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Field Observations of Scour Around a Rock Berm Over a Subsea Pipeline on a Clay Seabed

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The evaluation of scour in shallow water for a pipeline installed and covered with engineered rock-dump has been analysed based on survey data. The 3km long shore approach section of the 10" pipeline was installed in a trench and backfilled with rock dump. Due to the rapid siltation of the trench there was no trench to deposit the rock in and the rock formed a berm. Scour was found to occur either side of the berm due to the fast, turbulent near bed tidal currents. The magnitude of scour that occurred could be as large as the initial water depth in the shallowest depths of around 10m. The time series of scour is analysed and the characteristic timescales are determined.

I. INTRODUCTION

A significant proportion of the world's hydrocarbon pipelines are routed through areas with clay seabeds. However, despite the obvious importance of the stability design of pipelines in clay, there is very little engineering guidance or data in existence. One of the important design issues is scour, or rather prevention of scour, especially in areas with high current speeds.

Whereas scour in sandy seabeds is well studied and relatively straightfoward to predict the situation is very different when it comes to clay seabeds. The scour behaviour is very different to that of a sandy seabed and the magnitude of scour can be much larger because the soil, once eroded, can be removed from the local area by the currents.

In this paper we present a data set obtained during a pipeline project carried out by Saipem for CNOOC on the Pinghu oil and gas field in the East China Sea. Because an extensive monitoring programme was initiated it was possible to study the spatial and temporal development of scour that took place in the clay seabed, and to derive some engineering recommendations about how to deal with pipelines in this type of area.

II. PROJECT DESCRIPTION

The shore approach at Daishan Dao island for a 10" (254mm) oil pipeline is located approximately 140km south of Shanghai transporting product from the offshore Pinghu Field some 300km southeast of Daishan Dao. The first three kilometers of the pipeline passes offshore from the landfall to a water depth of around 10m below local datum TDDL, Theoretical Depth Datum Level, which was approximately Chart Datum (Fig.1). The tidal range is approximately 1.4m on neap tides and 3.4m on spring tides. The remainder of this section provides more details of the hydrodynamics and bed sediments with some details summarized from the report by COGC [1].

In terms of hydrodynamic forcing the area is dominated by tidal currents with extremely high currents of up to six knots. The tidal current in the shallow water off the northeast coast of Daishan Dao is very turbulent and a tidal race was observed less than 1km to the southeast of KP2.00. This is generated by the fast tidal flow around the headland to the south of the pipeline and the shallowing water depth. The axis of the bidirectional currents lies approximately northwest to southeast and hence perpendicular to the pipe route. Measurements of maximum velocities near the seabed for the ebb and flood tidal flows made in October 1995 were reported by COGC [1] as 2.67m/s and 1.94m/s respectively; the maximum values of surface velocity were higher. The flood current direction in the measurements lay between NNW and N and the ebb current between SSE and SE.

In addition to the prevailing tidal forcing, there are occasionally significant swell waves, mainly generated by typhoons. The one-year return period significant wave height is 3.2m. Therefore in terms of hydrodynamic forcing for pipe stability, engineered backfill stability and sediment transport both tidal currents and waves have to be considered.

The soils are characterized by soft, siltey, clayey sediments. A borehole (P18) at KP2.125 showed an upper sediment unit of 7.4m thickness comprising very soft olive grey clay with silty partings and pockets. The design value of undrained shear strength from testing was 7kPa, the submerged unit weight 6.6kN/m^3, and natural water content was 50%. For design purposes these parameters were taken to be constant over the depth of the soil unit. The clay was classified as inorganic and of medium to high plasticity. Inshore of P18 the boreholes showed presence of a silt unit overlying the clay. Over the 640m between P18 and P17 at KP1.485 the silt unit increased to a thickness of 2.5m. The median grain size of the surficial bed sediments along the pipeline was in the range 0.01 to 0.022mm.

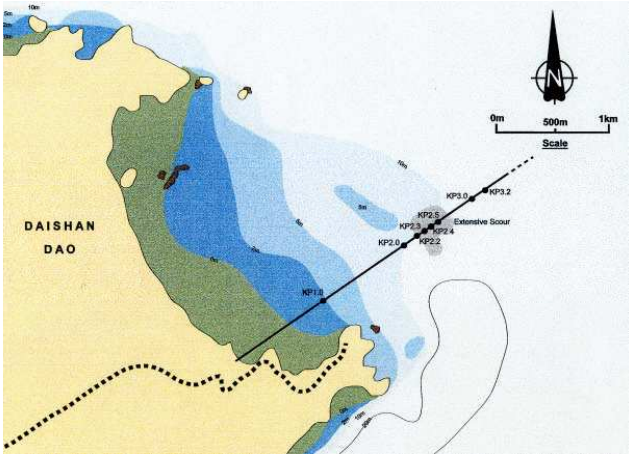

Figure 1 Location map of pipeline landfall section at Daishan Dao in East China Sea

The assumed maximum erosion or migration of the natural seabed at the landfall was limited to 1m over the 30 year design life of the pipeline. The pipeline was pre-trenched to a target depth of 3m below seabed level between the landfall and KP3.00 and the trench depth decreased from full depth to the seabed surface over the 100m between KP3.00 and KP3.10. The dredged trench profile had a bottom width of about 18m and side slopes in the range 1:10 to 1:15. Due to the dynamic nature of the site the trench filled in totally during dredging and before the pipe lay-barge arrived. The pipe was therefore laid on the backfilled trench, effectively at seabed level. The pipeline was lowered post-lay to the required 3m (bottom of pipe) by mobilizing a jetting machine. The trench backfilled almost completely during and immediately after the jetting process. Following jet lowering to comply with the rock armour requirements the pipeline was covered with a three-layer engineered backfill, as far as KP3.00. Firstly an inner layer of fine gravel (4mm) was placed, then an intermediate layer of graded gravel (50mm) and finally an armour layer of graded rock (200mm to 500mm). The armour layer was selected to withstand the combined action of 100 year waves and currents. In the trench transition zone no armour was applied to allow the post-lay trenching of the pipeline to a minimum depth of 1.5m BOP (Bottom Of Pipe) from KP3.00 onwards.

Following installation of the engineered backfill extensive scour was observed on either side of the pipeline between KP2.20 and KP2.60 where the backfill formed a berm which was higher than the adjacent seabed level. This was because the trench in that zone of shallow water had almost completely infilled with sediment during the post lay jetting and in the period between jetting and dumping of the rock. Additionally the rock dumping tended to form peaks rather than form a shallow uniform thickness protection to the pipe. The scour development along this section of the pipeline is assessed in this paper.

III. SCOUR RESPONSE OF BED

The pre-dredge survey of the seabed along the pipeline alignment showed the bed levels along the pipe route as indicated in Table I. The seabed topography around KP 2.00 was quite complex with a strong gradient in bed level from north to south of the pipeline associated with a deeper channel to the south of the pipe route at this location as indicated on Fig. 1. Beyond KP 2.55 the water depth becomes deeper.

The post-rock-dump surveys in the deeper water at KP2.00 showed the bed levels were reasonably stable but that the seabed at other KP points listed in Table I experienced scoring both north and south of the pipeline. The bed level changes from repeat surveys at the KP points in Table I were analysed as the project was underway and an example of the results have been plotted in Fig. 2.

TABLE I. PRE-DREDGE SEABED LEVELS MAY 1998

KP	Initial Depth S_0 (m)
2.00	16.0
2.10	13.5
2.20	11.0
2.35	9.5
2.45	9.5
2.55	10.5

Fig. 2 shows the pre-dump seabed level and the presence of the 1.5m high rock berm. The seabed survey shown for 21/06/98 was taken approximately 18 days after installation of the rock armour and at that time the seabed north of the pipeline had scoured by 6m and on the south side by about 8m.

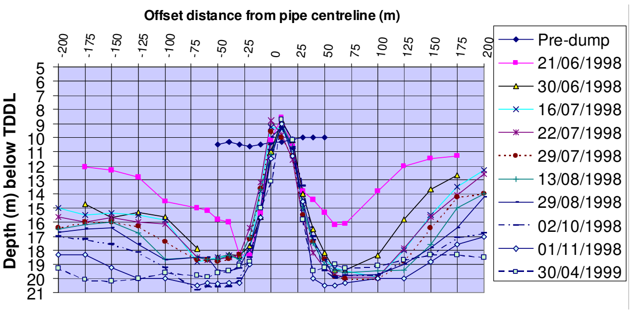

Figure 2 Seabed evolution at KP2.55. Survey profile lines run south and north of pipeline and show evolution of the seabed. South is represented by negative distances and TDDL is effectively local Chart Datum

The scouring continued over the following nine days to depths of 10m on the north side whereas on the south side the depth did not increase but the extent of scour did. By the end of April 1999 the scour areas had extended at least 200m from the pipeline but the depths of the scour pits adjacent to the rock berm were relatively stable and had shown a reduction in depth of a metre at this location. This is indicative of the long-term fluctuation in bed levels due to natural variations in flow and sediment supply adjacent to the pipeline.

The side slopes of the exposed rock berm were found to remain close to the theoretical angle of 25° (1V:2.1H) out to KP2.75 even in areas with scour such as those shown in Fig. 2.

The local scour response was attributed to the flow interaction with the rock berm structure giving rise to the generation of separated flow and high turbulence levels downstream of the berm. This produces a higher potential for sediment transport in the bed region immediately downstream of the berm which causes scour. Also with the fine sediment present at the site the rock berm will present a blockage to sediment transport from the upstream direction. The influence of the rock dump on the sediment transport is illustrated in Fig 3. With the strong bidirectional flow at the site this process leads to an alternating erosion on either side of the rock berm and hence the development of scouring leading to the reduction in sediment thickness Z above a given horizon with time. The increase in scour depth with time to an equilibrium level is illustrated in Figure 4.

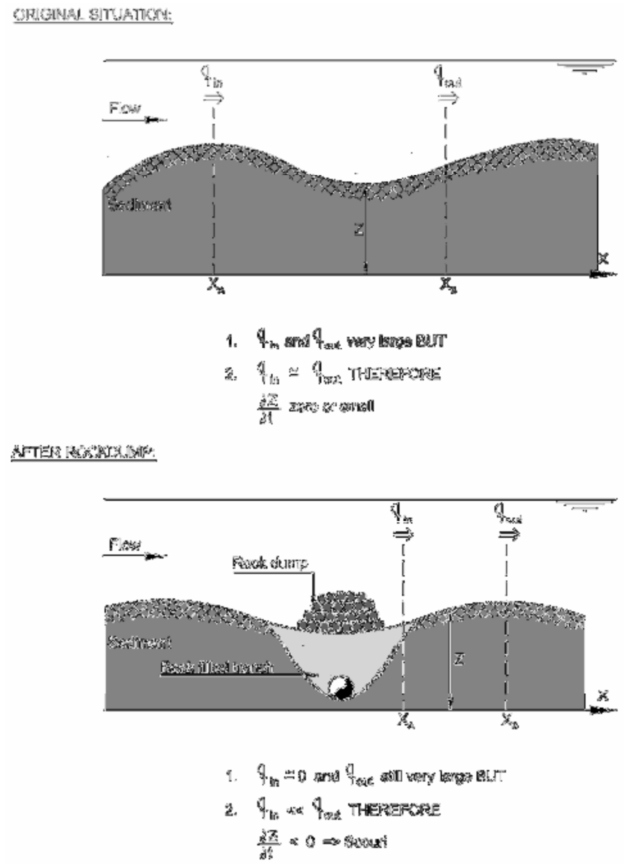

Figure 3 Schematic illustration of the influence of a rock berm on seabed sediment transport and scour development

The scour data was analysed for locations 50m north and south of the pipeline and the time histories of water depth below TDDL for KPs 2.1 to 2.55 were plotted (Figs. 5 and 6). The time of the main rock dump is shown on each of the figures and at those locations where remedial rock dump was carried out these are also shown on the Figures. The observed increase in water depth after the main rock dump is similar in form to the scour development curve sketched in Fig. 4. The scour development north and south of the pipeline at each KP follows a similar trend despite some differences in levels being observed at various times.

The maximum water depths recorded 50m north or south of the pipeline are listed in Table II and the increase in water depth is listed in Table III. Table III shows that at the two shallowest locations KP2.35 and 2.45 the water depth can increase by up to a factor of 2 from the initial values.

TABLE II. MAXIMUM WATER DEPTHS END APRIL 1999

KP	Max. Depth (m)
2.00	17.0
2.10	20.5
2.20	19.0
2.35	19.5
2.45	18.5
2.55	19.5

TABLE III. INCREASE IN WATER DEPTH MAY 1998 TO APRIL 1999

KP	Scour (m)	Ratio Scour to Initial Depth
2.0	1	0.063
2.1	7	0.519
2.2	8	0.727
2.35	10	1.053
2.45	9	0.947
2.55	9	0.857

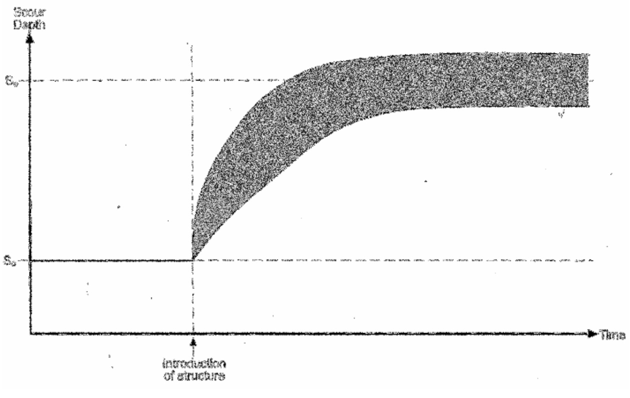

Figure 4 Illustration of scour depth evolution

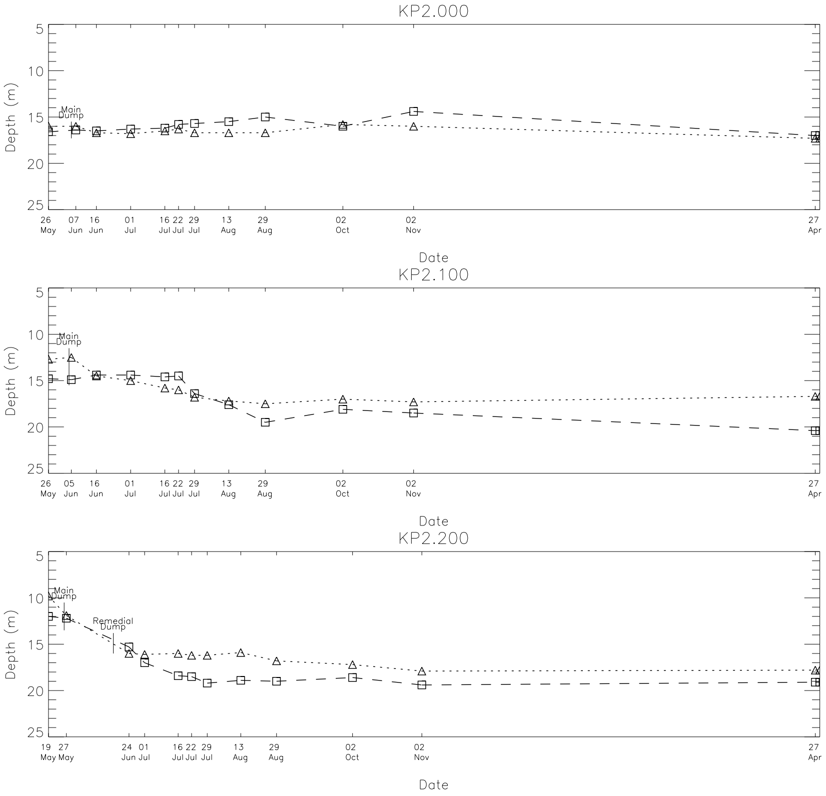

Figure 5 Seabed evolution at locations 50m either side of the pipeline (KP2.00 to 2.20)

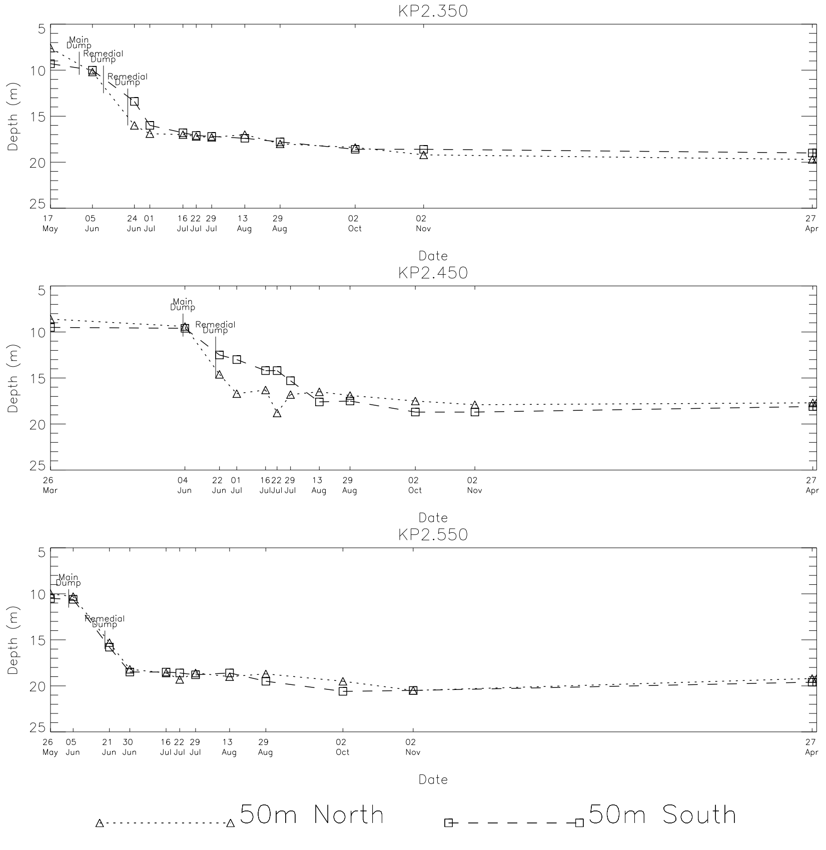

Figure 6 Seabed evolution at locations 50m either side of the pipeline (KP2.35 to 2.55)

IV. ANALYSIS OF SCOUR RESPONSE

The data was analysed to determine the characteristic response times for scour. This was carried out assuming the evolution of the depth of the scour hole with time S(t) at a particular location is adequately described by the equation:

$$S(t) = S_0 + S_{eq}\left(1-\exp^{-t/T}\right) \qquad (1)$$

Where S_0 is the initial depth before scouring occurs, S_{eq} is the equilibrium value of scour depth and T is the timescale of the scour process. The physical meaning of T is as follows: after a period of length T, the scour depth relative to the initial depth S(t) –S_0, is 1-1/exp or 63% of the equilibrium value. After a period of 2 times T the depth is 87% of the equilibrium value. Another way of viewing this is that approximately 90% of the equilibrium scour depth is reached after a time period of length equal to 2.3 times T. It is convenient to consider this time period as being the time taken for the scour to develop within 10% of the equilibrium value. The equilibrium value will fluctuate with time owing to natural variations and it is probably sensible to take 10% as being the level of precision that is achievable. In the present study the variation in scour depth after the initial period of scour development shown on Fig. 2 is of the order of 1m which equates to approximately 10% of the maximum scour depth. Differentiating the scour equation (1) with respect to time allows the initial rate of scour development to be estimated from the ratio S_{eq}/T.

An analysis of the data was made during the project (November 1998) using the data obtained up to October 1998. The results of that analysis are presented in Table IV based on the initial phase of scour development.

TABLE IV. INITIAL ANALYSIS OF SCOUR RESPONSE

KP	S_0 (m)	S_{eq} (m)	T (days)	S_{eq} / T (m/day)
2.00	16	0	0	0
2.10	15	3	14	0.21
2.20	12	6	46	0.13
2.35	10	9	35	0.26
2.45	10	9	44	0.21
2.55	11	10	30	0.33

Based on the results in Table IV for KP2.10 to 2.55 the values of 2.3 times T are 32, 106, 81, 101 and 69 days respectively. By comparison of these timescales with the elapsed time of approximately 125 days between the main rock dump and the date of the October survey it was concluded that the scour development was close to an equilibrium state.

Since more survey data was collected between October 1998 and April 1999 it has been possible to make an assessment of how close those predictions were in the light of this additional data. The scour equation has been fitted to the time series data of Figs. 5 and 6 to evaluate the scour coefficients obtained in Table IV. The equation provides a general form for the scour depth evolution for comparison with Table IV. The plots in Figs. 7 and 8 are obtained by plotting scour development curves using the estimates presented in Table V.

Based on the estimates using the scour equation, after 11 months the early assessments of S_{eq} are within a metre of the value of S_{eq} specified in Table V, and within 1 to 2 metres of the maximum recorded values (Table II). The comparison can be seen on Fig. 7 for KP2.20 where the scour depth for the south side at the end of April 1999 is slightly greater than the value obtained using equation (1) with the coefficients given in Table IV. The data for KP2.20 has also had a curve with S_{eq} of 8m and timescale of 51 days plotted to evaluate the sensitivity to the parameters selected. This overestimates the scour on the north side. It is interesting to note that in some cases the scour depth has reduced compared with the predicted curve, as can be seen in Fig. 8 at KP2.45 and KP2.55. This indicates some infilling of the scour hole has taken place at these locations after the October 1998 survey.

This exercise indicates the value of survey data in assessing the evolution of scour morphology through the application of a scour prediction equation such as (1). The coefficients can be estimated from the initial phase of scouring to make an assessment of the final scour depth and time to reach equilibrium.

TABLE V. FINAL ANALYSIS OF SCOUR RESPONSE PLOTTED IN FIGS. 6 AND 7

KP	S_0 (m)	S_{eq} (m)	T (days)
2.00	N/A	N/A	N/A
2.10	N/A	N/A	N/A
2.20	12.0	6* 8	46* 51
2.35	9.2	9.8	38
2.45	9.3	9.7	47
2.55	10.0	11	34

N/A Not Analysed

*Values from Table IV

The scour response is considered to have been mainly due to tidal current forcing, it was relatively calm in May and June 1998, although it may have been sped up slightly by wave action had severe weather occurred. A period of severe weather did occur in Autumn 1998 resulting from typhoon activity and the resulting wave conditions were examined. Wave hindcast data for the period between 19 September and 19 October showed five storm events exceeding 1.5m significant wave height in that period, of which the most severe had a peak significant wave height up to 2.2m and associated period 5.7sec. Examination of the scour time series showed no evidence for the scour depth that had already been reached as being significantly affected by the action of the waves.

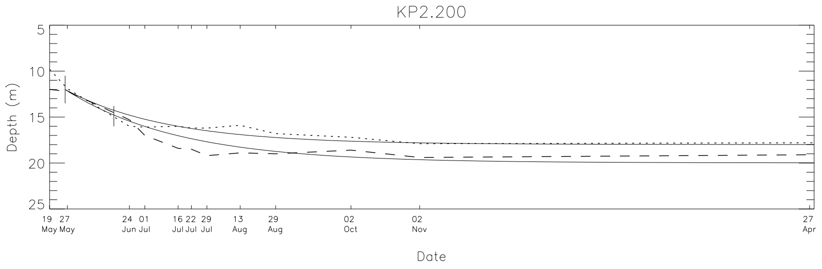

Figure 7 Scour curve fitted to seabed evolution data at KP2.20

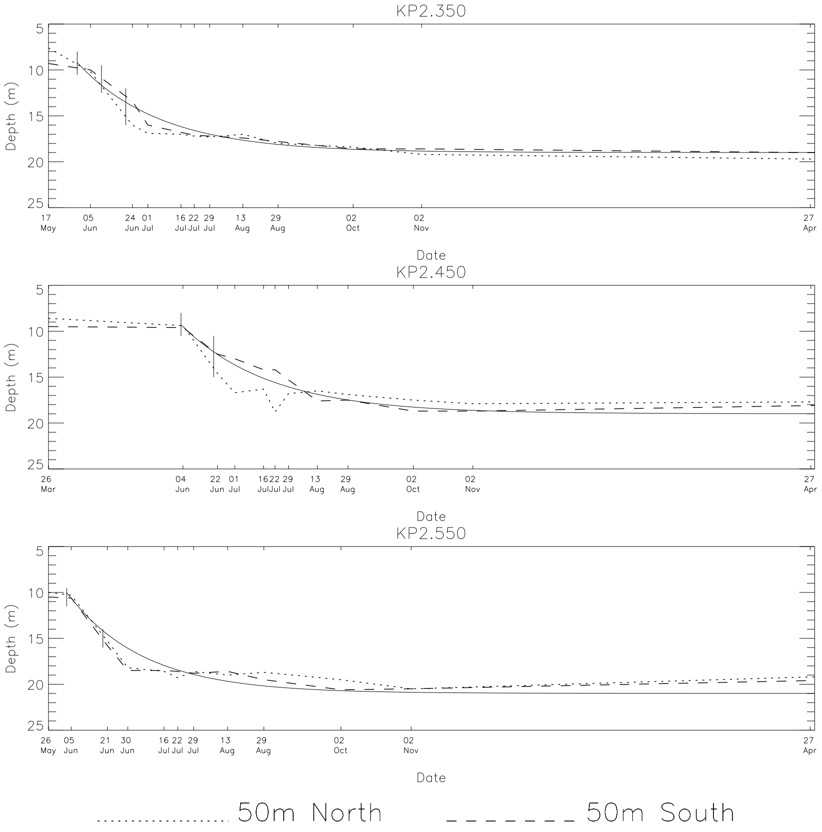

Figure 8 Scour curve fitted to seabed evolution data at KP2.35 to 2.55

In addition to the scour either side of the rock berm it is worth recording that significant scour occurred at the offshore end of the berm. This was attributed to the flow interaction with the rock berm structure giving rise to the generation of separation flow and high turbulence levels. The berm acted as a subsea dam and the flow acceleration round the end of the dam caused scour. It was this scour which gave rise to subsequent problems with the Pinghu pipeline, which is not the subject of this paper.

V. Final Remedial measures

During the end of August and in early September 1999 a remedial pipe protection was installed in the areas affected by scouring. This comprised a low height engineered solution laid over the pipeline alignment with a gravel dump (80mm to 10mm grading) armoured with an array of 0.5m thick 10m x 5m geotextile mattresses, filled with a gravel/sand mix, with their long axis installed perpendicular to the pipeline. The extensive scour that occurred at the offshore end of the berm was rectified with geotextile bags.

VI. Conclusions

The combination of the soft soils and fast tidal flows in an area with varying seabed topography led to the extensive scouring of the seabed soils either side of the engineered rock armour installed over a trenched pipeline. The scour development was rapid and led to a doubling of the original water depth over a period of about four months. Repeat surveys of the seabed topography were used to monitor the scour development and to inform appropriate measures relating to remedial rock dumping and the installation of geotextile mattresses some 11 months after installation.

For pipelines in soft soils with high current speeds in shallow water it is recommended that the engineered rock armour is placed over the pipeline within the depth of the trench. If rock armour cannot be placed within the depth of the original trench (i.e. so the finished level is flush with the seabed) then it is recommended that the need for and advantages of the rock armour are reconsidered. However, if the rock armour is unavoidable, the experiences on this project show that a rock berm can be used to protect the pipeline provided a sufficient volume of rock is used to account for scouring that will occur. It is recommended that the rock berm height is minimized and the rock berm is extended significantly each side of the pipeline location, rather than increasing the height. If rock armour is not required an alternative approach would be to consider enhanced self-burial of the pipeline with spoilers providing it was demonstrated that the flow and soil conditions were suitable to generate the tunnel erosion under the pipeline for this method to work. This has been proven effective on the recently completed offshore section of the Hangzhou Bay crossing in water depths of 10m, bottom currents of 0.8 to 1.6m/s and higher and loose, silty sands [2]. Engineered backfill was not adopted as a solution at that site because of the large range of natural bed level changes up to 6m that can occur.

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