatton/wip/poster_Agu_12_04.ppt) is just one example.

In certain situations, local scour can be beneficial. An example is self-burial of offshore pipelines, which occurs if they gradually sink into their own scour hole. This may save the costs of trenching or riprap coverage. As yet, numerical models of this phenomenon make use of standard concepts, such as clear-water scour, e.g. [9]. On the other hand scour may enhance upheave of buried leight-weight pipelines, particularly in liquefiable seabeds [17]. As the seabed in shallow shelf seas is morphologically active, further development of live-bed scour and bed liquefaction models (i.e. with a continuous transport component) is needed.

B. *Dike destabilisation*

According to a recent inventory of the probability of flooding of a number of dike rings in the Netherlands [13], the most serious threat to dike stability is piping, i.e. the formation of a fine sediment-conveying seepage-channel network just under dikes and dams. The susceptibility of a dike to piping depends on dike geometry and subsoil properties. Especially, geological anomalies such as ancient riverbeds may trigger this phenomenon. Understanding how these channels develop is only possible by bringing together knowledge of subsoil geology, soil mechanics, groundwater flow and sediment transport.

Figure 5. Piping, a serious threat to dike stability

Sellmeijer [15] developed a conceptual model for piping, projecting 3D reality to 2D. It combines hydraulics at micro scale and geotechnics at meso scale, in a consistent manner. The outcome reveals a typical behaviour: a self-healing potential until a critical hydraulic gradient and thereafter, progressive collapse. In the stable regime piping manifests at the lee-side toe of a dam as a peculiar sand boil (Fig. 5), and in the unstable regime a catastrophic breach may occur in a few hours (Fig. 6).

The suggested model has been validated on the basis of extensive physical tests and it is incorporated in a practical design tool (MSEEP). For a particular geological situation (Fig. 7), the natural variation in geometry and in relevant properties has been elaborated by a self-learning approach (neural-network) [16], which reveals dominant controlling parameters for this case and results in a simple and practical design rule:

$$H_c/L = \alpha D (kZ)^{-1/3} F[Z/L] \quad \text{for} \quad Z > L/20$$

Figure 6. Collapse in 4 hours initiated by piping (Japan)

Here, Z is the thickness of the piping layer, D the grain diameter, k the hydraulic permeability, and H_c/L the critical hydraulic gradient. The semi-empirical coefficient α incorporates microscopic effects, e.g. Reynolds number, grain weight and rolling friction [16].

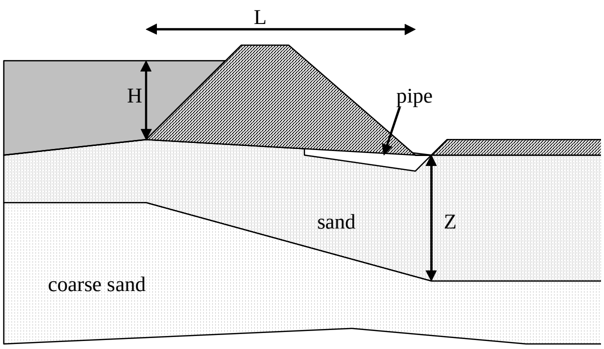

Figure 7. A specific situation prone to piping

Applying self-learning methods to evaluate (natural) variations in schematized situations is a promising new approach.

Another important dike failure mechanism is inner slope sliding due to overtopping. Due to alternate dehydration and saturation, the top layer loses strength. In fact, this is how most of the dikes in the southwest of The Netherlands failed during the 1953 flood disaster (Fig. 13). The amount and the frequency of overtopping a dike can sustain is still a topic of research. Clearly, it determines the height of the dike crest above the design water level (the freeboard or excess height), and hence influences the cost level of the flood defense system. As this freeboard can be different in different countries, it may lead to complications in case of transnational rivers (cf. the debate about the maximum possible discharge that can reach the Netherlands via the Rhine).

If a dike crest is too low and there is no space for a higher dike, sometimes a superstructure is built. Some examples are concrete Muralt superstructures on some dikes in the Netherlands, T-walls on the levees in New Orleans and the sheetpile in the crest of the Hondsbossche Sea Defence. Their purpose is to reduce overtopping.

Figure 8. Levee failure in New Orleans, 2005

Recent events in New Orleans have shown that these superstructures may fail under extreme conditions and destabilise the dike (Fig. 8). The probable causes, as understood from tests, are a combination of geotechnical and hydraulic processes, such as heavy overtopping, local scour, wall rotation, hydraulic shortcuts, piping and extreme soft soil deformation (peat layers). A proper design of such structures requires an intense interaction of expertise in surface water hydraulics, geohydrology and geotechnics.

C. *Toe scour and bank failure*

Another link between hydraulics and geotechnics concerns toe scour near dikes or riverbanks, which may lead to dike failure or bank collapse. Depending on the situation, this scour may be seasonal, which involves the risk of underestimating the maximum scour depth by lack of data under critical conditions. An example is the dike near Jiujiang City on the Yangtze River, China, which collapsed during the 1998 flood. Model computations [10] show that the scour depth at that location and at that point in time must have been significantly larger than expected. Fig. 9 shows an example of dike collapse, from the Red River in Vietnam.

Figure 9. Bank collapse along the Red River, Vietnam

A notorious example in The Netherlands are the dike failures along the Eastern Scheldt estuary, which occurred rather frequently until a few decades ago, when the toe protection was improved and the tidal motion was reduced by the construction of the storm surge barrier. The principal cause of these flow slides was the formation of deep gullies just adjacent to the dike (tidal gullies tend to stick to hard structures), which destabilised the subsoil and the dike body. Most probably these failures have been introduced by liquefaction in recent loosely packed sand deposits. Research into liquefaction and flow-sliding has been a concerted effort of Delft Hydraulics and GeoDelft since more than 15 years. De Groot en Mastbergen [6] discuss the typical shape of a scour hole (Fig. 10) as it develops with time. It develops due to morphological processes at micro scale and flow processes at macro scale, and at the steep edge of the hole local slope stability involves geotechnical aspects at meso scale, e.g. soil density, local pore pressures and internal friction.

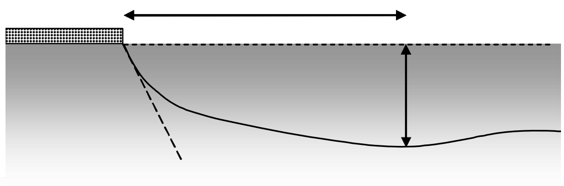

Figure 10. Typical geometry of a scour hole

Wave-induced or earthquake-induced pore pressure changes in the sand may cause sudden slope instability. A practical method for the evaluation of slope stability under cyclic pore pressure changes has been suggested by Barends & Ruygrok [2]. It includes preconsolidation, drainage and density effects. Elaboration of a massive slope failure at the Yamuna River bank in Bangladesh showed the critical slope angle for various soil constitutions (Fig. 11). This example reveals that the slope at the edge of a scour hole may gradually develop from a hydraulic viewpoint, but may show sudden drastic failure from a geotechnical viewpoint.

Tests and computations for wave-induced liquefaction phenomena are mostly performed under regular cyclic loading. In reality waves are random. The characteristic design value of random waves in hydraulic sense, i.e. the significant wave height, may be significantly different from an identical characteristic design value in geotechnical sense. For wave-induced liquefaction, a series of waves of smaller size seems more essential than fewer larger waves. The corresponding geotechnically significant wave height is less that the 'hydraulic' one, even down to 60%. Therefore, a moderate storm may already cause liquefied submerged slides [1]. For the interpretation of design values for hydraulic-geotechnical phenomena the aspect of randomness of loading needs special attention.

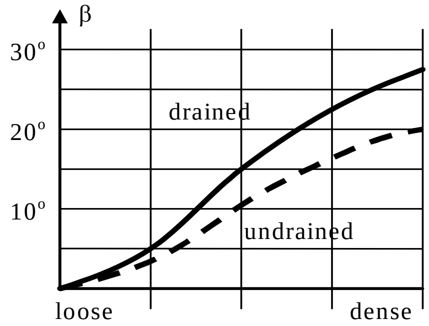

Figure 11. Critical slope angles of submerged sandy slopes subjected to cyclic wave-induced pore-pressure changes

D. Bank erosion and floodplain management

In natural rivers and estuaries, bank erosion is a ubiquitous phenomenon. It plays a key role in the functioning of the riparian ecosystem, since every part of the floodplain, including its vegetation cover, is eroded sooner or later and replaced by water, and – later on – by fresh deposits and new pioneer vegetation (Fig. 12). Thus the vegetation is intermittently rejuvenated, which enhances biodiversity. The rate of bank erosion is determined not only by the flow velocity and the water depth near the bank, but also by soil parameters and by the presence or absence of live vegetation.

Figure 12. Channel migration replaces old climax vegetation by new pioneer vegetation

In regulated rivers, the alignment is usually fixed and bank erosion and channel migration are prevented. This means that the floodplains tend to keep on silting up and that the riparian vegetation has time to reach its climax state. Floodplain lowering and rejuvenation then become maintenance activities [4].

An important additional problem is the pollution of the floodplain top layer, often with heavy metals. If heavily polluted, this material may not be removed and placed elsewhere. One way of coping with this problem is to dredge commercially valuable lower sand layers from under the top layer (for instance, see http://www.rijkswaterstaat.nl/rws/dww/home/assets/pdf/Folder_onderzuigen_22feb05def.pdf). The key issue in this scheme is the stability of the top layer during the dredging process. Knowing how to control this is a matter of combining knowledge on soil, groundwater mechanics and soil pollution.

Some recent river restoration schemes leave room for a certain degree of controlled bank erosion. This raises the issue, however, how to keep bank erosion under control without totally suppressing it. Here, again, the interaction of hydrodynamics, morphology, soil mechanics and the role of vegetation is the key process. Bank erosion modelling is still very much empirically based. Often, the water depth and the flow velocity near the bank are taken as the drivers, and the erosion resistance of the bank as an empirical coefficient [11].

E. Breach growth

The debate on a shift of policy from flood prevention to flood risk management [18] puts high demands on our prediction and simulation capabilities concerning dike breaching and flooding processes. Recently developed overland flow models (for instance, see http://wldelft.nl/soft/fls/int/overland.pdf) can describe the inundation process on the basis of a digital terrain model, but the location of the breach and the magnitude of the discharge through it need to be assumed. Adding geotechnical information and modelling expertise, especially concerning breach growth, would greatly enhance the predictive value of this type of model, especially because this process of breach growth also depends on the geometry of the foreland and the composition of the subsoil. Semi-empirical breach growth models are now under development ([21], [25]), but there seems to be scope for further enhancement of the geotechnical component.

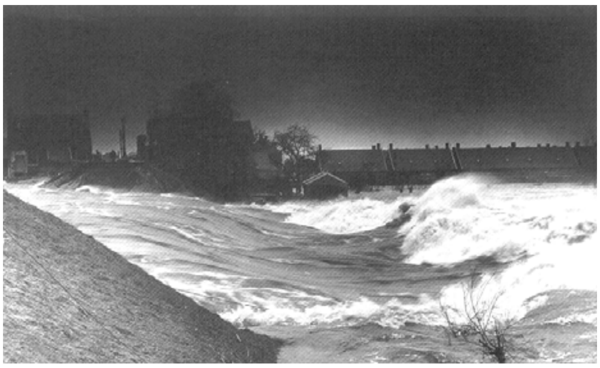

Figure 13. Dike breach, Papendrecht, 1953

A most important issue in dike breaching is to know in advance the specific locations where the structure is most vulnerable to breaching, so as to develop proper mitigating measures. Also, once a breach develops under storm or high water level conditions, one should know how to realise a quick provisional closure of the breach. Whether numerical models can play a role in such an emergency situation remains to be seen, but they certainly can in the development of contingency plans.

F. *Dune erosion*

Sandy coasts are not only attractive to tourists, but also to coastal managers, since they are flexible and, provided that the dune ridge is sufficiently wide, able to absorb dune erosion events. Even if the coast is globally stable, storm events may give rise to dune erosion, which is compensated by accretion under calmer conditions. The cross-shore extent of dune erosion during a single storm event is difficult to predict, even in probabilistic terms. This means that coastal managers take the safe side when defining the setback lines, i.e. the lines behind which safety against erosion is guaranteed. Since this is the most relevant to beach resorts, where the seaside is of great economical value, such a conservative approach means a loss of economic opportunities. Better predictions require a combination of hydraulic and geotechnical knowledge and expertise.

As stated above, recent geotechnical research has revealed that soil properties can be engineered using bacteria (see http://www.geodelft.nl). This might be an option for dune face stabilisation, thus preventing or reducing dune erosion (Fig. 14). An interesting follow-up question is what the beach will do once the dune face has been stabilised. Hard structures, such as sea walls, are known to yield a lowering of the beach, e.g. [22].

Figure 14. Dune erosion, can it be prevented?

Another important issue related to sandy coasts is the embedding of hard structures, such as buildings or boulevards. Especially the connection with the adjacent sandy coast turns out to be susceptible to erosion or accretion. How this works, how it can be predicted quantitatively and how problems can be prevented or mitigated are points of further joint research at the interface of the two disciplines.

IV. FAR-FIELD EFFECTS

Depending on the situation, a structure may not only give rise to scour and deposition in its immediate vicinity, but also further downstream, for instance via the formation of vortex streets, or nearshore circulations. These may extend over a substantial distance from the structure and usually turn out to be very efficient in picking up sediment, thus causing distal morphological effects

The so-called groin flames in rivers are an example (Fig. 15). These are large-scale patterns of erosion and deposition related to and induced by groins. Although present-day numerical models produce similar phenomena. e.g. [23] and [24], the underlying mechanisms are still partly in the dark. The modelling of sediment transport in the vortex streets shed from the groynes is probably the weakest point in the chain. Detailed 3-D vortex-resolving simulation models, including a dynamic model of grain motion and grain-grain interactions, may be of help to develop a better parametric description of this effect.

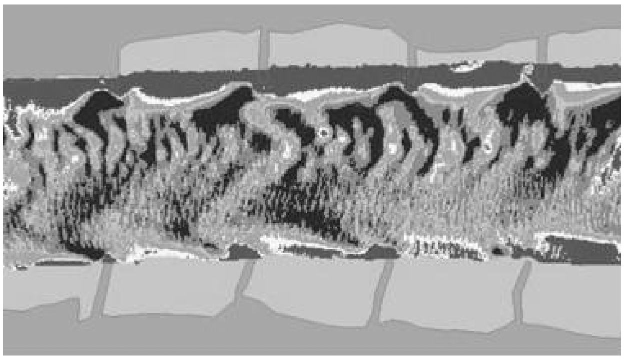

Figure 15. Groin flames in the river Waal, The Netherlands

A coastal example of larger-scale effects is the end effect of a series of shore-parallel breakwaters (Fig. 16). The local effect of these structures is positive, in that they keep the coastline in place, but the distal effect is negative: severe beach erosion at the downdrift end. In fact, the problem is not solved, but displaced. Such end effects are known from many coastal protection schemes. In fact, the phenomenon manifests itself wherever the longshore transport picks up after having been artificially interrupted (Fig. 17).

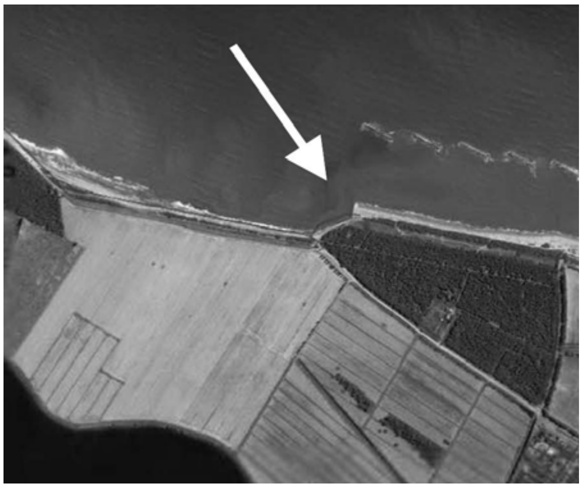

Figure 16. Beach erosion at the downdrift end of a series of shore-parallel breakwaters, Ravenna, Italy

Models describing this type of phenomena have been around for quite some time [12], but they assume immediate availability of the coastal sediment whenever there is an erosion tendency. Later on, erosion reducing factors such as cliff resistance and engineering works have been included in the models, but the soil mechanical component is still open to improvement.

A combination of far-field effects may give rise to a change in the morphological response, like in the case of an offshore windmill park, offshore sand mining, or offshore hydrocarbon mining, which may trigger an eigenmode of the seabed morphology [14].

These large-scale effects can usually be described with simpler models than micro- and meso-scale effects. Empirical sediment transport formulae in combination with an adequate flow model are usually sufficient.

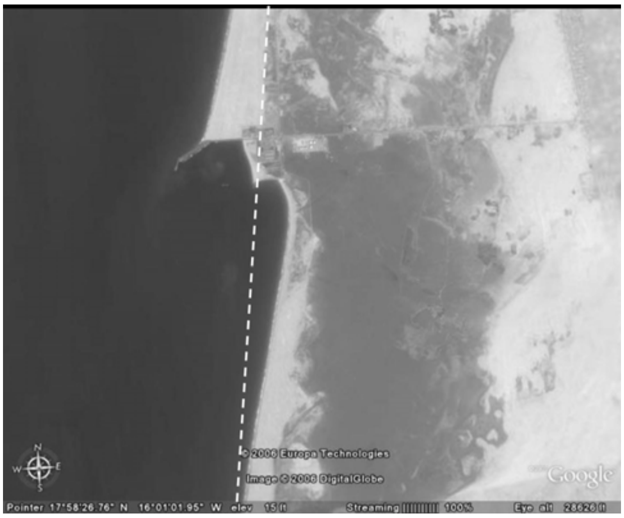

Figure 17. Downdrift erosion due to interruption of the longshore drift at Port de l'Amitié, Nouakchott, Mauretania (dashed line indicates the position of the original coastline)

V. Conclusion

Hydraulics and geotechnics meet each other in a wide variety of phenomena that are relevant to civil engineering and delta management. They can strengthen each other in describing, analysing and modelling these phenomena. Therefore, bringing these disciplines together in one institute, like the envisaged Delta-institute in The Netherlands, offers excellent perspectives of innovation in these sectors.

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