

Cyclic morphologic changes of the ebb-tidal delta, Texel Inlet, The Netherlands



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Received 11 November 1987; accepted in revised form 25 March 1988

Key words: Cyclic, ebb-tidal deltas, Frisian Islands, morphodynamics, tidal inlets, Wadden Sea

Abstract

Cyclic morphological changes occur in the ebb-tidal delta system of Texel Inlet (The Netherlands). This geomorphological cycle lasts about 70 years. The cycle starts with the development of a main ebb channel in the southern half of the inlet. A large ebb delta shoal forms north of this ebb channel. The shoal grows upwards into the inter- to supra-tidal zone and moves eastwards under the influence of wind and waves. The flood channel north of the shoal is forced to rotate clockwise, and it approaches the shoreline of Texel. The marginal ebb channel in the southern part of the inlet develops due to the tidal currents deflected to the south by the eastward migrating shoal and slowly rotates clockwise, forced by the small flood marginal channel that adjoins the mainland coast to the east. The cycle is completed by shoal attachment to the southern tip of Texel Island, which causes the northern marginal channel of the inlet to be buried. The eastward migration rate of the shoals is about 60–70 m per year, which involves a sediment transport rate of order of 580 to $0.64 \times 10^6 \text{ m}^3/\text{year}$.

Introduction

The geomorphology of ebb-tidal deltas is controlled by tidal currents, waves and wind, and their interaction (Oertel, 1972, 1975; Hubbard, 1975; Hubbard et al., 1977, 1979; Nummedal et al., 1977; Nummedal & Penland, 1981; Hayes, 1980). Conversely, the geomorphology of ebb deltas can influence the dynamic processes, especially the flow pattern. In many cases, currents have determined the orientation and the distribution of shoals. In other cases, shoals clearly function as shields that determine the pattern of inlet water flow (Oertel, 1977). The interrelationships between the morphology of ebb deltas and the dynamic conditions commonly result in their cyclic development (Oertel, 1977; FitzGerald, 1984). Geomorphological

records clearly show a similar cyclic pattern in Texel Inlet (Fig. 1) and other tidal inlets along the Wadden Islands (Joustra, 1971; Luck, 1976; Rijkswaterstaat, 1). Nevertheless, the interrelationships between the geomorphology and the dynamic processes are not clearly understood. The dynamic processes in the ebb-tidal delta of Texel Inlet are particularly complex, caused by the interaction of strong currents, waves and wind. The cyclic geomorphological pattern in the ebb delta of Texel Inlet is discussed in this paper with attention centred on the dominant processes involved.

The evidence presented here is based mainly on the analysis of historical data. The tidal range is calculated from records of the tidal station at Den Helder, wind data are compiled from records of 10 years (1965–1975) from the southern shore of the

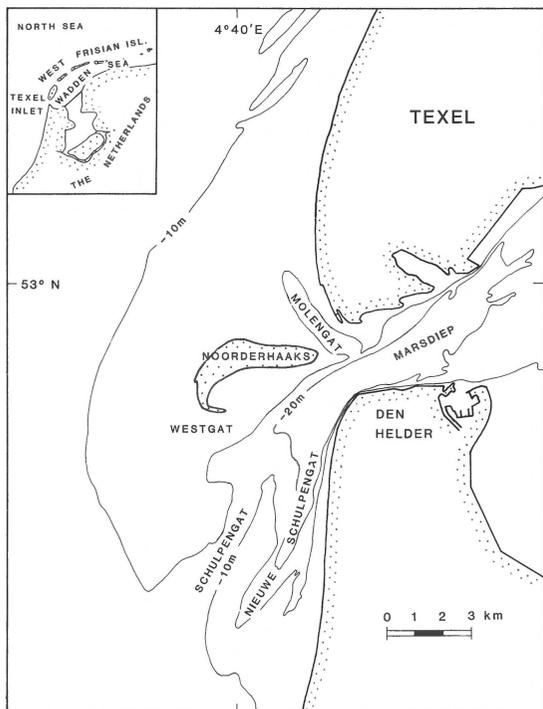


Fig. 1. Location map of the ebb-tidal delta of Texel Inlet.

inlet. Mean wave height is calculated from observations by the Ministry of Transport and Public Works and the wave energy flux is calculated by the method of Nummedal & Stephen (1978). Old hydrographic charts and echo-sounding maps from the Ministry of Transport and Public Works provide an extensive data base to reconstruct the morphologic evolution of the ebb delta and the inlet.

Physical setting

Texel Inlet (Fig. 1) is the most westerly tidal inlet of the West Frisian Islands. It faces west, is about 2.5 km wide and the maximum depth is about 50 m. The well-developed ebb-tidal delta extends ca. 10 km seawards. The tidal basin behind the inlet (the most western part of the Wadden Sea) covers 713 km², 122 km² of which (17%) are intertidal flats. The inlet is almost entirely tide-influenced, as the input of fresh water is negligible. Supply of clay

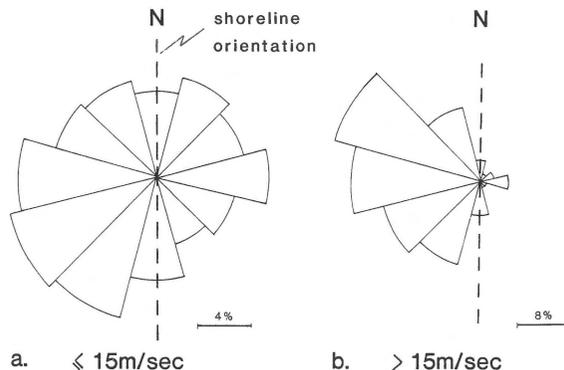


Fig. 2. a. Directional distribution of wind (<15 m/s, 97% of total observations). b. Directional distribution of wind (>15 m/s, 3% of total observations) (data from the Ministry of Transport and Public Works).

and sand to the Wadden Sea occurs from the North Sea through the inlets (Postma, 1982; Sha, 1987; Wiersma & Van Alphen, 1988). At present there is hardly any direct input of terrestrial sediments, especially sand-size particles, into this part of the Wadden Sea.

The inlet has a semidiurnal tide with a diurnal inequality. The mean tidal range is 1.38 m and the mean tidal prism is about 10⁹ m³ (Reus, 1980). The yearly average mean wind velocity is 7 m/s (Eisma, 1980). The prevailing wind is from the WSW; dominant winds (≥7 Beaufort) come mainly from the

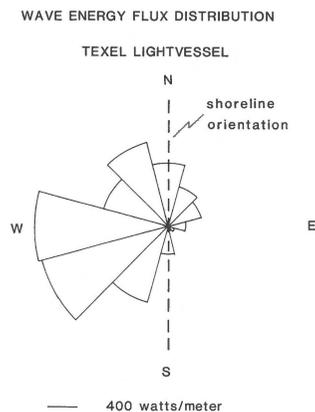


Fig. 3. Wave energy flux distribution (data from the Ministry of Transport and Public Works). Wave data were compiled from data based on regular measurements in 1975.

WNW (Fig. 2a & b). The mean wave height offshore is 1.16m. Most of the mean annual wave energy flux is directed normally to the shoreline (Fig. 3). The resultant longshore component of wave power is relatively small, so that no significant longshore sediment transport is generated by waves. Southward sand transport may occur during storms as storm waves are mainly from the WNW. Tidal currents do transport sand northwards in the

offshore area along the Dutch coast, but no reliable quantitative estimate has been made of the amounts involved.

Sand transport pattern

A short summary of the sand transport pattern in the ebb delta of Texel Inlet (Fig. 4; Sha, 1987) is

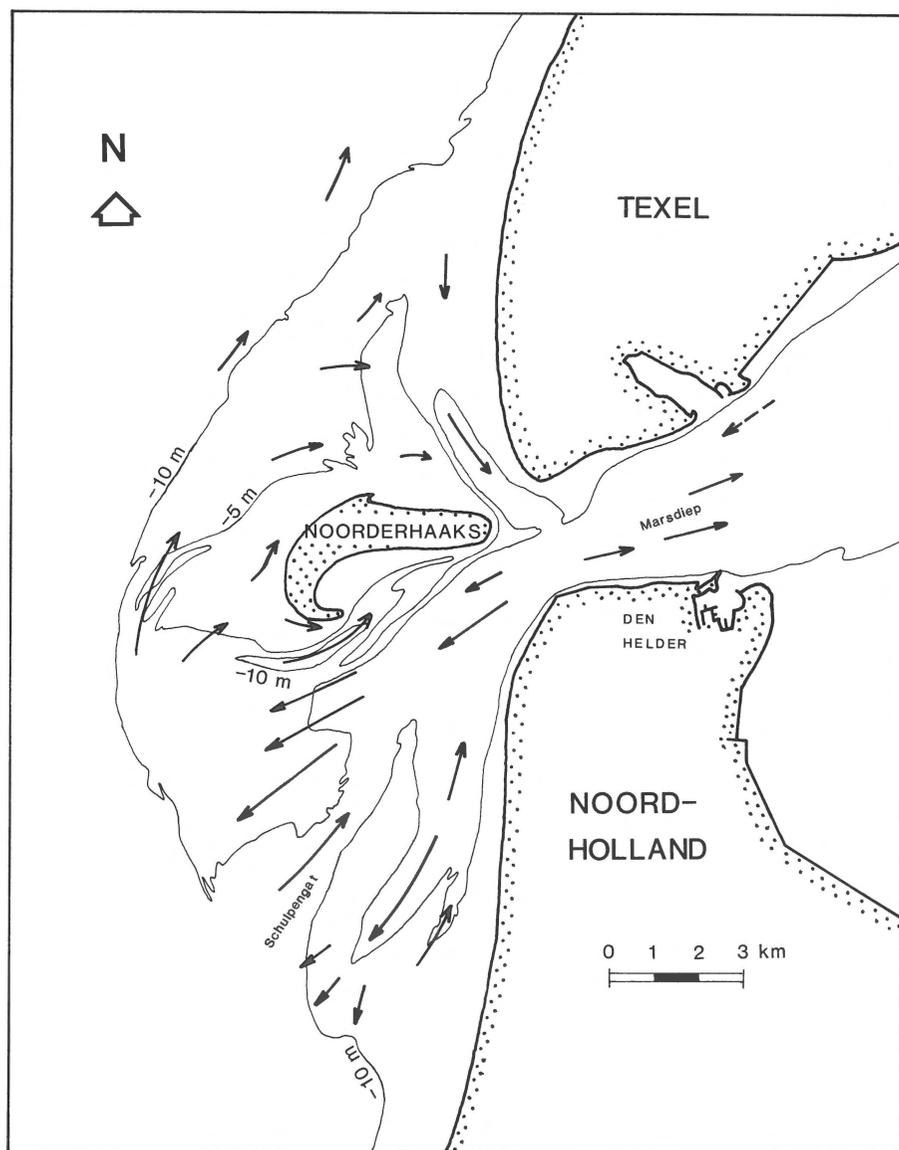


Fig. 4. The sand transport model proposed (Sha, 1987). It is drawn on the basis of bedforms, sedimentary structures, geomorphology and current data. Arrows indicate the net sand transport direction.

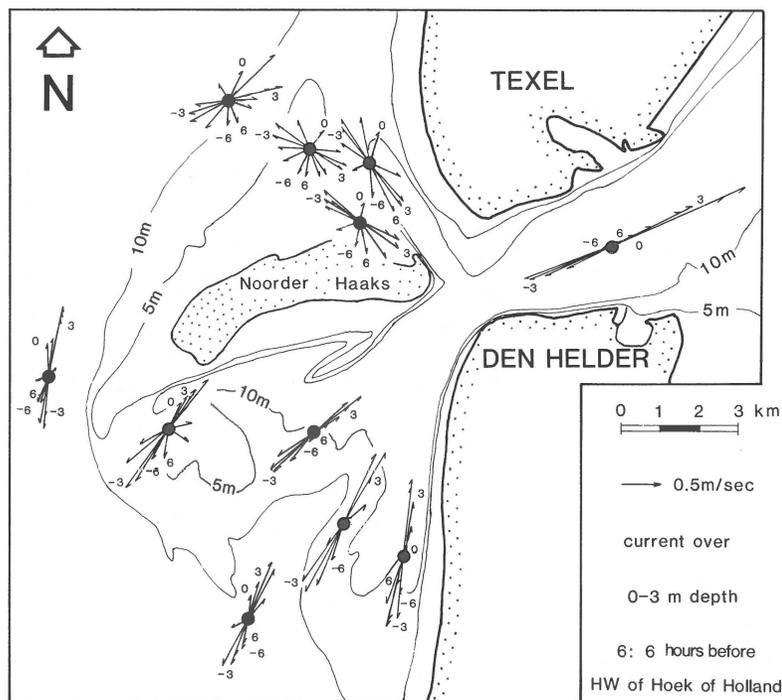


Fig. 5. Tidal current velocities and directions in the ebb delta and Texel Inlet during a 12 hour period compiled from the Stream Atlas of the Netherlands, 1963. The current velocities are averaged in the upper most 3 m below the water surface. Figures indicate the time (hours) before or after HW of Hoek of Holland. Arrows indicate the current direction at that time and their lengths represent current velocities (see legend).

given here to allow a clearer picture of the geomorphological processes that are active.

Tidal currents along the coast supply sand from the North Sea and the adjacent coasts into the ebb-tidal delta system. Sand is transported to and from the ebb delta through adjoining ebb and flood channels, and also into the Wadden Sea. Relatively strong flood tidal currents transport sand northwards along the seaward margin of the ebb-tidal delta. Some of this sand is trapped in the northern delta shoal due to the weak rotational current pattern there (Fig. 5). The interaction between the shore-parallel tidal currents and the shore-normal tidal currents through the inlet means that currents are relatively strong south of the inlet and relatively weak north of it (Sha, 1987). Part of the sand returns to the main inlet channel through the Molengat channel. Westerly waves modify the shoal morphology. They erode the seaward margin of the shoal and deposit sand on its landward margin.

Aeolian processes shape the surface of the supratidal part of the shoals, and transport sand to the east.

Cyclic morphologic evolution

Shoal migration in the northern part of the ebb delta

For the northern part of the ebb delta, the reconstructions based on the historical hydrographic charts show that the shoals which extend above the mean low water line move eastward, i.e. in the predominant direction of wind and waves, and that the associated channels north of them also shift eastward with a clockwise rotation.

In the period 1851–1908, the shoal 'Onrust' (Fig. 6) thus moved 4 km to the east (about 67 m/year). This shoal first appeared near LWL in 1838. Between 1908–1916, the shoal attached to Texel Island and now forms the sand spit at its southern tip.

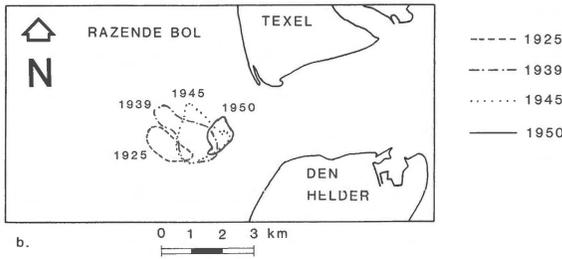
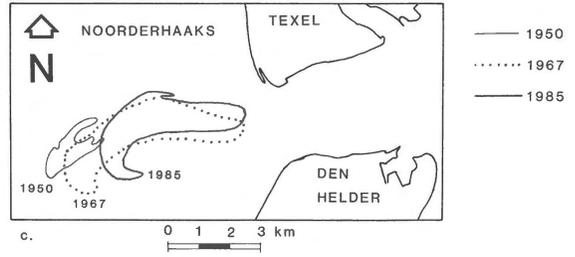
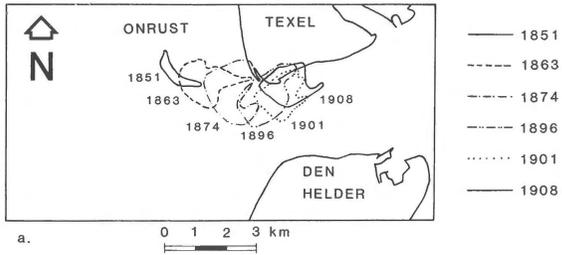


Fig. 6. Migration of the inter- to supra-tidal shoals in the ebb delta of Texel Inlet. a. The shoal 'Onrust' from 1851 to 1908. b. The shoal 'Razende Bol' from 1925 to 1950. c. The shoal 'Noorderhaaks' from 1950 to 1981.

The Noordergat channel north of the 'Onrust' was already situated in front of, and parallel to the shoreline of Texel in 1796 (Fig. 8a). It approached the southern tip of the island and was filled by the 'Onrust' shoal when it became attached to the island.

The present Noorderhaaks shoal (Fig. 7) is a

combination of two shoals, 'Razende Bol' and 'Noorderhaaks' (Fig. 6b & 6c). The Razende Bol (Fig. 6b) has been permanently above the mean low water line since 1925. It migrated 1.5 km eastward from 1925 to 1950 (60 m/year). Between 1956 and 1960, the shoal 'Noorderhaaks' (Fig. 6c) west of the Razende Bol extended eastward and the two

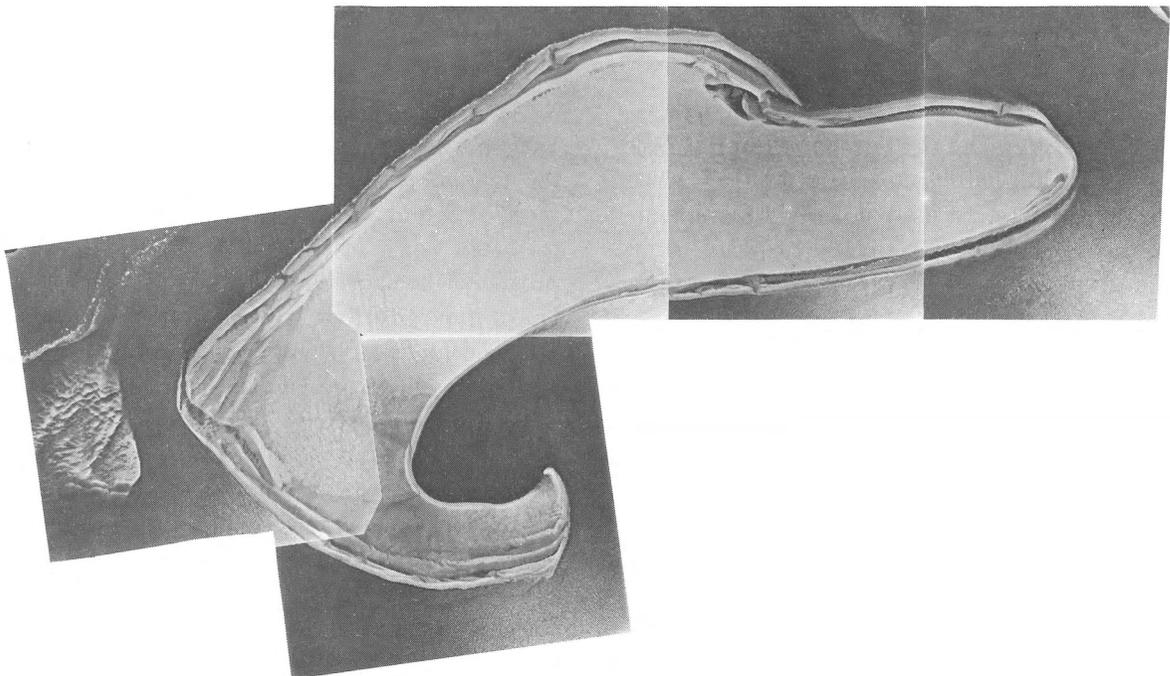


Fig. 7. Aerial Photo showing the present shape of Noorderhaaks (from Ministry of Transport and Public Works). Refer to Fig. 1 for location and scale of Noorderhaaks.

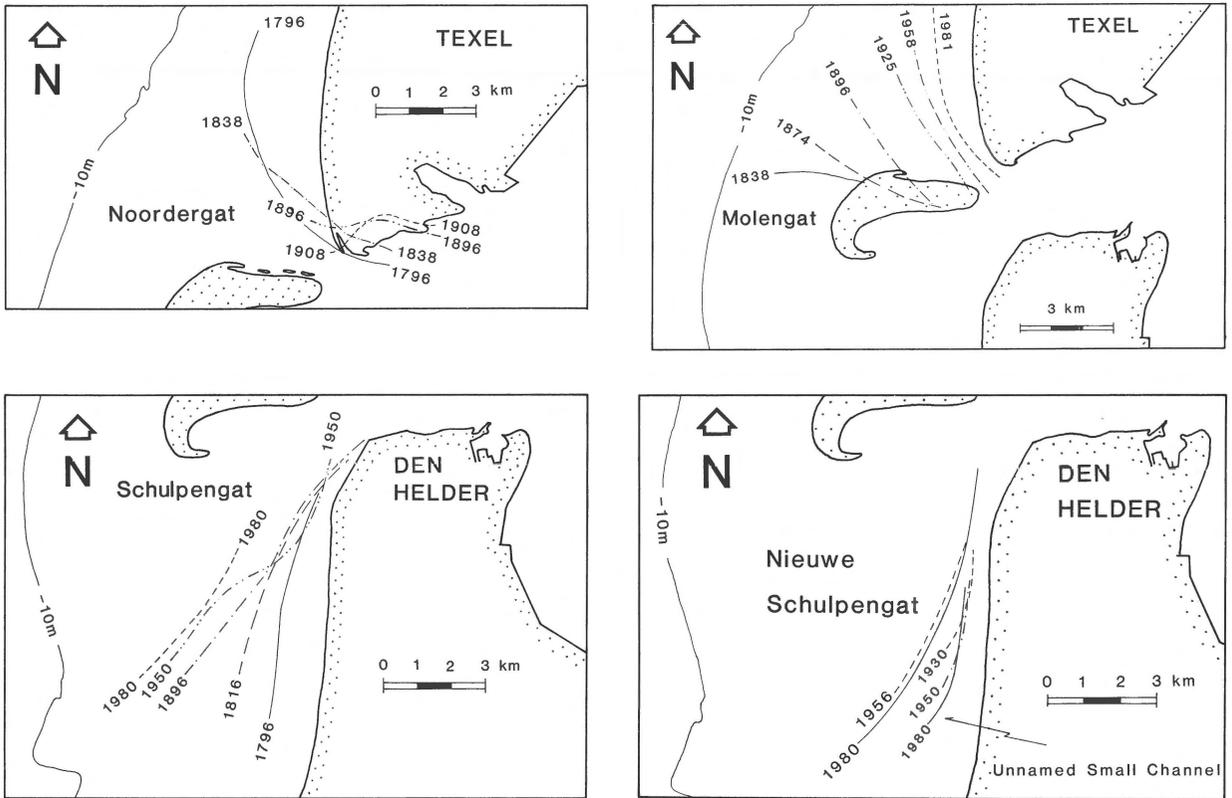


Fig. 8. Migration of some channels in the ebb delta of Texel Inlet in time. a. (upper left). The channel axis of the Noordergat channel 1796–1908. b. (upper right). The channel axis of the Molengat channel 1838–1981. c. (lower left). The channel axis of the Schulpengat channel 1796–1980. d. (lower right). The channel axis of the Nieuwe Schulpengat channel 1930–1980.

shoals coalesced. The eastern margin of this coalesced shoal has hardly moved further east since 1950, but the western margin of the shoal underwent rapid erosion and retreated eastward about 1.7 km from 1950 to 1980 (34 m/year). There is a sand spit at the southwest of the shoal. This spit has gradually recurved to the east under the influence of waves. The Molengat channel north of Noorderhaaks (Fig. 8b) has rotated about 90 degrees between 1838–1981. At present the Molengat channel nearly parallels the shoreline of Texel Island and the axis of the channel is approaching the shoreline.

These two morphological cycles are shown on cross section A'–Q' (Fig. 9b & 9c). In the period from 1796 to 1851 the Noordergat channel approached the shoreline, resulting in shoreline retreat there. As 'Onrust' moved into the inlet after

1851, the shoreline at that point prograded due to the channel recurving (Fig. 8a, line 1908) and the shoal attaching itself to the island. The shoreline retreated again after 1896 as the Molengat approached the shoreline (Fig. 9c). If the Noorderhaaks moves further into the inlet and becomes attached to Texel Island in the future, shore progradation will occur again at the same place.

For the period since 1796, two major cycles can be distinguished in the appearance and migration of the tidal shoals above MLW. It took about 70–80 years from the emergence of 'Onrust' in about 1838 to its shore-attachment in about 1908–1916. The second cycle has been going on for the last 60 years, since the Razende Bol shoal emerged permanently above MLW in 1925. It is suggested that this cycle terminates as the shoal becomes attached to Texel Island.

Main ebb channel development

The channel development along the shoreline south of the inlet has a complex pattern. Generally, the channels developed parallel to the shoreline, and rotated slowly clockwise, while, at the same time, a new, small channel developed to the east. This can be seen in the Schulpengat (Fig. 8c & 8d).

The development of the main ebb channel in the ebb-tidal delta is related to the cyclic shoal migration. The Westgat (the main channel to the west) reached its maximum extension in 1838 (Fig. 10a). Subsequently, as the shoal gradually moved into the inlet, the current strengths to the west and southwest increased. In this period (1863–1896), the main channel (Westgat-Marsdiep) deepened further (Fig. 9d) and the tidal shield between the main ebb channel and the Schulpengat channel was breached in 1896 (Fig. 10b). After the shoal 'Onrust' became attached to the shoreline, the Westgat channel reached a maximum depth of 18 m in 1925 (Fig. 9d). Through onshore migration of the second shoal (Razende Bol) by 1950 (Fig. 10c), the tidal currents were deflected to the south, since the shoal was located in front of the inlet mouth. The southward extension of the spit (Fig. 10c & Fig. 1) at the eastern end of the shoal shows the interaction between the ebb currents and the eastward moving shoal. This caused the shoaling of the Westgat (1925–1981) (Fig. 9d) and the development of the 'Nieuwe Schulpengat' (Fig. 9e & Fig. 1). Correspondingly, the tidal discharge decreased in the Westgat and increased in the Nieuwe Schulpengat.

Ebb-tidal delta volumetric change, sand budget and sand transport rate

The total sand budget of the ebb delta calculated using the method of Dean & Walton (1975) is $490 \times 10^6 \text{ m}^3$. Due to the migration and growth of the shoal complex in the north, there is a cyclic change in the distribution of sand in the ebb-tidal delta. When the bar reached its maximum size for the two examples known, the part above the mean water line was about 6.5 km long and over 1 km wide and contained at least $32.5 \times 10^6 \text{ m}^3$ sand (about 7% of the total sand budget). During onshore migration, it may have decreased in size, but it still brought a large amount of sand to the shore-

line. For example, in about 1908, the shoal 'Onrust' attached to the shore which thus gained sand of a minimum of $9.2 \times 10^6 \text{ m}^3$ (about 2% of the total sand budget).

The estimated eastward sediment transport rate by shoal migration was on average at least $0.61 \times 10^6 \text{ m}^3/\text{year}$. This is about 0.13% of the total sand budget in the delta.

Discussion

Mechanism of the Cyclic Morphologic Process

A comparison of the length of the main ebb channel (measured on the -10 m line) in different years and the tidal prism at different inlets along the West Frisian Islands shows a strong correlation between the two (Fig. 11). Although the channel length for a certain tidal prism at an inlet is variable through time, the upper and lower limits of the channel length in the history of the inlets correlate almost linearly with the tidal prism through that inlet. This means that when the channel length is below the upper limit, the channel is in a developing stage, and when it approaches the upper limit, the main ebb channel loses its efficiency, starts to silt up and then is progressively abandoned.

The formation of the shoal is related to the development of the main ebb channel. Conversely, the shoal migration influences the channel development.

As the main ebb channel develops, it extends seawards and interrupts the shore-parallel tidal currents (Sha, 1987). This leads to a large dynamic 'shadow' area north of the main channel and as a result, there a large delta shoal develops and the water depth decreases significantly over a large area. Onshore waves dominate the shallow bottom, form swash bars and push them onshore. When the shoal rises above the low water line, aeolian transport becomes important. It dominates as the shoal becomes supra-tidal. Thus, both the westerly waves and winds result in the eastward migration of the 'Onrust' and 'Noorderhaaks'. The importance of aeolian transport on the Noorderhaaks was observed during field work in 1986 (Fig.

a.

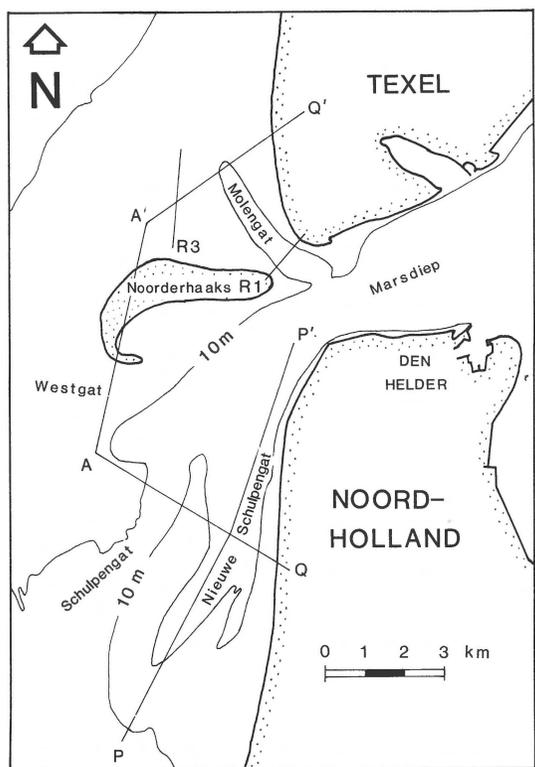
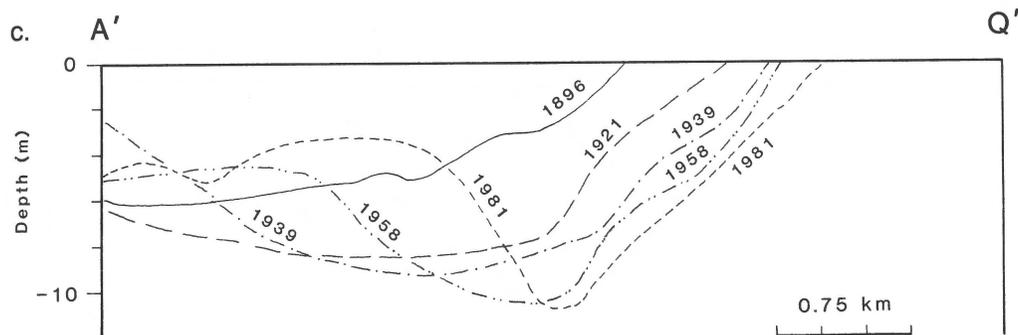
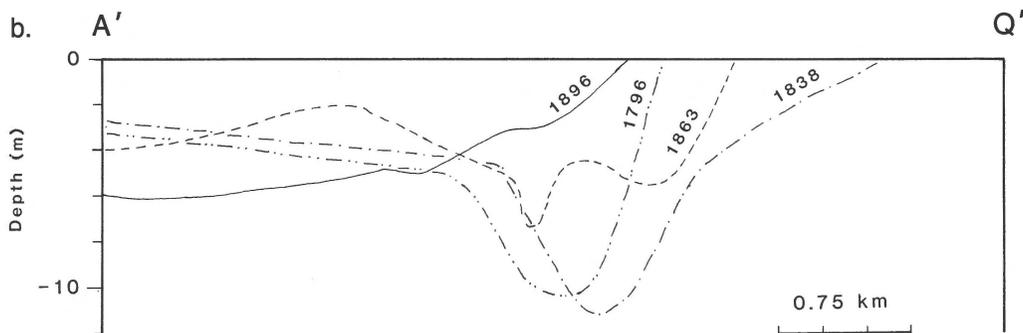
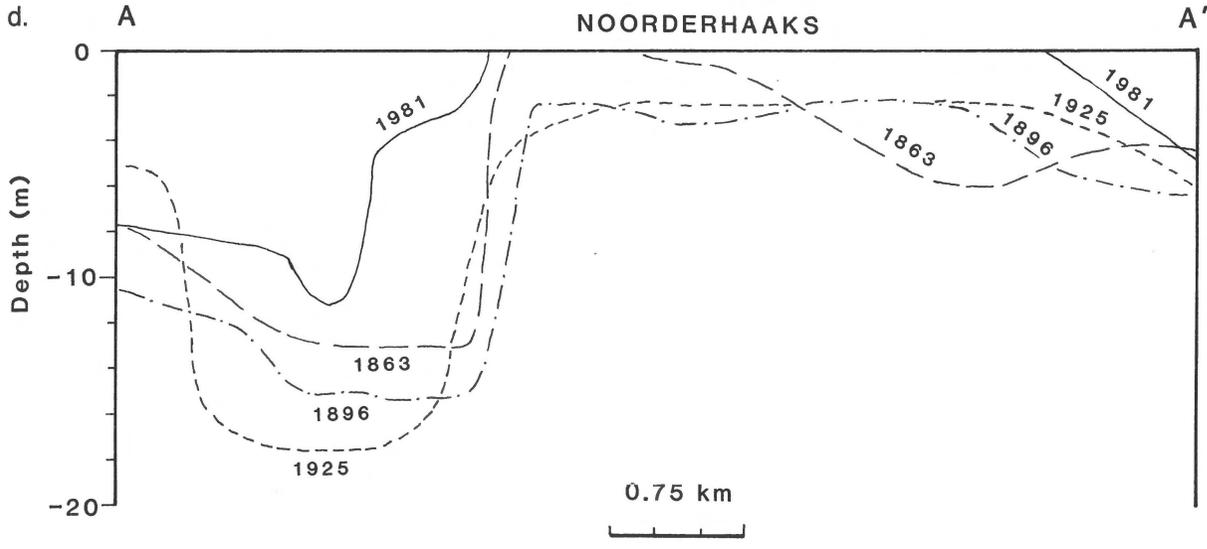


Fig. 9. Geomorphological evolution along several cross-sections in the ebb delta of Texel Inlet.

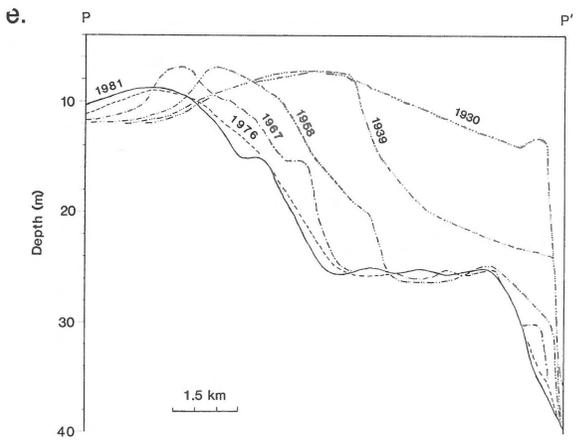
a. Location map (left).

b & c. Cross-section A'-Q' from 1796-1896 and from 1896-1981 (below).





d. Cross-section A-A' from 1863-1981 (above).



e. Cross-section P-P' from 1930-1981 (left).

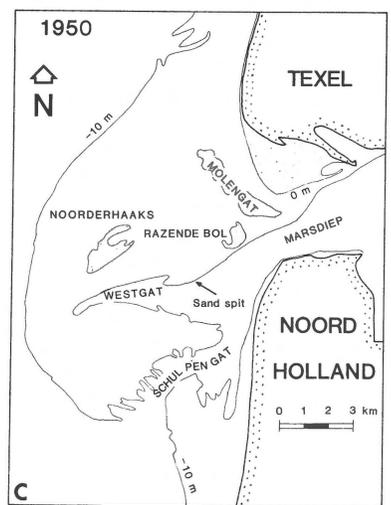
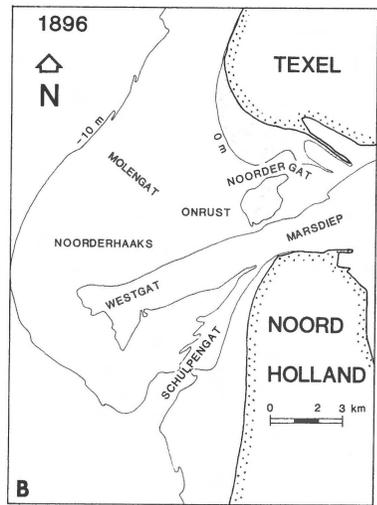
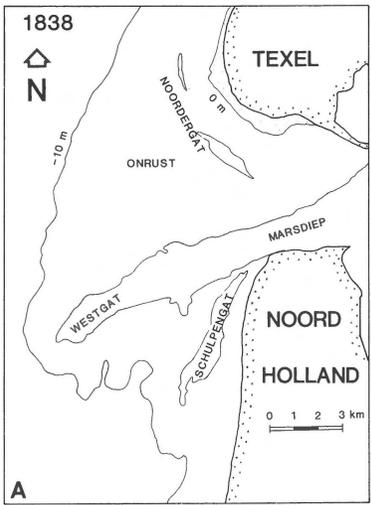


Fig. 10. The bathymetric maps of the ebb delta in (a) 1838, (b) 1896 and (c) 1950. Note the sand spit and channel-shoal development.

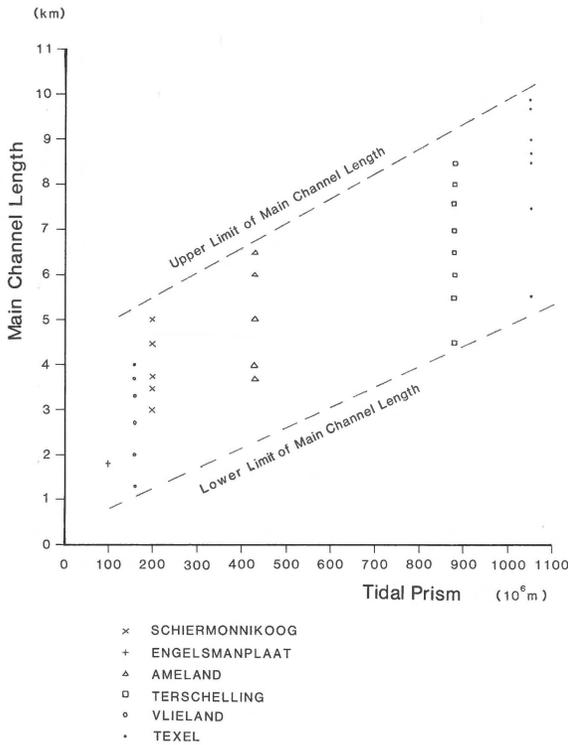


Fig. 11. Relation of the main ebb channel length in different years (1796–1981) and the tidal prism in various inlets along the West Frisian Islands. Tidal prism through individual inlets is assumed to be stable.

12). The runnel along the beach of the shoal was completely filled during a single storm.

Due to the eastward migration of the shoals, the channels north of them are forced to rotate clockwise. As the shoal moves close to the inlet mouth, depending on its location relative to the main ebb channel and the inlet, there can be two distinct outcomes:

In Case 1 (representing the actual situation between 1838–1916) (Fig. 13A), the shoal is located well away from the main ebb channel (Fig. 13 A.2.). The main ebb channel is not strongly influenced by the onshore migration of the shoal. During the process of the shoal becoming attached to the island (Fig. 13 A.3.), the inlet channel cross-section decreases and tidal currents become strong in the main channel. At this stage, a new cycle may start due to the development of the main channel (Fig. 13 A.4.).

In Case 2 (representing the situation since 1925) (Fig. 13B), the shoal is located more in front of the inlet mouth and the onshore migration (Fig. 10c & Fig. 13 B.2, B.3 & B.4) of the shoal deflects the ebb currents to the south. The spit extended southwestward from the east margin of the Razende Bol (Fig. 10c). This led to silting of the Westgat and the development of the Nieuwe Schulpengat after 1925. After a further attachment of the shoal to Texel Island, the main ebb channel may breach again through the area to the west (cf. FitzGerald, 1982), where waves eroded the sand during the first cycle. A new cycle then starts (Fig. 13 B.5 & B.6).

The end of a cycle and beginning of a new one are likely to be triggered by storm waves, e.g. the attachment of 'Onrust' to the Texel Island was completed by a storm (Ministry of Transport and Public Works, Department of Hoorn, 1987, pers. comm.).

One aspect, which is not discussed due to a lack of data, is the influence of the closure of the IJsselmeer-Afsluitdijk in 1932 on the ebb-tidal delta. It is known that the tidal range increased after the closure of the dike, and possibly there has been an increase of the tidal prism. This may have extended the main channel seaward or switched the channel orientation. The closure of the dike may influence consequently the cycle duration.

Practical implication: the future of the Noorderhaaks

Analogous to the history of Onrust, the Noorderhaaks shoal is expected to move into the inlet and to become attached to the southern tip of Texel Island. At the same time, the main ebb channel may open up again to the west. However, recent data do not show a continued and significant eastward migration of the shoal. This may be related to the stabilization of the southern shoreline of the inlet by construction works. If, and when the shoal moves eastward towards the inlet, it will decrease the cross sectional area of the inlet and thereby increase tidal current velocities. Stronger tidal currents erode the east side of the shoal. Eastward shoal migration thus is balanced by erosion of the east side of the shoal by tidal currents. Slow northward migration, however, does occur. Possibly, a



Fig. 12. Photo of eolian dunes on Noorderhaaks (May 12, 1986). Note that the wind dunes migrated towards a wet beach runnel. Hand shovel/spatula for scale.

further northerly movement of the Noorderhaaks will lessen the influence of the ebb currents coming through the inlet on the shoal and finally will lead to attachment of the shoal to the land during a storm event.

Geological record

The observed cyclic process of the ebb delta of the inlet system has important implications for the understanding of the geological record. For example, inlet sequences produced by successive shoreward moving shoals will show that paleo-channels are successively buried by shoals, in an overall progradational barrier/spit sequence (Fig. 14). In ebb deltas, the preservation of sand bodies is the end-product of several cyclic processes. Due to the frequent migration of the channel-shoal system, the preservation of a single channel sequence may be rare, instead a sequence of channel floor sheet

deposits, formed by the lateral shifting of channels, especially of marginal channels, is more likely to be preserved. In systems with a scale and dynamics comparable to those of Texel Inlet, these surfaces will normally be formed at depths of about 10–20 m (depending on the inlet size).

Conclusion

The ebb-tidal delta and inlet system of Texel Inlet, shows a cyclic morphologic development. This process involves a maximum extension of the main ebb channel, formation of a large delta shoal to the north, onshore migration of the shoal, and flood channel rotation north of the inlet. The cycle ends with the attachment of the shoal to Texel Island. The development and silting up of the main ebb channel are related to the tidal prism of the inlet (Fig. 11) and are influenced by onshore migration

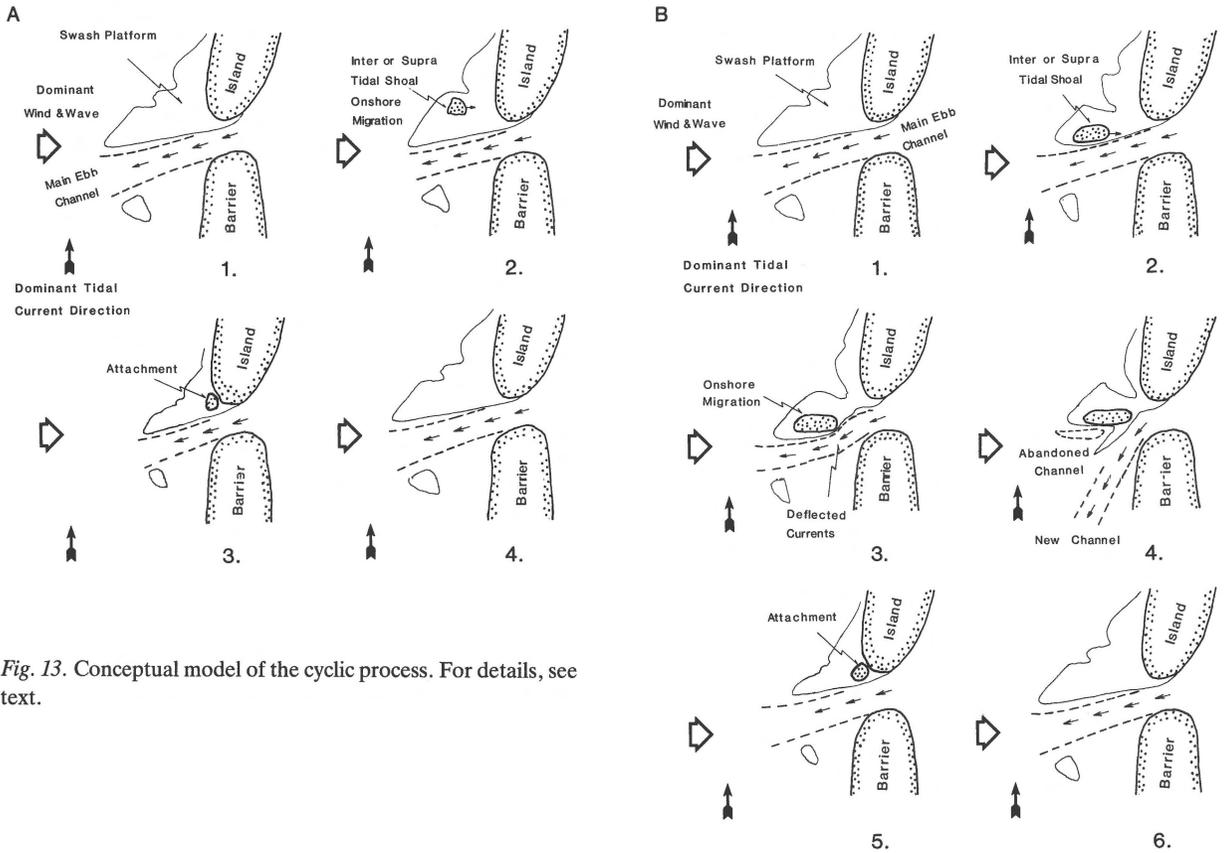


Fig. 13. Conceptual model of the cyclic process. For details, see text.

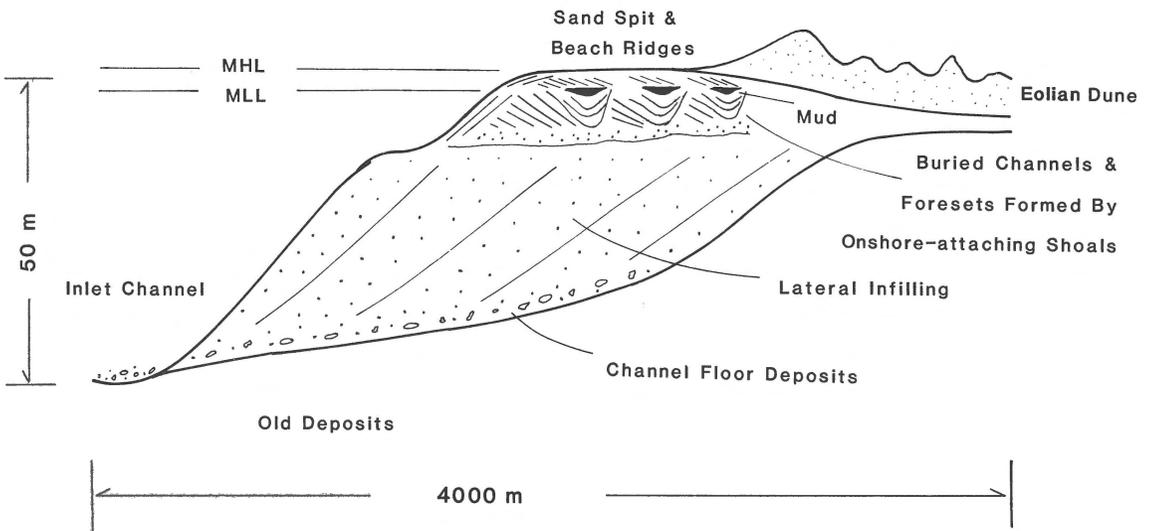


Fig. 14. A schematic model showing the inlet sequence produced by inlet migration and successive onshore-attaching shoals.

and enlargement of the shoal-complex.

The morphologic development of the inlet-delta system clearly is a feed back response system of dynamic processes and morphologic development. In fact, it is in this way that the inlet maintains dynamic equilibrium.

Eastward migration of Noorderhaaks is presently slowed down by erosion of ebb currents from the inlet at the eastern margin of the shoal. Eastward migration may possibly resume after the shoal has shifted further north and it may ultimately become attached to Texel Island, probably during a major storm.

Acknowledgements

I acknowledge the support of the Netherlands Institute for Sea Research and of the Ministry of Transport and Public Works for this research project. I thank Dr P.L. de Boer, Dr D. Eisma, Dr S.D. Nio, Dr Tj.C.E. Van Weering and Dr J. Wiersma, for their very active support and help during the research work. Special thanks are due to Dr P.L. de Boer, in particular for his very careful work on my crude manuscript. Very helpful checking and suggestions from Dr D. Eisma, Tj. C.E. Van Weering, J. Wiersma, and many others, are appreciated. Dr J.S. Pethick has corrected the language of the manuscript. The study department of the Ministry of Transport and Public Works in Hoorn supplied many valuable data, which is gratefully acknowledged. Finally, my thanks are for the help at sea by the captains and crew of the Mss. 'Navicula' and 'Aurelia' and the technicians of the Netherlands Institute for Sea Research.

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