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SUCCESSFUL BEACH MODELLING, MONITORING AND MANAGEMENT FOR A LARGE LNG FACILITY

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Abstract

A temporary construction harbour was built for the Egyptian Liquified Natural Gas (ELNG) facility in Abu Qir Bay on Egypt's Mediterranean Sea coast, west of the Rosetta Nile. A shoreline impact assessment was undertaken during the planning process which involved modelling the existing beach processes as well as shoreline development during construction, operation, decommissioning and recovery. Based on this assessment and modelling, a schedule of shoreline management and monitoring was proposed to ensure that the temporary harbour did not have a negative impact on the shoreline over its three year life. ELNG followed the proposed programme under scrutiny from the Egyptian Shoreline Protection Agency (SPA) and successfully restored the beach to its pre-construction state. This paper discusses the ELNG project, beach modelling, monitoring and the management programme as a case study, and assesses the beach modelling against the unique field data set.

1. Introduction

The Egyptian LNG facility, located within Abu Qir Bay on the Mediterranean Sea coast (Figure 1), receives natural gas from wells offshore of the Nile Delta (West Delta Deep) and exports liquefied natural gas (LNG). The liquefaction plant and the associated marine facilities for tanker export were built between 2002 and 2005. A construction dock was required for the off-loading of plant from shallow draft barges directly to the site. Given the exposed nature of the site, the dock was protected within a small dredged harbour formed of rock breakwaters at the shoreline, with a dredged navigation channel connecting to deeper water. Tanker facilities for LNG export were built further offshore to minimise the need for maintaining a dredged channel across the shallow nearshore zone and LNG was piped to the tankers using a 3km long trestle (Figure 1).

As it was recognised that the harbour could have a significant impact on coastal processes, it was planned to be a temporary structure. The impact was to be monitored and managed throughout its life, with the intention of reinstating the shoreline to its natural form following removal. This approach was intended to satisfy the regulating authorities, but also ensured that the LNG facilities would not be at risk from erosion or flooding as a result of the disruption to beach evolution processes. A management plan based on desk studies and numerical modelling was agreed and then implemented and scrutinized by the Egyptian Shoreline Protection Agency (SPA) over the period from construction in the spring of 2003 to removal of the harbour in the autumn of 2005.

The intensive management period resulted in an extensive beach data set from the pre-existing natural beach through construction, operation, removal and reinstatement. These data provided an opportunity to assess model predictions against measured shoreline changes, and the success of the proposed management plan.

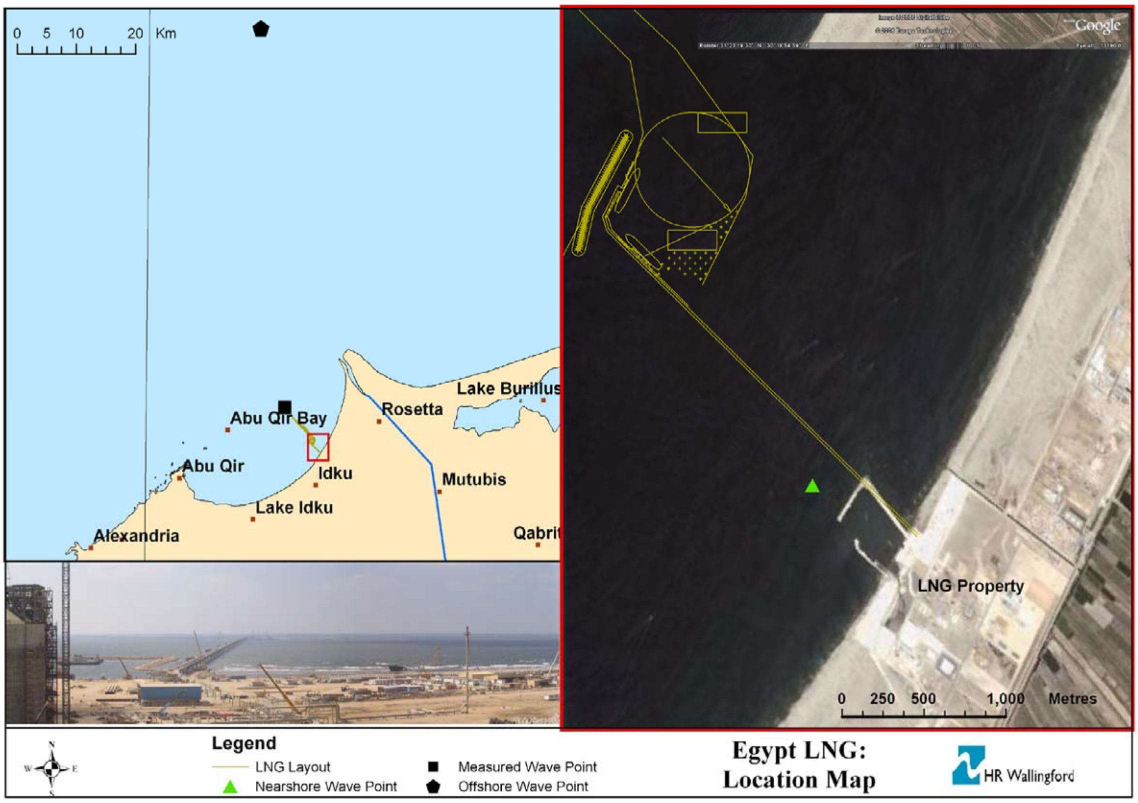

Figure 1 Location Map

2. Site Description

Abu Qir Bay is less than 20m deep and about 33km wide from the partially sheltered area in the lee of the reefs and islands off Ras Abu Qir in the west, to the rapidly eroding delta of the Rosetta Nile in the northeast. The shallow waters of Idku Lake lie just behind a barrier beach in the southern part of the Bay. The shore is exposed to dominant north-westerly waves, driving a strong easterly longshore drift along most of the Nile Delta coast (Fanos *et al*., 1995 and Frihy *et al*., 1991) but with a local south-westerly drift direction along the shore of Abu Qir Bay to the north of the ELNG plant location. The Bay has a small tidal range (typically ~0.2m), and the main driving forces for currents and sediment transport are wind and waves. Fresh water flows into the Bay via the Rosetta Nile and Idku Lake, although both sources are now low volume and considered to have little impact on coastal processes in relation to winds and waves.

Understanding of the coast and seabed evolution is based on information derived from historic maps and charts, satellite images, published research papers, unpublished reports, project specific field surveys and numerical modelling of sediment transport. In summary, the seabed and beaches are formed of fine sand and silt, subject to continuing change due to the dramatic reduction in sediment supply from the Rosetta Nile following construction of the Aswan dams, combined with the moderately high energy wave conditions typical of the Egyptian north coast. The net longshore shoreline drift is from northeast to southwest in the area of the ELNG plant, but is subject to short term reversals and a high level of annual variability. There is evidence, from sediment sampling, of offshore transport of silt and some fine sand to deeper water across the mouth of the Bay. At decadal timescales the shoreline is considered to be stable or slowly accreting in the area of the LNG facility, with a reasonable balance between sediment transport alongshore and losses offshore.

Previous beach and nearshore surveys carried out by CoRI (Coastal Research Institute, Egypt) over the 12 years prior to construction of the facility indicated that the natural shoreline and nearshore seabed levels were subject to substantial short term variability in response to seasonal conditions, up to ± 40m relative to a mean position, Fanos (2001).

It was anticipated that sand would accumulate to the north of the harbour, and that there would be areas of erosion to the south. An updrift accretion could potentially cause problems of infilling in the harbour and downdrift erosion could result in unacceptable loss of land to the LNG property or further along the coast. The nearshore bed was also expected to change both seasonally and over longer time periods, with some transport around the seaward face of the breakwaters, possibly causing infill of the dredged navigation channel.

3. Shoreline Impact Modelling

Potential impacts of the construction harbour on the shoreline were assessed using a suite of numerical models. Offshore wave conditions were defined and then transformed to create a time series of nearshore conditions as input to longshore drift predictions for the open coast and in the presence of the harbour breakwaters.

The wave climate offshore from the ELNG facility was evaluated by a combination of numerical modelling methods, with the offshore wave climate established using "Eurowaves", which are model data based on the ECMWF (European Centre for Medium Range Weather Forecasts) hindcast model. At the time of this study seven years of sequential Eurowaves data (1992 – 1999) were available for the model point 30.5°E 32°N (Figure 1). The offshore wave predictions were calibrated against wave measurements made over a six-month period (November 2001 to April 2002) at the seaward end of the proposed approach channel (Figure 1).

Nearshore wave conditions over the seven year period were then modelled at a number of locations along the ELNG site on the 6m contour below Chart Datum (CD – approximately LAT at Alexandria). The time series of six-hourly predicted values of wave height, period and direction at a point just offshore from the northern harbour breakwater was used to model the likely changes to the shoreline.

The simplest measure of sand transport along a beach is the "potential mean annual transport rate", denoted here as Q_{mean}. This single statistic allows an initial assessment of the scale and pattern of any beach erosion / accretion following installation of coastal structures. It must be emphasised that Q_{mean} is:

- Subject to considerable uncertainty, because of the difficulties involved in calculation (i.e. it is extremely sensitive to the precise wave conditions and the beach orientation at any given point along the frontage;
- Averaged over a number of years and may be subject to substantial annual variability; and
- Dependent on the availability of suitable sediment to feed the drift.

The nearshore time series waves were transformed up to the breaking point of each condition. The values of wave height, period and direction at breaking were then used to derive the instantaneous longshore transport rate for sand for each six hour period using the CERC formula modified by Ozasa and Brampton (1980). The cumulative transport rates at the end of each month and year were defined. Finally, all the results were averaged over the seven years to produce the predicted mean annual nett transport rate, Q_{mean}. The best estimate prediction of Q_{mean} was approximately 480,000m^3/ year (south-westerly), as presented in Table 1, with a standard deviation of 196,000m^3/year. These figures give an indication of the potential variability in annual longshore drift, albeit from a small sample.

Table 1 provides a breakdown of the contributions to the drift rate produced by various categories of nearshore wave. Waves arriving from 310°N - 010°N produce a northeast to southwest drift (positive values), while waves arriving from 260°N - 300°N produce a southwest to northeast drift (negative values). The dominating effect of the waves between 1.5m to 2.5mH_s can be appreciated by considering the entries in the "Total" column, which show that these wave heights generate over 60% of the nett "positive" drift. The effect of the largest waves on drift direction is also important, indicating that very stormy periods are likely to be associated with drift reversals.

Table 1 Annual drift and % Wave height

Resultant wave height (m)	Direction sector (°N)									Total	% Wave Height
	275 - 285	285 - 295	295 - 305	305 - 315	315 - 325	325 - 335	335 - 345	345 - 355	355 - 005		
0.0 - 0.5	-263	-172	-23	1,193	1,259	978	1,946	2,324	511	7,751	15.91
0.6 - 1.0	-525	-5,131	-967	37,743	23,645	13,295	14,655	7,371	2,900	92,986	32.42
1.1 - 1.5	-426	-20,283	-7,036	57,570	18,058	15,893	22,844	12,007	615	99,244	22.23
1.6 -2.0	..	-28,789	-22,089	100,526	43,162	11,170	24,483	4,604	..	133,065	14.67
2.1 - 2.5	..	-29,176	-23,819	147,537	45,452	8,860	11,708	..	..	160,563	8.25
2.6 - 3.0	..	-26,248	-11,793	80,032	16,891	2,992	..	..	..	61,874	3.49
3.1 - 3.5	..	-19,550	-15,885	36,165	8,273	..	..	..	..	9,003	1.28
3.6 - 4.0	..	-7,883	-10,623	11,549	6,784	..	..	..	..	-173	0.55
4.0 +	..	-75,668	-86,721	71,009	7,612	..	..	..	..	-83,768	1.22
Total	-1,225	-212,901	-178,955	543,324	171,136	53,188	75,637	26,306	4,036	480,547	100

Table 1 also shows that about 60% of the mean annual drift rate is produced by waves with heights in excess of 1.5m. Such waves occur for less than 30% of the time (see Table 1), and hence it can be appreciated that a "calm" year, with fewer than average storms, will be likely to produce a very different drift rate to a "stormy" year with more storms.

Figure 2 shows the calculated variations in the nett longshore transport rate from month to month over the seven-year period. This indicates that transport is relatively constant in direction and rate during the summer months, at approximately 50,000m^3/month towards the southwest, but during the winter months the drifts can be much stronger, in one month alone the drift rate is equal to a years mean drift and in some cases there may be a reverse in drift direction. This had implications for the harbour entrance, since there was a danger that infill could occur by sand travelling from southeast to northwest.

The figure for Q_{mean} of 480,000m^3/ year at the north end of the harbour was considered to be a conservative prediction (i.e. overestimating) and the actual rate may be less due to the nearshore wave predictions not accounting for dissipation effects during storms from the shallow silty seabed. Furthermore the drift calculation is sensitive to the assumed beach orientation and sensitivity tests indicated that a change to the beach orientation of 1° gives a corresponding value of Q_{mean} altered by approximately 240,000m^3/ year. Therefore as the shoreline curves continuously, Q_{mean} will decrease significantly along the site towards the south, potentially even reversing immediately south of the LNG frontage. The sensitivity of drift predictions to small changes in wave direction is also similar. Since it is hardly possible to measure, let alone predict, nearshore wave directions to accuracies better than ±5°, then the uncertainty of the computed Q_{mean} value can be appreciated.

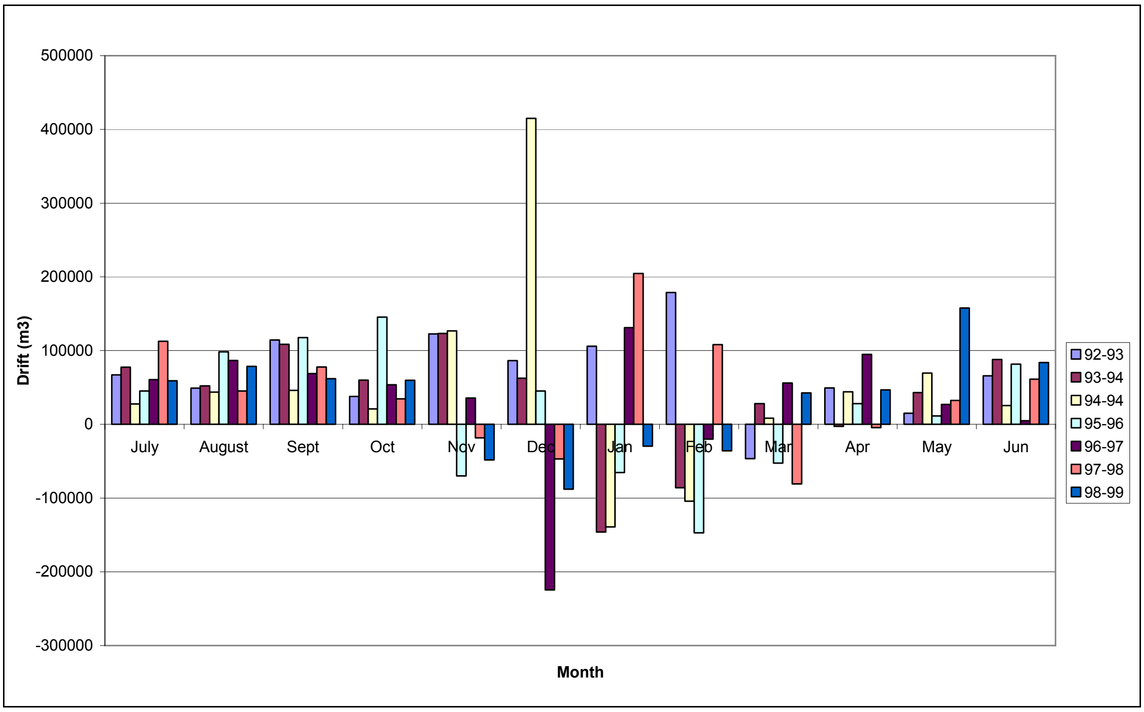

Figure 2 Monthly potential net drift

4. Beach plan shape evolution

4.1 Introduction

The changes in the plan shape of the beach around the temporary harbour were examined through the use of the HR Wallingford BEACHPLAN 1-line beach model, (HR Wallingford 2004 and Ozasa & Brampton 1980). This model uses the same wave conditions gathered at the LNG site as used in the drift calculations, in the form of a time series (from July 1992 to June 1999). Ideally, when predicting shoreline evolution the model is calibrated against historical shoreline positions and detailed up to date beach and nearshore profiles are used to assess the active beach. A lack of suitable data for this study required the need for a conservative approach to predicting drift rates so that the potential for shoreline changes and subsequent mitigation measures would not be underestimated. Similarly, to be on the conservative side, no attempt was made at simulating the bypassing of sand around the seaward end of the harbour and although no nearshore survey data was available at this time it was assumed that the cross-shore extent of significant transported extended to at least the 5mCD contour. These and other model parameters were all chosen on a basis of experience and using a conservative approach in order to provide suitable guidance for the pattern and scale of beach changes and the subsequent mitigation requirements i.e. recycling.

The BEACHPLAN model was run for a number of different scenarios to provide initial assessment of the potential beach response to the proposed construction harbour. The model runs presented within this paper consider the following:

- Beach response to the harbour over 3 years, assuming no management measures.
- Beach recovery over 3 years following removal of the harbour.

4.2 Modelling runs: Natural response to the harbour

The model was first used to examine the potential changes in the shoreline following the construction of the harbour breakwaters. The model was run for three years to simulate the beach changes likely to develop over the life span of the harbour. Figure 3 shows the predicted beach plan-shape six months after the completion of the harbour. Substantial accretion of up to 150m is predicted, after 3 years, on the east side of the causeway, and a maximum of up to 100m of landward movement of the coastline to the west of the western breakwater. This figure also presents the predicted changes after 1, 2 and 3 years. The beach position after 1 year is very similar to the beach position after 6 months and it could be interpreted that the beach has not moved a great deal in this time period. However on examination of the results in more detail, on a monthly basis for example, it was predicted that the beach varies a great deal and as a result of storm activity, the drift rate is higher and more variable, often with periods of a reversal, as shown in Figure 2. The variations in the wave climate therefore resulted in a predicted beach position after 12 months similar to the one seen after 6 months. The longshore extent of predicted accretion and erosion was about 3km either side of the harbour. This is considered to be a qualitatively realistic though conservative scenario.

The model was not set up to indicate the potential volume of sand that may by-pass the breakwaters, which would largely be expected to be deposited within the dredged navigation channel leading to the dock, and would therefore result in more accretion on the updrift side. The results indicate that under conditions of "average annual" littoral drift substantial accretion was expected east of the temporary harbour with high rates of coastal erosion to the west.

4.3 Modelling runs: Beach recovery

The model was also used to examine the changes in the shoreline after removal of the harbour. The initial situation was taken as the final shoreline position after three years with the harbour in place. The model demonstrated an initial rapid beach response followed by a gradual reorientation of the beach towards its original alignment over time. It is predicted that in less than three years from removal the beach would recover to its pre-construction state.

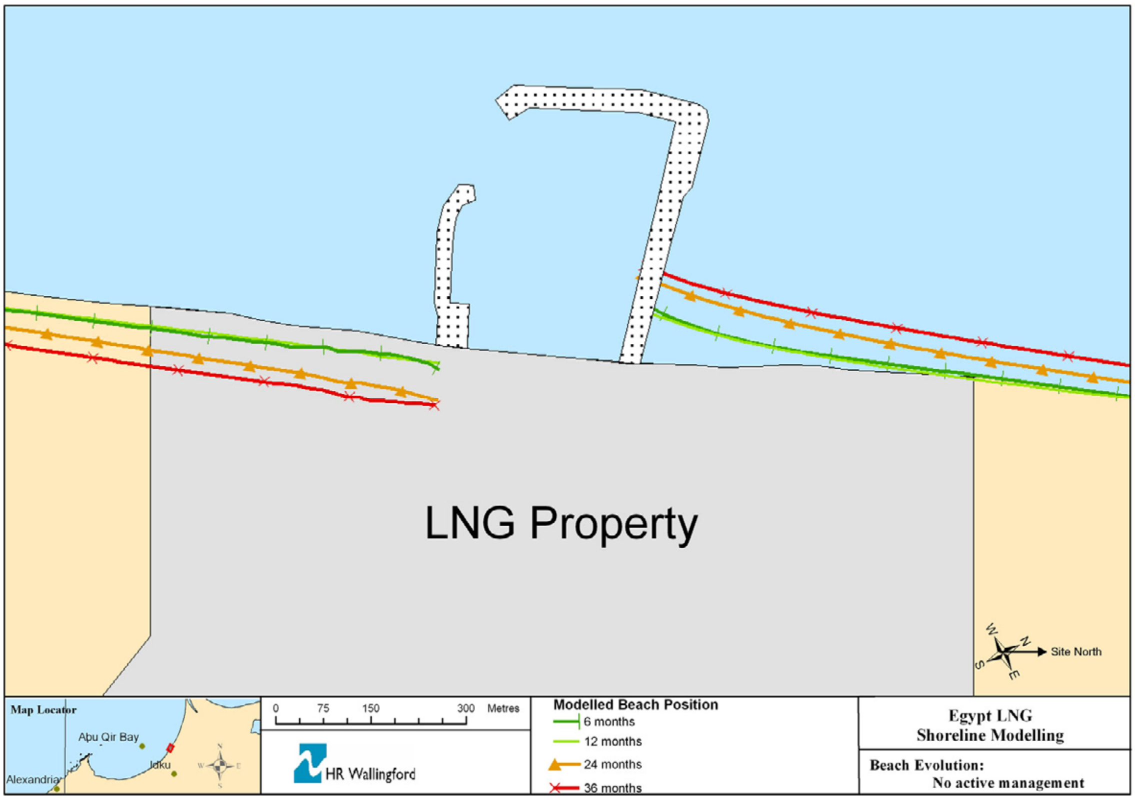

Figure 3 Modelling of beach plan shape evolution

5. Beach management

A beach management plan was prepared for ELNG to minimise any impacts of the temporary harbour on the natural environment, as required by the Shoreline Protection Agency. The main aims and objectives of the management plan were to:

- Keep both the accumulation of beach material on the north-east side of the harbour and erosion south-west of the harbour to within agreed limits representing the envelope of beach variation under natural conditions;
- Minimise the rate of siltation of dredged areas in the harbour or its approach channel; and
- Return the shoreline to its pre-construction equilibrium state following removal of the harbour.

An envelope of acceptable shoreline movement was defined, based on the recorded movement of the shoreline over the previous decade, Fanos (2001) and the beach plan-shape modelling. The acceptable limits recognised that the beach would re-orient itself to a new position following the installation of the harbour and was considered not to be a problem as the shoreline would rapidly return to its pre-construction position. Provided that the shoreline stayed within this envelope, no immediate management action was required. A further envelope of tolerable short-term erosion and accretion was defined allowing the contractor some leniency while undertaking bypassing operations. Variation outside this envelope was considered contractually unacceptable.

In order to maintain the beach within the agreed limits regular bypassing was proposed to move sand from areas of accumulation to areas of erosion. It was also proposed that any clean sand dredged from the navigation channel or the dock area would be deposited onshore for beach management purposes. A sand bypassing scheme using trucks was recommended as more efficient and flexible than any schemes involving pumps or dredging plant. It was anticipated that bypassing of up to 40,000m³ of sand might be required each month, but that this rate would vary in response to seasonal and storm conditions. The actual volumes of beach material moved are presented in Table 2.

A flexible management system was recommended because the beach and drift modelling highlighted that actual beach changes can occur very quickly (Figure 2) and are subject to the vagaries of the wave climate. It was not possible to determine the exact location of sand pick up and set down positions for sand bypassing and it was recommended that this would be determined by means of regular shoreline and nearshore monitoring.

A beach and nearshore survey programme was instigated to monitor the changes as a result of the temporary construction harbour and to facilitate in the management of the shoreline adjacent to the harbour.

The programme involved an assessment of the pre-construction shoreline and nearshore bathymetry, with frequent monitoring throughout the life of the facility. The survey programme comprised six-monthly bathymetric surveys out to about the 6mCD contour, two-monthly beach profile surveys accompanied by photographs and fortnightly waterline surveys. Furthermore volumes of any dredging and sand bypassing required to maintain the shoreline position were logged.

As shoreline data were recorded at frequent and regular intervals throughout the life of the harbour, an efficient data management and analysis system was set up. ArcMap GIS was used to store and analysis the data as it allowed efficient data management, a rapid analysis of shoreline changes and a cost effective method for monitoring contractor performance and compliance with SPA's requirements.

Table 2 Management Activities

Date	Activity	Volume Removed	Volume Added	comments
Feb-03	Construction of the temporary harbour begins			
Apr-03	Capital dredging begins	120,000m	10,700m	109,300 stored onsite
May-03	Temporary harbour complete			
Jun-03	Removal of sand from north beach	400m		Used to fill voids in breakwater
Aug-03	Maintenance dredging	38,200m	38,200m	
Nov-03	Sand Bypassing	22,000m	20,000m	
Jun-04	Maintenance dredging	15,200m	15,200m	
Apr to Oct-04	Sand Bypassing	44,750m	42,750m	
Jun-05	Removal of temporary harbour	Redistribution of sand		

6. Analysis of Survey Data

6.1 Nearshore Surveys

The beach and nearshore surveys collected every six months, eight in total, illustrate clearly the response of the shoreline to the presence of the temporary construction harbour. Although these surveys only represent the situation on individual days they also show the patterns of accretion and erosion.

The February 2003 survey (Figure 4) was completed prior to any construction work. The contours are largely parallel, with a distinct nearshore channel/bar system typical of a "winter" beach condition. By the April 2003 survey (Figure 5) the harbour was part built, and was beginning to have an impact on the nearshore processes. The nearshore bar is still clearly present to the north of the breakwater, but to the south there is a channel, indicating a loss of about 2m elevation. There is also a deep scour hole (5m deeper than the surrounding seabed) near the end of the breakwater, which was thought to be caused by waves reflecting off the structure and possibly by longshore currents being turned offshore.

Over the summer of 2003 the bathymetry changed in a way that is often observed on sandy shorelines and by the October 2003 survey, the nearshore channel/bar system had flattened off, leaving a more even slope down from the beach typical of a "summer" profile i.e. the bars had migrated onshore. This indicated a continued loss of total sediment volume, despite the dumping of some 49,000m^3 of dredged sand onto the beach during the late summer 2003. There was also an accretion of sand to the north of the harbour, extending out to the contractual limit agreed with the SPA. As the harbour arm was extended for the completion of the harbour (Table 2), the scour hole migrated further offshore to form a stable but extensive feature off the northwest corner, Whitehouse (2005). This scour hole caused an instability of the trestle structure that runs alongside the temporary harbour and as a consequence a section of the northern arm of the harbour breakwater was realigned to a parallel orientation approximately 50m to the south, as shown in Figure 6.

By April 2004 the nearshore profile had again adopted a "summer" shape with a reduced nearshore bar, but there was still a clear build up to the north of the dock and a much steeper profile to the south. The south beach was also affected by the presence of a 300m long rock revetment built along the backshore, although the survey plot does not show this. The effect of the revetment was to limit the landward migration of the waterline, but it did not slow the total loss of material from the beach and nearshore and downdrift erosion occurred beyond the site of the LNG.

The rock revetment was removed during the summer of 2004.

Despite the management effort between April and October 2004 (Table 2), the October 2004 survey (Figure 6) clearly showed a continued build up of material to the north of the harbour. There was also a build up of sand around the outer edge of the breakwater indicating that natural bypassing processes were occurring, with likely infilling of the dredged channel. It is also evident that the south beach had a much steeper profile and there were no signs of the bar and channel system that existed pre-harbour construction, as shown in Figure 5. The April 2005 survey showed a similar pattern of sand movement with a continued build up of material to the north of the harbour.

During the period February 2005 to July 2005 the removal of the construction harbour took place. The final survey was undertaken in July 2005 and is presented in Figure 7. This Figure clearly shows that the shoreline had largely returned to its natural position except for the small residual promontory between profiles 10 and 11, and the remaining cut-back south of the ELNG site at profiles 21 – 23. The offshore contours still exhibit the effects of the harbour, with a substantial build up remaining in the area north of the harbour. The nearshore loss to the south, and particularly the loss of the nearshore bar feature, is a cause for concern, as the beach may no longer be able to respond to severe wave conditions in a natural and dynamic way.

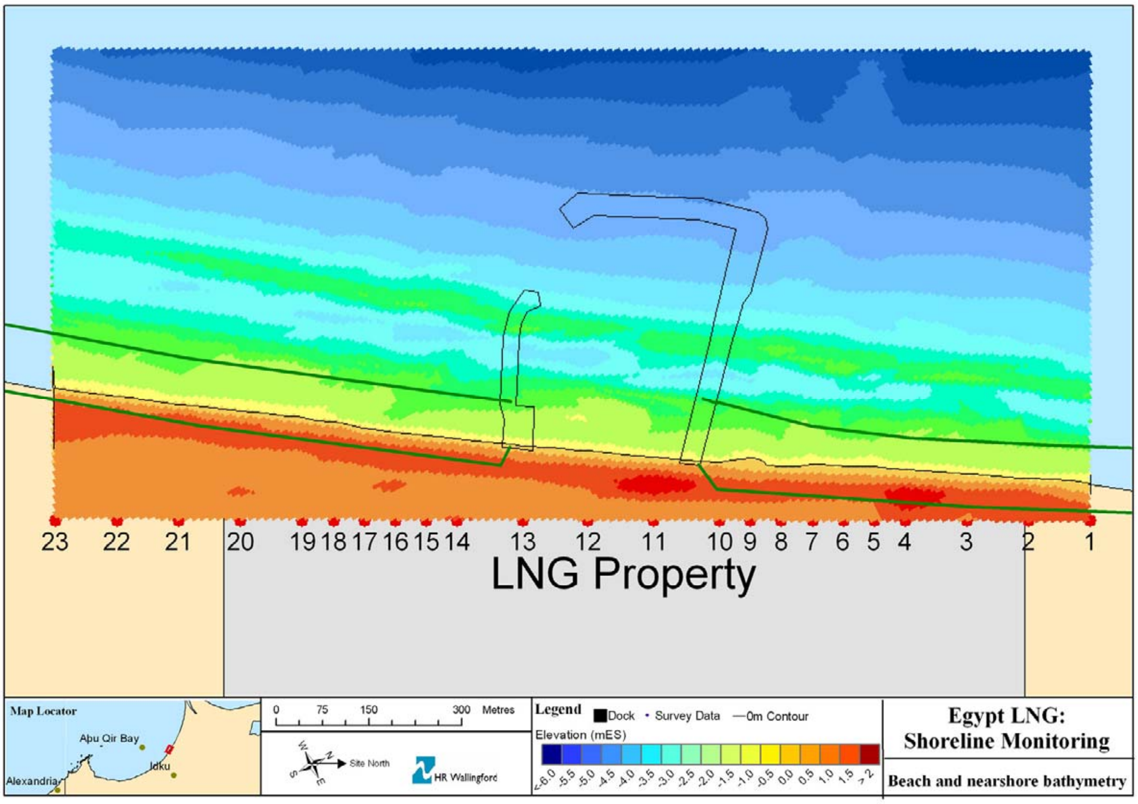

Figure 4 Pre-construction beach/bathymetric contours: February 2003

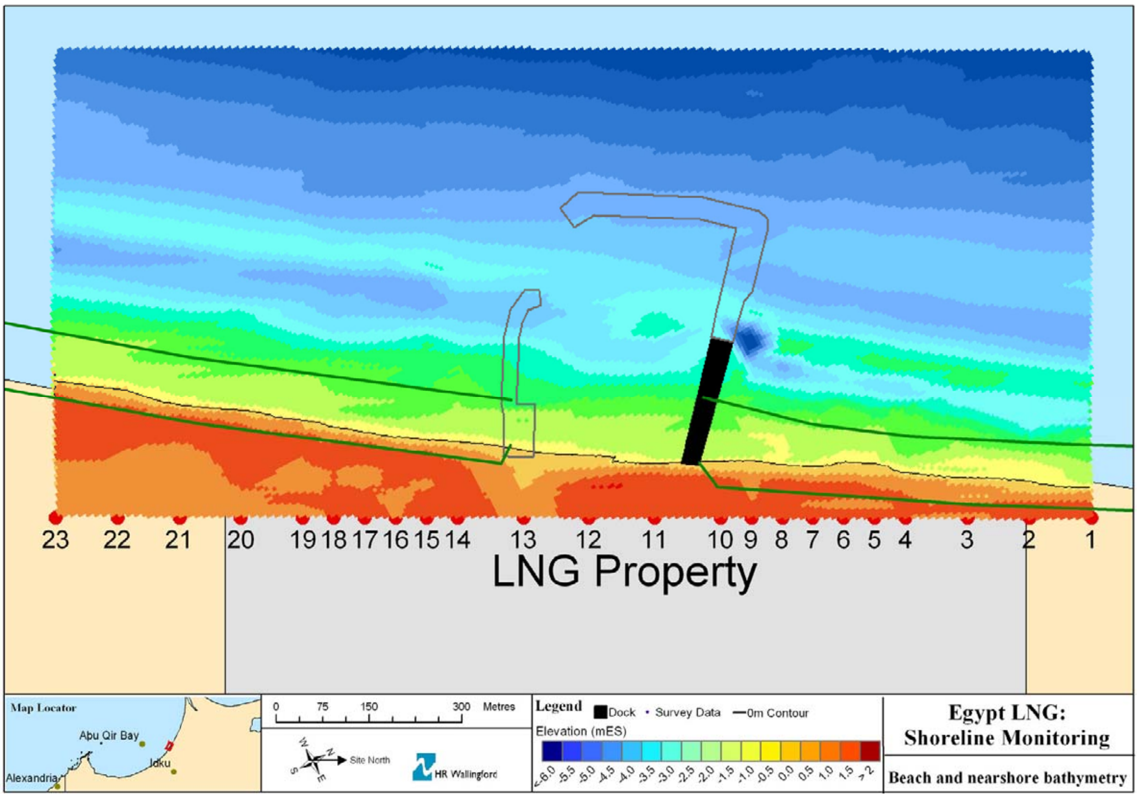

Figure 5 Beach and bathymetric contours: April 2003

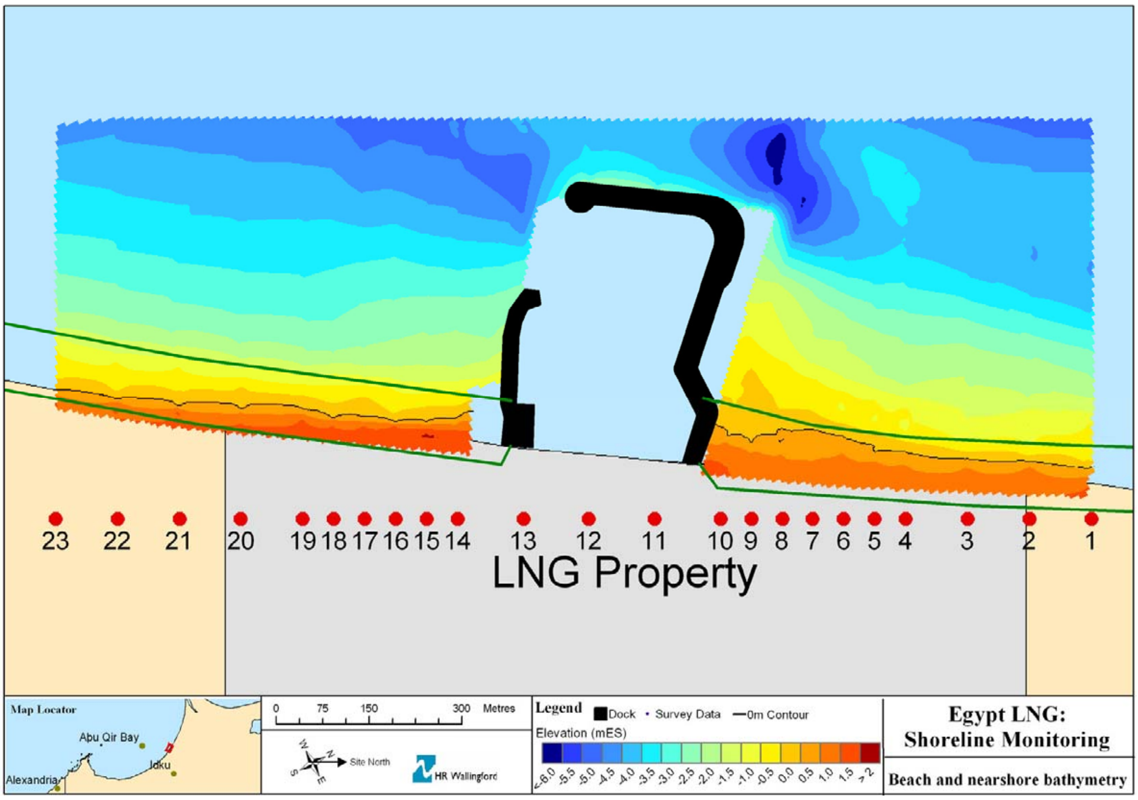

Figure 6 Beach and bathymetric contours: October 2004 (Note new dock layout)

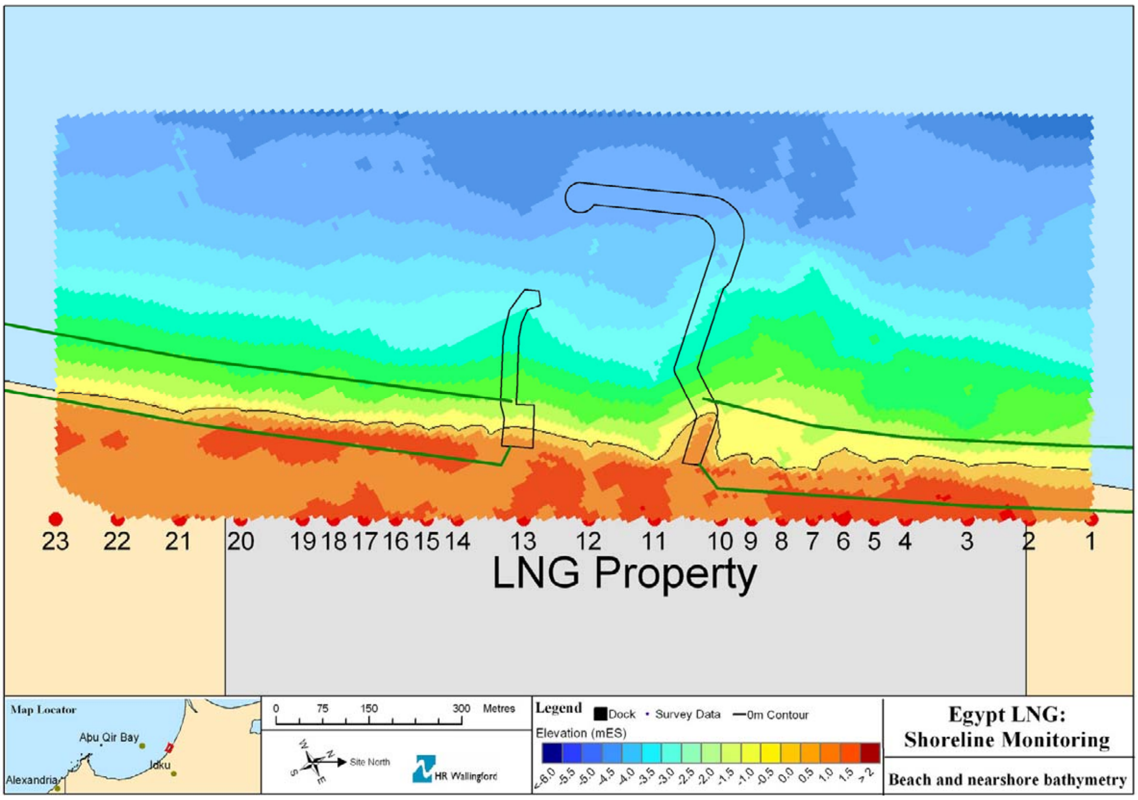

Figure 7 Beach and bathymetric contours: July 2005 (note dock now removed)

6.2 Shoreline Position

The intended fortnightly waterline position surveys were actually completed at intervals from weeks to months. Measurements of the distance from a fixed baseline to the waterline were taken at intervals along the ELNG frontage to assess short term variability. The method used was simple and rapid and therefore allowed the contractor to respond to shoreline changes before the more detailed surveys and therefore keep the shoreline within the agreed limits of variation.

The peak rate of change in shoreline position was calculated and shows that the shoreline was accreting by 2.5m/wk at the north beach and was eroding by 1.3m/wk at the south beach during the first few weeks following construction and highlights the rapid response needed to effectively manage the shoreline.

7. Model performance

Prediction of accurate drift rates by numerical models is notoriously difficult, especially on open coastlines where there is little accurate historical data or even obstructions to the drift to provide evidence of the direction and intensity of the sediment transport rate. The monitoring programme at the ELNG has provided a unique dataset of measured beach evolution over the whole project (including removal of structures), therefore allowing an assessment of the performance of the numerical modelling undertaken as part of the initial shoreline impact predictions.

The use of GIS to store and plot both the modelled shoreline positions and the subsequent measured shoreline positions has allowed a direct comparison to be made between the two data sets, as shown in Figure 8. This figure clearly demonstrates that the modelled shoreline position after 6 and 12 months closely match the corresponding measured shoreline position (August 2003 and February 2004) to the north of the harbour. The maximum amount of accretion against the north harbour arm after 6 months was predicted by the modelling to be 78m and when this is compared with the 83m accretion measured by the August 2003 survey, it is clear the model was accurately predicting the shoreline evolution. The predicted figure also compares well against the shoreline position measurements over the same time period. Looking further ahead in time, 24 and 36 months, the predicted shorelines do not match the measured. This is understandable as the shoreline was required to be maintained within agreed limits of movement and beach bypassing was undertaken in a responsive manner beginning in November 2003. Volume calculations of the survey data, although of a crude nature also tie in to the average longshore drift along the modelled stretch of coastline.

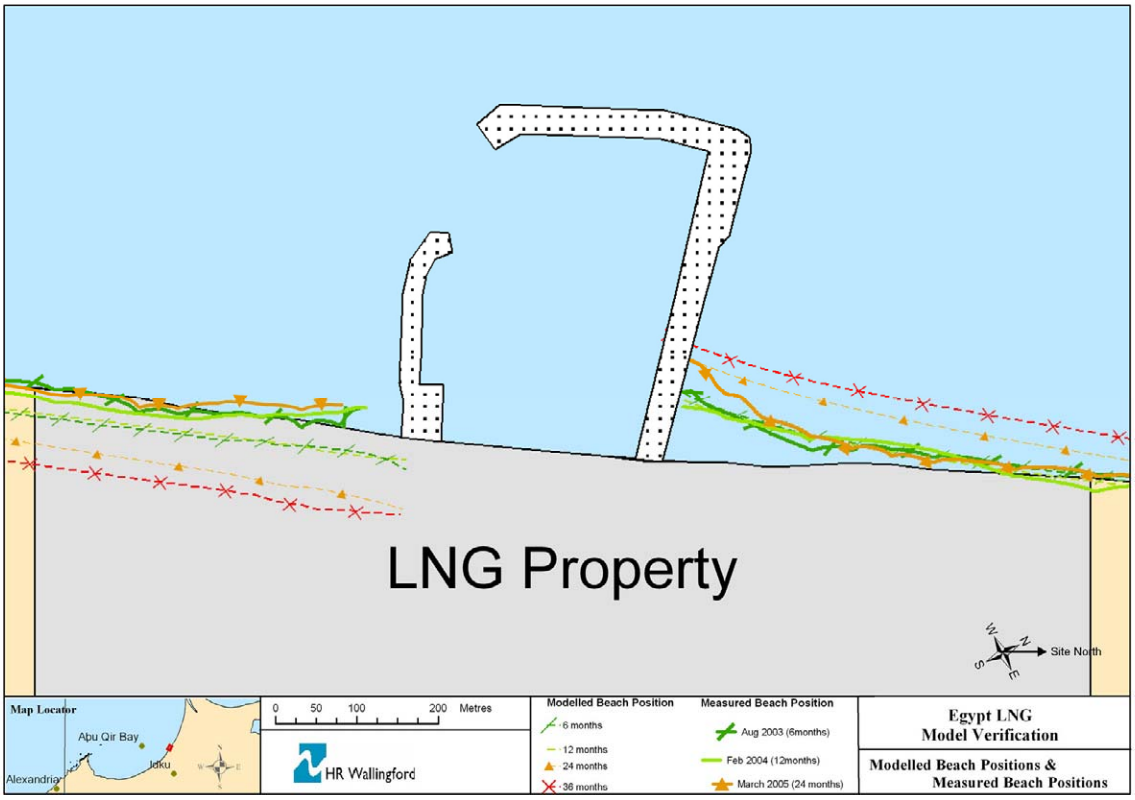

Figure 8 Comparison of predicted beach positions and monitored beach positions

On the beach south of the harbour the surveyed positions do not match the shoreline position predicted by the modelling. However, the weekly shoreline position measurements tie in with the rate of erosion predicted at this location and as a result of the rapid erosion beach management (Table 2) was required before the August 2003 survey. Furthermore a rock revetment was placed along the shoreline to restrict any further landward movement of the shoreline south of the harbour. Therefore the surveyed shoreline position will not match the predicted shoreline position.

The beach plan shape model predicted that the beach would return to its pre-harbour position within three years after removal. Following removal of the harbour the waterline was artificially restored to its pre-existing state and it has subsequently not been possible to verify the recovery element of the modelling.

8. Conclusions

A comprehensive desk study of coastal processes was undertaken to assess the impact of the temporary construction harbour for the ELNG facility, before the BEACHPLAN model was used to predict future beach evolution. This model is applied as a first-stage tool in understanding coastline behaviour and the impact of engineering works upon it.

Drift rates are notoriously difficult to accurately predict and are sensitive to small changes in beach orientation (or wave direction). Caution must therefore be exercised when calculating them and sensitivity test should be carried out. In this study a shift in beach orientation of only 1° led to a 50% change in drift rates. This is clearly important when modelling along a curved shoreline such as the one in this study and led us to make a conservative estimate of the drift rates for the purpose of providing guidance to the required beach management.

Following the analysis of the survey data a comparison between measured and predicted beach position revealed that the modelling turned out to be reasonably accurate, despite the lack of any suitable calibration data. In situations where there is a lack of good data for calibration a comprehensive desk study and the undertaking of sensitivity tests gain increasing importance and any modelling should be done with a suitable amount of caution and conservatism.

As a result of the identification of the scour hole its subsequent impact on the trestle, it was recognised that that it is important to carry out a separate study to assess these impacts using a 2-D wave/current sediment transport model.

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