CHAPTER 156

Assessment of Coastal Processes for the Design and the Construction of the Zeepipe Landfall in Zeebrugge

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ABSTRACT

Early 1991, Statoil started with the installation of a 40 inch diameter gas pipeline between the Sleipner and later Troll field in the Norvegian sector of the North Sea and the harbour of Zeebrugge on the Belgian coast.

The connection between the offshore and the onshore pipeline was performed in August 1991, in the landfall area of Zeebrugge. The design and the construction of the landfall in the nearshore area required an extensive survey and engineering program taking the environmental parameters and the coastal processes into account.

1. INTRODUCTION

The Zeepipe Gas Pipeline Project for the delivery of natural gas extracted from the Sleipner field was approved by the Norwegian Parliament in December 1986. Den Norske Stats Oljeselskap A.S. (Statoil, Stavanger - Norway) is the operator on behalf of the Zeepipe owners and is responsible for the planning, the construction and the operation of the Zeepipe system.

Zeepipe is the largest offshore pipelaying project undertaken up till 1991. Approximately 810 km of 40", 38 km of 30" and 230 km of 20" pipelines will go through the Norwegian, Danish, German, Dutch and Belgian sectors of the North Sea.

Zeepipe is a pipeline system for the transport of gas from the Norwegian Sleipner field to Zeebrugge on the Belgian Coast.

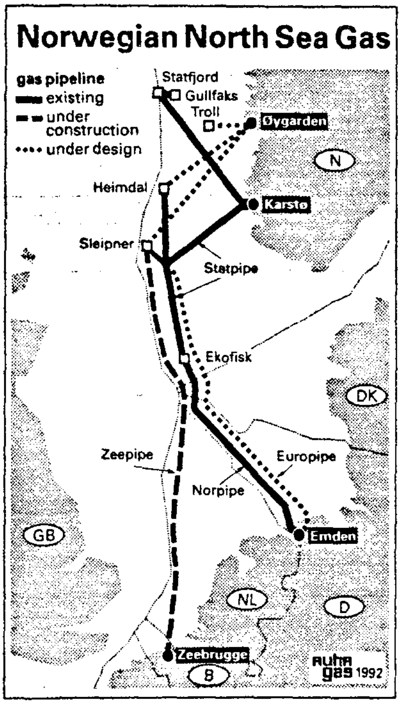


Figure 1 : Description of Zeepipe system

In the North Sea (figure 1) the Zeepipe system will also be connected to the existing Statpipe- and Norpipe systems (Stolberg - 1992).

Via the terminal in Zeebrugge Zeepipe will be connected to the European gas distribution system. The gas will be distributed to purchasers from Germany, France, Belgium, the Netherlands and Spain.

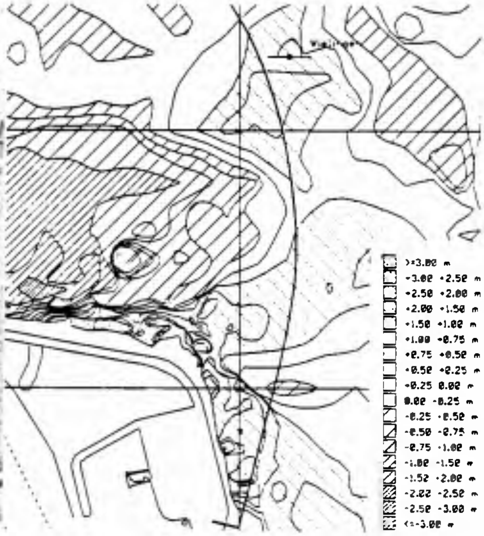
The landfall of Zeepipe was planned to be in the Zeebrugge Harbour with the Landfall Valve Station (LVS) on the LNG-peninsula of Zeebrugge.
The design of the landfall had to take all nearshore coastal processes, geotechnical and sedimentological characteristics of the area into account to allow proper pipelaying and pipeline operation.

2. THE ZEEBRUGGE LANDFALL AREA

2.1. General site description and morphology

The landfall area on the Belgian Coast is located on the eastside of the Zeebrugge Harbour southeastern dam (rubblemound breakwater). The offshore area in which Zeepipe is installed is a part of the Southern Bight of the North Sea.

The area (figure 2) under concern for Zeepipe and the landfall is part of the fore-delta of the Western Scheldt estuary. Strong hydrodynamic, morphological and sedimentological conditions are characterizing this region of the North Sea where relative "young" quaternary deposits occur on the seabed.
Some kilometers north of the Zeebrugge harbour, two important shipping lanes are draining most of the in- and outgoing traffic to and from the Western Scheldt estuary, i.e. the Scheur and the Wielingen.



<u>Figure 2</u> :
Nearshore and shore approach area for the landfall of Zeepipe in Zeebrugge.

<u>Figure 3</u> :
Differential map (1990-1986) of the shore approach and beach area processed with DTM.

In order to assess the environmental conditions related to the bottom lithology and the soil conditions during the engineering, detailed pre-laying surveys have been executed.

2.2. <u>Bathymetric survey</u>

In order to provide recent and detailed data on the seabed topography, bathymetric surveys have been carried out in a corridor, centered along the Zeepipe axis (corridor width : 1000 m).

The bathymetric survey has been executed using the Atlas Fansweep 200 kHz swathe echosounder (sweep angle : 126°) simultaneously with a dual-beam Atlas Deso 20 echosounder (detection of loose mud deposits).

The swathe echosounder Fansweep, used for the first time on operational basis, delivered very detailed bathymetric maps with on average 1 depth value/m² (Vessel used : "M.S Pegasus" from Geoconsult A.S). Tide-reduction was achieved by using the official tide-gauges and 1 extra shorebased and 1 extra offshore selfrecording tide gauge.

Bathymetric survey data were processed using advanced DTM-processing (Digital Terrain Model) on HP-9000 CAD-computer to produce the combined survey maps.

Parallel to these bathymetric surveys, all available existing hydrographic data from 1980 to 1990 and in a 5 km wide corridor along Zeepipe were collected (data-base Haecon N.V.) and processed as differential maps to determine natural and man-made recent morphological changes of the seabed (e.g. fig. 3)

2.3. Geophysical survey :

Because of the known soil heterogeneity and the local presence of outcropping tertiary geologic layers, shallow seismic survey has been conducted in the surveyed Zeepipe corridor in order to pilot the geotechnical/geologic soil investigation.

A shallow seismic survey was carried out by using alternatively a 50 J EG & G Minisparker and a Thompson Pipeliner (3,5 + 7 kHz) in order to optimize penetration.

The significant seismic reflectors are associated with important layers for the design, i.e. :

a. the erosion surface of the tertiary layers marking the transition from tertiary to recent quaternary deposits (often associated with gravel) ;
b. overconsolidated tertiary clay layers

In combination with the shallow seismic tracks, side-scan sonar surveys were executed (apparatus : Klein 531T (100 kHz) + EG & G260 (100 kHz)) in order to identify :

a. possible obstacles (wrecks, cables, ...) ; 4 significant obstacles were detected ;
b. morphologic bottom features such as ripples, sand-waves, ... reflecting residual bed-load transport directions ; ripple and sand-wave fields crossing Zeepipe at Bol van Heist Sandbank could clearly be identified.

All geophysical data were digitally transferred to the HP-9000 CAD and Intergraph 6040 workstation for combined map production.

2.4. Geotechnical/geologic surveys

Different geotechnical/geologic surveys with corings and piezocone penetration testings (PCPT) were executed along the Zeepipe route in the offshore and onshore part to ascertain/verify geophysical survey and to get

geotechnical information for the design of the pipelaying and landfall works.
Vessels mobilised for the soil investigation include the self-elevating platform "Tijl II" (HSS) and the "M.S. Bucentaur" (Farmand Survey).

Coring was executed by continuous sampling of the soil layers (figure 4). Piezocone penetration testing was done to investigate soil cone resistance, sleeve friction and pore-water pressure ; geotechnical parameters such as friction angle, relative density and undrained shear strength could be deduced.

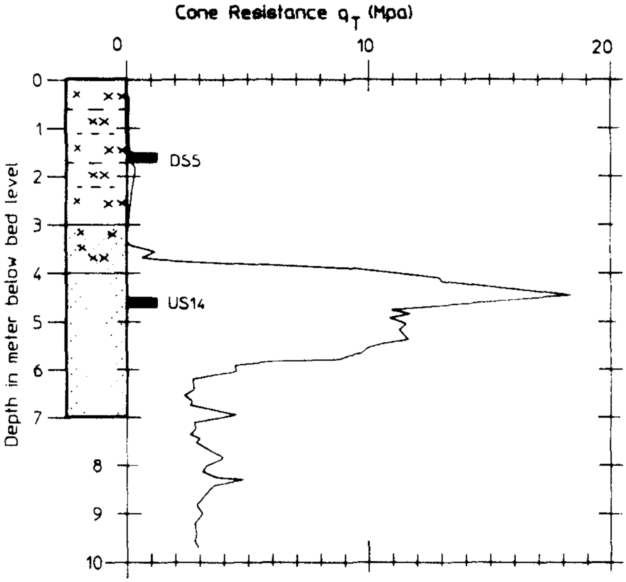


Figure 4 : Example of geotechnical/geologic soil investigation results.
Coring + PCPT in the landfall area.

All geotechnical data were digitally transferred to the HP-9000 CAD and Intergraph 6040 system for the production of the combined survey maps.

In selected boreholes wireline loggings (density and resistivity logs) were done in order to assess porosity and density of the soil layers. These parameters are important for the assessment of soil compaction degree and liquefaction potential.

2.5. Geochemical analysis

During the geotechnical survey, soil samples were frozen and stored in a freezing installation.
According to the Convention of Oslo, chemical characteristics of the samples were analysed in order to assess a possible contamination and/or contaminant remobilization during trenching/dredging. Heavy metal and organic compound contents were found to be below base quality reference material contents.

2.6. Hydrometeorological conditions

Vertical tides are important in this part of the North Sea. Tides in Zeebrugge range from 3,00 m (Neap Tide) to 5,00 m (Spring Tide).

The tidal currents (SW : ebb ; NE : flood) in relation to the vertical tide are the strongest and highest in the shallow parts of the North Sea such as the Belgian nearshore area. Offshore current roses are either elliptical or circular and nearshore ones are usually bidirectional. This means that offshore water is constantly flowing while nearshore water circulation is similar to that in an estuary.

Storm surges may be particularly dramatic in this part of the North Sea because of wind set-up combined with the relative high tidal ranges. Dominant wind directions are SW with NW for storm conditions.
NW, N and NE-winds together with atmospheric depressions are able to cause considerable wind set-ups (up to 2,00 m in extreme conditions).

Wave action is intense in the Southern Bight due to shallow water depths, refraction, reflection and diffraction. Registered wave characteristics show typically short period and steep waves.

3. COASTAL PROCESSES

3.1. Tidal gulleys

The morphological evolution in the nearshore and landfall area is influenced by the tidal mechanisms in the North Sea, by the discharge of the Scheldt river and also, locally, by the Zeebrugge harbour. Long term seabed variations are due to the continuous development of the ebb - and flood gulley system.

Ebb - and flood gulleys are closed in the direction of the residual sediment transport, are typically approx. 4

to 10 km long, approx 1 to 4 km wide and have depths of 0,50 m to 3,50 m w.r.t. original seabed ; they interact closely and form a hydrodynamic and physical equilibrium. Flood gulleys are shallow and more frequent close to shore. Ebb gulleys are deeper and located more offshore.

3.2. Sand banks and sand waves

The Zealand banks located in front of the Belgian coast seem to be stable sand bodies. During storms, some of the megaripples and sand waves on top of the banks are crest-cutted but soon afterwards they are built-up again. Sand wave height is approximately 1,5 m to 2,5 m and the wave length ranges between 100 and 200 meters.

3.3. Turbidity maximum area (TMA) and sediment transport

The nearshore area is characterized by a much varying bottom lithology with essentially the presence of muddy tidal flats (C. De Meyer, B. Malherbe 1986).
Intensive field measurements have been executed in this part of the North Sea since several years. Such measurements allowed to establish a general residual sediment transport pattern. Figure 5 shows the variation of tidal elevation, tidal currents and suspension concentration. They revealed the existence of an encounter zone of residual sediment transports in front of the Belgian Coast which results in a marine Turbidity Maximum Area (T.M.A.).

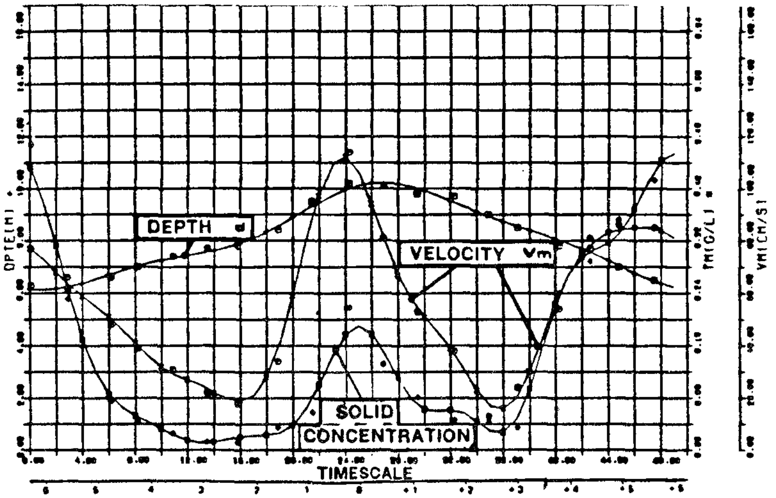


Figure 5 : Simultaneous recordings of tidal elevation, tidal currents and suspension concentration close to the Landfall Area.

The T.M.A. is characterized by a loose mud deposit layer (thickness : 0,50 - 1,00 m) trapped within the T.M.A. The volume of this loose mud is significant and may amount to several millions of tons dry material. The T.M.A. centre of gravity is further moving in function of the residual flow and sediment transport.

3.4. Beach stability

The sandy beach on the landfall area could be subjected to morphological changes due to wave response; these morphological changes are unavoidable modifications in the beach equilibrium profile.

Before the extension works of the Zeebrugge harbour started (1977), the seabottom level was almost equal to MSL -7,00. Afterwards, a progressive accretion / sedimentation has taken place which is due to human activities (disposal of dredged material) and to natural sand accumulation (trapping of longshore transport by eastern dam of Zeebrugge).

4. LANDFALL OF ZEEPIPE : DESIGN ASPECTS

4.1. Design criteria for the landfall

The different criteria used for the design of the Zeepipe Landfall are related to the following parameters :

a. geotechnical stability of the pipeline
b. foundation of future marina dams which have to cross the Zeepipe route
c. depth of the marina access channel and basin
d. technical requirements for trenching, dredging and pulling equipment
e. tidal gulley development
f. allowable stresses in the pipeline
g. pipelaying/welding requirements
h. beach erosion
i. risk analysis of the pipe in relation to navigation
j. authority requirements

The geotechnical stability is related to the liquefaction potential and the differential settlements.
Liquefaction is likely to occur if no artificial backfill of the trench is done. Natural backfill with sand is very progressive and repeated liquefying effects by short wave action may consequently cause progressive pipeline uplift during trench filling. Natural backfill with loose mud deposits (ρsat = 1,05 - 1,15) will generate more

consolidated mud deposits (ρsat = 1,40 - 1,50) after ca. 1 or 2 months ; this may as well cause progressive pipeline uplift.

The different marina master plans in this area foresee the building of a sanddune (visual barrier) and a marina dam which will be built as a rubble-mound breakwater with a foundation of soil-replaced sand.

The sanddune (height : ca. 30 m) is likely to cause the most important settlements (up to 0,20 m). Due to the heterogeneity of the quaternary seabed soil layers (mud, sand, peat) differential settlements are to be expected.

The foundation of the marina breakwater dam will need an excavation of the natural quaternary soil layers with poor bearing capacity. Cutter suction excavation works have to be avoided in the close vicinity of Zeepipe. Because there is a limit to the trenching depth of Zeepipe an adapted foundation solution has to be found for this part of the marina breakwater.

The marina access-channel and basin (design depth is greater than TOP : top of pipe) will have to be designed in accordance with the Zeepipe "as-laid" profile.

The equipment for the trenching, dredging and pipe-pulling have given water depth requirements, i.e. ca. MSL - 9,00 m (Castoro II pulling barge ; Vlaanderen XIX CSD). Therefore, the minimal trench depth is fixed to MSL - 9,00 m.
As can be seen on figure 3 a typical flood tidal gulley has been developing close to the Zeepipe route since the end of the Zeebrugge Harbour Works. Such tidal gulley developments are followed carefully by interpreting differential bathymetric maps.

Regarding the soil-pipeline interaction it can be stated that the pipeline profile will influence the stresses in the pipeline itself. The stresses may be induced by temperature loads, internal pressure settlements (soil deformation), seismic waves, etc ... Thorough stress calculations have been executed, taking the particular soil conditions in this area into account.

To execute the dry tie-in (in a dry cofferdam) of the spool and the landfall-string by welding a maximum working depth within the cofferdam of - 7,25 m MSL was required. This means that the tie-in part of the landfall has been designed at that level.
Beach erosion phenomena may affect the submarine beach up to a depth of ca. - 6,50 m MSL. Beach erosion and equilibrium slope calculations was done to evaluate beach

response to the design storm conditions (water level + wave height with e.g. R.P. of 50 years). Recent beach evolution can also be assessed from differential mapping.

Damaging risks during operation and within life-time (50 years) had to be assessed in order to design the appropriate cover and/or protection. Therefore a risk-analysis was executed taking all external factors such as navigation, maintenance dredging, ship's collision, etc ... into account.
This risk analysis has a major relevance for the crossing of the Scheur and Wielingen navigation channels.

Authority requirements refer essentially to the soil conditions after pipeline-installation and the stability of the existing harbour infrastructure. Furthermore an environmental impact assessment (EIA) had to be done in relation to the planned dredging, trenching and dumping works (LDC/OSCON-convention).

4.2. Landfall design alternatives

The arrival point of the offshore pipeline was fixed, i.e. the Landfall Valve Station on the LNG-peninsula of the Zeebrugge Harbour.

Three major landfall alternatives were identified :

1. by directional drilling and subsequent pipe-pulling from sea to land ;
2. by micro-tunnelling with a pushed tunnel from shore to sea ;
3. with a conventional sheet-piled cofferdam for the shore approach in combination with a cross-breakwater solution.

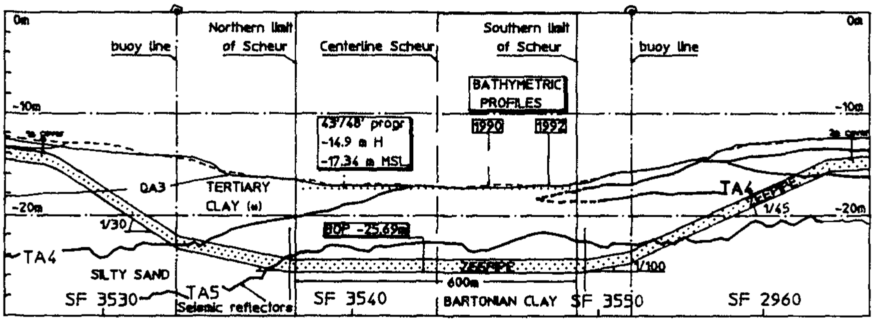
The original landfall-concepts, by directional drilling or micro-tunneling, were abandoned due to the particular soil conditions and the close vicinity of the rocky rubble-mound breakwater.

The alternative concept basically consists of a conventional landfall, with a sheet-piled cofferdam into which the pipeline, is pulled ashore. The pipeline is tied into a spool piece that goes through and above the breakwater and which connects Zeepipe to the Landfall Valve Station.

4.3. Trenching/dredging of the pipeline

In order to fulfill the design-criteria the pipeline had to be trenched over a wide stretch of the nearshore and shore-approach area.

In the Scheur shipping channel the trench was designed taking into account the risk-analysis, the soil conditions with quaternary sands and tertiairy overconsolidated clays and silts, the authority requirements and the plans for deepening the channel. On figure 6 the designed crossing of the Scheur is illustrated. The trenching works were designed to be executed by seagoing cutter suction dredgers. (N. Pille, F. Warnier, B. Lahousse - 1988).



<u>Figure 6</u> : Design of the crossing of the Scheur shipping lane by Zeepipe.

In the "Wielingen" Shipping Lane the designed pipelaying/trench is less deep than in the Scheur. Therefore a combination of predredging (trailing suction hopper dredgers) and post-trenching (jetting sledge with jet-barge) has been foreseen.
Between the "Wielingen" and the shore a 1750 m shore-approach trench up to - 9 m MSL (bottom width : 50 m) has been designed (initially box-cut and subsequently 1/7 slopes). The shore approach trench connects to the sheet-piled cofferdam (figure 7).

Because of the dry tie-in of the pipeline into a spool piece and the need for extra work space, a temporary artificial island was built along the eastern breakwater. Excavation works were executed within the cofferdam for :

a. connection between offshore trench and tie-in area ;
b. soil replacement works (with gravel) because of the presence of muddy soil layers(cone resistance Qct < 1 MPa) likely to cause (differential) settlements.

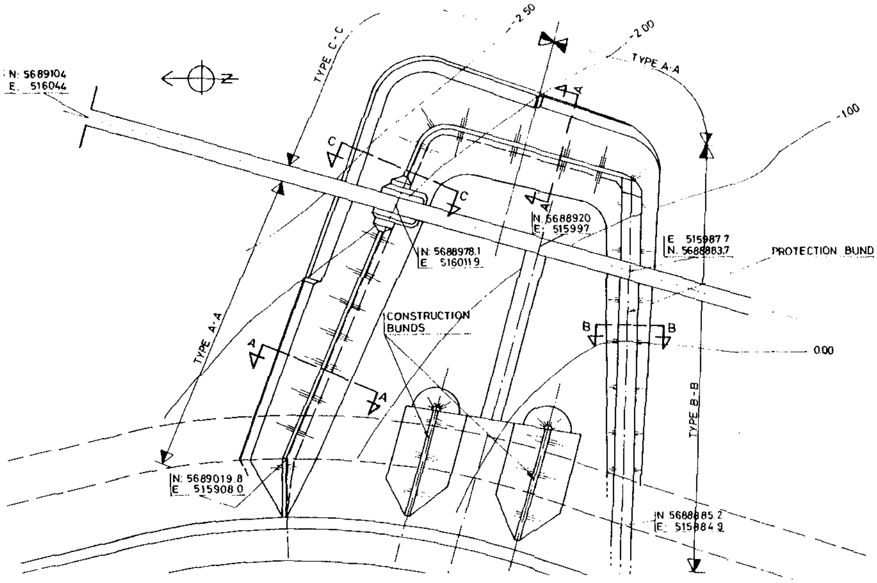


Figure 7 : Shore approach trench in sheet piled cofferdam and artificial landfall island.

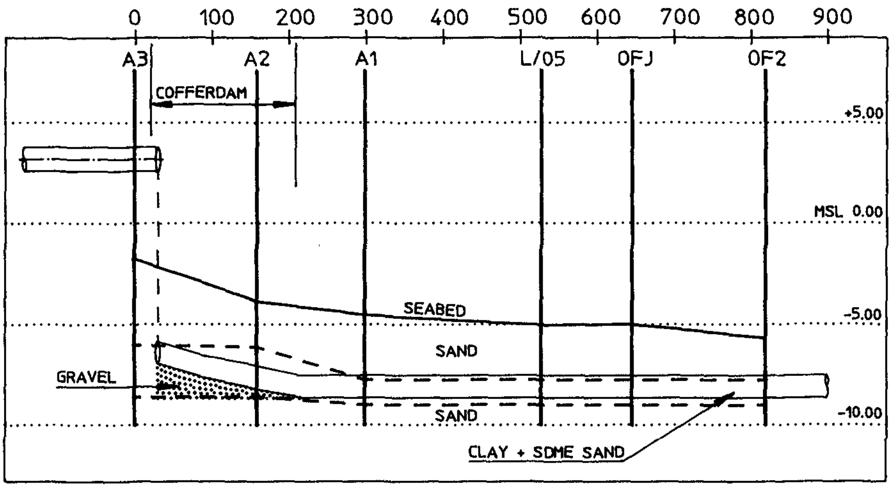


Figure 8 : Pipeline profile in the landfall area

In this way the pipeline would be in a safe operational condition from a stress point of view, i.e. below 70 % of the specified minimum yield strength.

4.4. Backfill of the pipeline trench

To avoid damaging risks of the pipeline due to navigation hazards (trailing anchors, sunken ships, etc ...) and/or maintenance dredging, a continuous gravel cover (gravel diameter : 0,11 m) of the pipeline was designed in the Scheur crossing area.

The design of the backfill of the shore approach trench in the transition zone between pre-trenching and post-trenching does fulfill the criteria, related to, a.o. :

- pipeline stability against liquefaction and flotation
- authority requirements

The backfill was designed by a series of separated gravel berms alternating with sand berms (figure 9) in order to optimize the backfill costs.

The gravel solution was retained because :

a. it offers a better solution against liquefaction (to ensure vertical stability) ;
b. it reduces execution problems if the trench is filled with loose mud deposit.

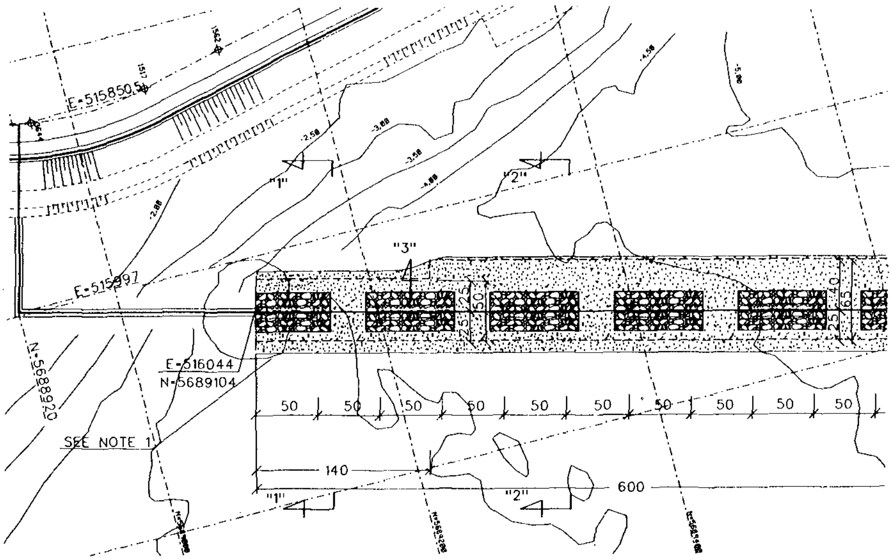


Figure 9 : Scheme of backfill of the shore-approach trench.

The backfill operations were designed to be executed by split hoppers and side-dumping vessels.

4.5. Crossing of the breakwater

For the crossing of the breakwater the upper layers of the rubble-mound structure had to be carefully dismantled, taking into account the as-built drawing and the foundation of the dam (soil replacement, willow-matrass, berm). In the berm and breakwater crossing a sandasphalt core in which the spool piece is bedded has been designed (thickness of sandasphalt under and above pipe ca. 1 m).

5. ZEEPIPE LANDFALL CONSTRUCTION

In order to execute the pulling ashore operation in controlled environmental conditions, a sheetpiled cofferdam has been constructed first.

The landward end of the cofferdam has been driven in a temporary artificial island. The purpose of this temporary island was to provide a protection against sea conditions during the opening of the breakwater and the installation of the spoolpiece across the breakwater.
A trench has been excavated within the cofferdam, into which the pipeline has been pulled ashore from a flat bottom laybarge by winches placed on the beach.
The island has than be used as a work platform in front of the trench.
After the pipeline was pulled ashore, the cofferdam has been plugged with clay and dewatered allowing the tie in operation to be done in dry conditions.
The seaward end of the cofferdam has been filled with seagravel and sand.
Finally the pipeline has been tied-into a spoolpiece that has been laid across the breakwater previously.

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