

Experimental manipulation of sandwaves to reduce their navigation hazard potential, Jade shipping channel, N. Germany

John H. REDDING

Independent Geological Consultant acting for Silt (UK) Ltd

Fax: +44 (0)1424 870294

Email: info@silt-uk.co.uk

ABSTRACT

In March 1997 the Jade Shipping Channel was the location for a trial, to determine the ability of a water-jetting device (the Wing Excavator) to lower the crests of sandwaves, which pose a navigation hazard. Several methods of operation were tried, including displacement of sand from the crests and deep trenching through the crests. State-of-the-art surveying techniques were used to establish the location and morphology of the sandwaves, and determine the volumes of excavation. Despite encouraging results from each of the trial stages, the final cumulative volume of excavation proved surprisingly low and was insufficient to convince the Waterway Authority of the effectiveness of the technique. Subsequent re-evaluation of the data has shown that, rather than surveying errors being responsible for the anomaly, rapid re-building of the sandwave crests was the cause. Re-building appears to take place in a matter of hours or days, provided that the crests are not lowered by more than 50% of their original height. Crests that were deeply trenched did not re-build in the same way. Symmetrical trochoidal sandwaves of the type present in the trial area are common in the Jade. Oblique imagery of the sandwaves derived from the processed swathe bathymetry, reveals many features that would accord with a Hulscher-type of sandwave building mechanism. Rapid re-building of the crests highlights the inefficiency of any technique that seeks to control the navigation hazard by displacing or removing material from the crests. By considering the dynamics of sandwave/water flow interaction, an alternative method for reducing the up-building tendency is proposed.

INTRODUCTION

The Jade tidal inlet (Figure 1) forms an important waterway access to N. Germany. The inlet has a 34km long by 300m wide, centrally-located shipping channel, which carries mainly in-bound crude oil and out-bound refined petroleum products. To ensure safe passage for large bulk tankers, the Waterway Authority (Wasser –und Schiffahrtsamt GmbH, Wilhelmshaven - "WSA") regularly surveys this channel and carries out dredging work to maintain designated minimum water depths. These depths vary from 19.4mSKN (German Chart Datum) at the entrance to 18.0mSKN near the port of Wilhelmshaven, at the head of the channel.

The channel was last deepened, by capital dredging, in the late 1950's, when the depth was increased to between 20 and ()mSKN; approximately 5m below the natural channel bed. Along a significant portion of the channel, sandwaves have developed and pose a potential hazard for deep-draught vessels, because their crests regularly extend above the maintained navigation depths. Despite frequent maintenance dredging, the crests rebuild, although the shoal areas do not always re-occur at the same location. This means that the WSA are locked into a constant cycle of surveying and dredging, in order to keep the waterway clear. Disposal of the dredging arisings has significant cost and environmental implications, since wherever dredging takes place in the channel, the material has to be transported to offshore dumping grounds in the German Bight.

During the period 19-25 March 1997, an alternative method of sandwave crest lowering was tried along a short section of the shipping channel off Hooksiel (as indicated in Figure 1). The trial involved the use of the Wing

Excavator - a water jetting system specifically designed for controlled excavation in sand (Figure 2 and 3). The system works by eroding the in situ material wherever the jets impinge on the bed, and re-depositing it at a relatively short distance from the excavation site. Because there is no net removal of material, there are obvious benefits to its use for bed lowering where nearby deeper water is available to accept the excavated material. Lowering the crests of sandwaves by means of water jetting can be seen as a process of bedform manipulation and, therefore, potentially more efficient and environmentally "friendly" than conventional dredging.

In terms of planning the trial, two important factors had to be considered:

- How to reduce the crests of sandwaves to achieve an acceptable and lasting increase in water depth.
- How to verify the volumes excavated for payment purposes, given that no material was to be physically taken away. It is worth noting that conventional dredging is typically costed on a hopper volume basis.

Accurate surveying, using high-resolution multi-beam swath bathymetry was considered to be an essential part of the trial. A pre-survey was required to enable initial identification of the position and morphology of the sandwaves, with intermediate (pre- and post-) and final surveys to monitor the progress of excavation and to confirm final cut and fill volumes.

Commercial pressures at the time meant that the trial was not as scientifically controlled as it might have been. Also, because the results appeared inconclusive and the survey data seemingly ambiguous, the WSA were not moved to instruct further work that could have provided the opportunity to evaluate the trial results more fully and monitor the changes in sandwave form over a longer period of time. Interpretation of the March 1997 trial in relation to sandwave dynamics was, therefore, put on hold. For the author, the inability to explain certain features of the trial data has been a lingering source of irritation since 1997. Recently, however, the opportunity to carry out a comprehensive review of sandwave morphology and dynamics, prompted a fresh look at the Jade data from a slightly different perspective. The outcome of this re-evaluation is the subject of the present paper.

1-HISTORICAL BACKGROUND

The Jade can be considered the birthplace of sandwave morphological research and also a classic area in terms of developmental thinking on sandwave internal structure. Although, this was not fully appreciated at the time of the trial.

Among the very first references to the morphological study of marine sandwaves is that of Lüders (1929) who described the contribution of tidal currents to the construction of Giant Ripples (colloquial name) in the outer part of the Jade. More recently, Reineck and his co-workers at the Senckenberg Institute in Wilhelmshaven (Reineck 1963, Reineck and Singh 1967, Wunderlich 1969, 1978) have studied the internal sedimentary structure of these bedforms.

Published features of the Jade sandwaves, which seems to set them apart from sandwaves in other areas and makes generic comparison of their dynamics more difficult, are as follows:

- The Jade sandwaves are frequently of the symmetrical trochoidal type (van Veen 1936) or variants on this type (Figure 4A).
- The internal structure is one of complex cross bedding, which is a consequence of their having been built up from mega-ripples (Figure 4B).
- Thin layers of mud frequently occur interbedded with the sand, which is a reflection of the very turbid water conditions within the inlet.
- The crests of the sandwaves are covered with coarse sand, while the intervening troughs comprise fine sand.

2-PREPARATION FOR TRIAL

In the days leading up to the Jade trial, the WSA kindly provided survey information to assist with planning and the selection of suitable locations. The information included the results of repeat hydrographic surveys carried out along the channel over the preceding 2 years, as well as tidal and current data for the immediately preceding 2 months. A section of channel opposite the small harbour at Hooksiel (Figure 1) was selected for the trial.

Examination of the WSA single beam echo sounder line survey data (a detail of which is shown in Figure 5), revealed the sandwaves within the shipping channel to have the following outline characteristics:

- Their crestlines run transverse to the channel and more or less at right angles to the tidal currents.
- They have heights of 2-3m and wavelengths of approximately 50m
- Crestlines of the larger sandwaves appeared to extend across the full width of the channel.
- There was evidence of the lateral extremities of the sandwaves being "rooted" to the sides of the channel.
- Slight movement of some sandwaves was discernible over the 2 year period for which survey information was available, although individual sandwaves appeared to maintain their identity.
- Most, but not all, of the high points on sandwaves occurred on the lateral extremities.
- The broad trough areas between the sandwaves extending to below 20mSKN, providing ample space to accommodate the material excavated from the crests.

It was confirmed by the WSA that while some reduction in sandwave crest levels does occur naturally during storms, lowering of high points does not happen spontaneously and has to be dealt with by dredging.

Tidal current data for the nearest location in the channel (approximately 8km north of the trial area, see Figure 1) indicated rectilinear and nearly symmetrical ebb and flood tidal flow aligned with the channel; the periods of slack water being very abbreviated. Peak velocities appear to alternate from flood to ebb over the spring/neap cycle.

3-THE WING EXCAVATOR TRIAL

Operational Spread

The Wing Excavator system was mobilised from Wilhelmshaven on-board the "Steinbutt", a converted DP stone-dump barge (Figure 2). A specially constructed stern A-frame was used to deploy the Wing, which was supported from four corner suspension wires. The wires could be operated either in pairs, to enable the Wing to be raised and lowered, or independently, to provide precise attitude adjustment. In the operational position, the Wing was suspended cradle-wise approximately beneath the wheelhouse of the Steinbutt (Figure 3). A motion sensor on the Wing enabled continuous monitoring of Wing azimuth and attitude.

A Seabat 9001 multi-beam swathe bathymetry system was used to record water depth and changes in bed configuration. The Seabat sonar head was mounted through a small central moon-pool on the vessel, with the orientation of the head being manually adjustable. An athwartships beam orientation was used during normal surveying operations, with an alongships orientation being adopted when operating the Wing. With the latter orientation it was possible to observe the progress of excavation on a monitor screen. Unfortunately, processing of the Seabat data could not be carried out on-board and there was a minimum 24hour turn-round time for processed data, which posed a major constraint in terms of control of the whole operation. Positional control was with Trimble RTK DGPS.

Wing Thruster Characteristics

The two Wing thruster motors are powered by electricity generated on the support vessel and transmitted to the Wing by separate umbilical cables, so that each thruster can be operated independently. The thrusters are mounted vertically and ()m apart and during normal operation they produce two downward-directed jets of water. The direction of the jets can, however, be adjusted by changing the attitude of the Wing. At full power, each of the 165kW thrusters produces a discharge of 5.8m³/s, at a nozzle velocity of 7.6m/s.

With distance from the nozzle, the jets entrain water from the surround host water body. This results in a spreading of the jet and a reduction in jet velocity both axially and more particularly towards the margins. However, even at a distance of 4m where the jets start to overlap, the velocity is still well in excess of the threshold for sand erosion and the volume discharge is many times greater than at the nozzle. With the two jets operating together, at a stand-off distance of 4m, the erosion capacity in sand is of the order of 1500-4000m³/hr.

Morphology of Sandwaves as Revealed by Preliminary Survey

A preliminary survey was carried out of a 350m long by 225m wide section of the shipping channel between Km17 and Km18. Seven individual sandwaves (identified by the letters A to G in Figure 6) were encompassed by this survey, and their geometrical characteristics are summarised on the figure. They are all symmetrical trochoidal forms with curvi-linear crest lines, which as Figure 6 shows are better formed towards the northern end of the trial area. Towards the southern end, they become somewhat more branching .

An interesting alternative visualisation of the preliminary survey data, generated using () software, is given in Figure 7. This shows an oblique (vertically exaggerated) image of the trial area viewed from the northeast. The effect of the perspective is to reduce the relative size of the more distant sandwaves, but the form of the near-field sandwaves (sandwaves A, B and C) is clearly evident. This image will be referred to again in the subsequent discussion. However, it is worth noting that with this form of survey, high points on the sandwaves can be picked up which might otherwise be missed by conventional line survey.

Methods and Results of Wing Operation

Based on the preliminary survey of sandwave locations and geometries and bearing in mind that the primary objectives of the trial were sandwave crest lowering and volume excavation, three methods of Wing operation were selected, as follows:

Method 1

This consisted of running lines up and down the channel parallel to its axis, keeping the Wing at a fixed depth of about 14m below the surface. Clearly, with this method, the excavation ability of the jets will be constantly fluctuating due to the variation in water depth along the vessel track, and excavation of the sandwave crests will be intermittent. However, the simplicity of this method from an operational and navigation standpoint made it attractive. At a 0.25kn speed of traverse, and with the support wires maintained at a fixed length, the Wing tended to set back slightly in the water, giving an upward tilt in the direction of travel of about 5°.

The results of this method of operation carried out on the 20th March are clearly evident in Figure 8, which shows areas of cut and fill determined by comparing the DTM (Digital Terrain Model) from the preliminary pre-survey with that from an immediate post-survey. Particular features evident in Figure 8, include:

- The relative dispositions of the areas of cut and fill, which straddle the sandwaves and clearly define their crestlines, even without reference to the base topography.
- The fact that cut areas always occur on the upstream and the fill areas on the downstream side of the sandwaves relative to the direction of vessel travel. Note that these orientations are reversed on adjacent up- and down-channel lines.
- The maximum depth of cut with each pass was of the order of ()m.

The trial excavation shown in Figure 8 was carried out during neap tides over a period of slack water, so that the influence of tidal currents is at a minimum.

Method 2

This method was designed to achieve more efficient and rapid excavation of the sandwave crests and consisted of orientating the vessel parallel to the channel and crabbing sideways along an individual crestline. Clearly, this method requires precise knowledge of the location of the sandwaves, as well as DP and skilled vessel handling.

The results of this trial, carried out on the 21st March, are presented in a similar cut and fill chart in Figure 9. During this method of operation the Wing jets were directed vertically downwards and this is reflected in the fact that excavated material is displaced equally into the trough areas on either side of the sandwave crests. An average of 1.0m of crestline lowering was achieved with four passes along each of the more northerly sandwaves. On the more southerly sandwaves, a lesser number of passes was used and this is reflected in the smaller depth of excavation. Note that this method was applied to the same sandwaves previously subjected to the Method 1 excavation on the 20 March.

Method 3

Method 3 was very much an experimental method intended to disrupt the lateral continuity of the sandwave crestlines and thereby (hopefully) cause the sandwaves to break up and disperse. At the time, the author was not aware of any previous attempts to control sandwaves in this way, although there was some precedents in the form of pipeline trenches cut across sandwaves. Anecdotal evidence, however, seemed to suggest that such trenches tended to infill quite quickly and so no great reliance was being placed in this method.

The procedure adopted was to "park" the vessel over a sandwave crest and traverse slowly backwards and forwards keeping to the same line. Again, this required DP, although the vessel handling was less demanding than Method 2. The trial was carried out late on the 21st March and the results are also shown in Figure 9. With this method it was relatively easy to directly observe the increase in water depth using the Seabat monitor. Cut depths of up to 2.4m were achieved using this method. Note that this method was applied to areas previously excavated by Method 1, although the Method 2 and 3 areas were kept separate.

Excavation Volumes

The WSA were particularly concerned with the total volume of material excavated from the sandwave crests and so a target figure of 50,000m³ of excavation was originally agreed before the start of the trial. This was the main reason why all of the trial work was initially carried out in one area, to facilitate measurement of the cumulative excavation volume. It was recognised that to achieve the target volume without completely flattening the sandwaves, more of the channel would have to be included and the intention was thus to move on to other sections of the channel once the most efficient method of excavation had been established.

For a variety of reasons (bad weather, equipment failure, survey processing delays, vessel breakdown) the amount of operational time within the six 12-hour days allocated for the trial was severely curtailed and amounted to only 19% of the total time. The loss of operational time meant that the target excavation figure was never going to be achieved and other sections of the channel were, therefore, never included. Nevertheless, the provisional total volume of excavation, based on a summation of the individual volumes following each trial method of operation, amounted to 23,000m³ and compared quite favourably with previous excavation work in giving an average rate of excavation of 1700m³/hr. A final post-survey of the area was carried out on the 25th March and formed the basis for calculation and verification of the total volume of excavation. When the DTM for this survey was compared with the DTM from the pre-survey, the volume of excavation only amounted to some ()m³.

Bearing in mind that the excavation work was spread out over quite a large area, to a relatively shallow depth below the original bed level, errors in vertical and horizontal referencing would have a potentially large impact on volume calculations. Added to which, adjacent areas of filling would also have a particularly adverse impact if they were not accurately referenced within the DTM. Survey referencing errors, amongst a variety of other reasons, were put forward to explain the apparent ambiguity. One explanation that was not considered at the time, was that the sandwaves might be re-building themselves and in effect reversing the effects of each of the individual elements of excavation work.

4-DISCUSSION AND RE-INTERPRETATION

With the benefit of hindsight, rapid sandwave re-building can be seen to offer a plausible explanation for the apparent anomaly in excavation volumes. It also gives a startling insight into sandwave dynamics, but raises serious questions regarding how best to deal with the Jade sandwaves as a navigation hazard.

Closer scrutiny of the post-survey (Figure 10) revealed that, while those individual sandwaves subject to excavation to less than 50% of their crest height appeared to have more or less completely recovered, the deeply trenched sandwaves still showed clear evidence of the trenching to nearly the original depth. Closer examination also revealed smaller secondary sandwaves forming on the upstream side of sandwaves A and B that were not present on the first pre-survey. Local "necking" was also evident along these same two sandwaves at locations that had experienced the greatest overall amount of excavation by Method 1 and 2.

The ability of large sandwaves to recover their crestline height following lowering by storms is well-documented (Terwindt 1970, Langhorne 1982, Dalrymple 1984, Houthuys 1994). However, the depth of lowering that will still permit recovery of the sandwave to its former size and shape appears not to have been researched. Sandwave height recovery and rates of recovery have also not been evaluated in relation to specific sandwave geometries or hydrodynamics. It is worth stating again that the Jade sandwaves are symmetrical trochoidal forms, and as such may have to be treated as a special class of bedform.

One indication of this uniqueness is shown in Figure 11, which is a graphical plot of the geometrical characteristics of sandwaves from a number of different tidal environments. The base for this plot is the diagram (Figure 9) given in the paper by Berné et al (1993) on the sandwaves of the Gironde Estuary. The Gironde is similar to the Jade in many respects, particularly in its tidal characteristics, although there is an additional fluvial influence, not present in the Jade. Other features that have been added to this figure include:

- The $L/H \geq 30$ criteria established by Yalin (1964), which defines a regime (in the upper part of the diagram) of essentially mobile sandwaves. Note the Yalin criteria apply primarily to unidirectional and water-depth-limiting flow conditions.
- The corresponding angle of slope of the steeper (lee) face of the sandwave based on standard geometrical characteristics. Note that while a 14° slope does appear to form a bounding line to the data points, the individual slope lines shown are tangents drawn from the crest to the base of the slope. They are not, therefore, a true representation of trochoidal sandwaves, which have concave slopes.

A particularly interesting feature of the diagram, is the apparent absence of symmetrical sandwaves with L/H in the range $20 \leq L/H < 30$, although there is a clear transition through this range in the case of weakly to moderately asymmetrical forms. It has to be recognised that this may be an artifact of the data, but assuming it to be real, it suggests that if trochoidal forms are flattened sufficiently, they will not spontaneously re-build to their former height. In the case of the Jade sandwaves in the trial area, the height (H) would have to be less than 1m (i.e. 1.5m of lowering) for re-building not to occur.

Clearly, this amount of lowering was not achieved in the majority of cases and to have to systematically reduce the height of Jade sandwaves by more than 50% to effect control over their re-building, would not be a practicable solution. However, such lowering was achieved locally in the case of the Method 3 trial and seems to have curtailed the rapid re-building process. Nevertheless, a change in sandwave geometry, *per se*, cannot be seen as a validation of Figure 11, or of the foregoing argument. An alternative way of looking at the problem is to consider the hydrodynamics.

Recently, Hulsher (1996) has demonstrated growth of sandwave-size bedforms in a numerical model. The mechanism for sandwave building is residual currents that develop as a result of tide-topography interactions. The sense of movement of these residual currents is shown in Figure 12 and is characterised by convergence of flow towards the sandwave crest on both sides, during ebb and flood tides. Similar types of converging flow, originating in different ways, have previously been proposed by Houbolt (1968) and Allen (1980).

The oblique image of sandwaves from the trial area, shown in Figure 7 and referred to earlier, is considered to be as close to a realistic "snap-shot" of sediment-water flow interaction as current (1997) technology would allow.

If vertical exaggeration and foreshortening due to perspective are disregarded, the sandwaves on the right-hand side of the image (Sandwaves A and B) can be seen to have many of features that might be expected from the type of sandwave building mechanism postulated by Hulscher:

- The crestlines are very sharp, wavy and vary in height along their length. This is considered to be indicative of converging currents of varying strength, which meet at the apex of the sandwave where they cause the crestline to oscillate.
- The flanks of the sandwaves are ribbed and striated, which is seen to be an indication of the strength of the rising currents, causing sediment streaming and scouring as material is carried up to the crest. These sandwaves may thus not simply be depositional bedforms, but also erosional features excavated into underlying older sediments. Note that the striations run at right angles to the crestline, indicating an absence of diagonal water and sediment movement.
- The flat-lying troughs clearly represent a different environment, which is not part of the bedform. The troughs are evenly covered in irregular humps and hollows, which in reality are probably 3-D mega-ripples with pronounced scour pits. They would be the expected manifestation of irregular descending currents and highly turbulent main stream currents and eddies developed in the lee of sandwave obstructions.
- On the lower flanks of the sandwaves these supposed mega-ripples can be seen to climb above the general trough level, although only part-way up the sandwave flanks. The absence of mega-ripples on the upper flanks of trochoidal sandwaves appears to be a characteristic feature, which is evident in other published examples (see for instance Kirby & Oele 1975, Wunderlich 1978). It may be indicative of plain-bed conditions towards the crest associated with higher velocities and/or coarser sediment grading. Published examples also invariably indicate the mega ripples on the lower flanks to have their steeper slopes facing towards the sandwave crestline on both sides, another indication of the crestward direction of net sediment transport.
- Branching is also a feature of the trial area sandwaves, with the subsidiary branches showing the same type of symmetrical form, but often extending away from the main sandwave at a rather obtuse angle.
- The edge of the shipping channel can be seen in the background of the image, with the sandwaves clearly "rooted" to this face and the crestlines rising towards the channel rim. One small sandwave on the eastern side of the channel appears to be growing outwards from the edge of the channel.
- The angles formed between the sandwaves and the edges of the channel and between the larger sandwave branches themselves, appear to enclose rounded hollows, which are also evident on the contour charts. They are thought to be indicative of circular eddy currents and diverging residual currents, tending to prise apart the sandwave branches. Branching, therefore, appears to be a splitting rather than a joining phenomenon.
- Overall, the sandwaves appear to act as partitions between the trough areas (or cells) in which the near-bed residual current circulation takes place. The cells can be either laterally elongated, extending across the full width of the shipping channel, in which case the sandwaves are well-formed 2-D types (Sandwaves A and B). Or they may be smaller and more elliptical in form, in which case the sandwaves are more branching and 3-D in type.

While a Hulscher-type of mechanism would seem to accord with many of the morphological features of the Jade sandwaves, the growth limiting term currently embodied in the model (Hulscher 1996) would need to be suppressed to permit the rapid crestal up-building, which is one of their main behavioural characteristics.

Diagonal water flow and sediment movement is neither a feature of the Hulscher model nor, apparently, of the Jade sandwaves. However, lateral transfer of momentum within the rising secondary currents, due to high eddy viscosity, may well be. Eddy viscosity is a function of turbulence intensity, and high turbulence is indicated by the 3-D type of mega-ripples present in the trough areas. Advection would thus ensure a well-developed transverse continuity within the residual current flow across the sandwave flanks, and in turn help to generate and sustain the 2-D form of these sandwaves.

It follows, however, that lateral distribution of sediment along these sandwaves cannot be a very active or spatially uniform process. This is in direct contrast to asymmetrical sandwaves or flat symmetrical forms, which often have regular patterns of diagonally orientated and advancing mega-ripples on their flanks. With the Jade sandwaves lateral distribution of sediment can be visualised as taking place (relatively slowly) by the constant transfer of material from one side of the crest to the other, combined with persistent flexing of the crestline. Local culminations (high points) along the crestline are thus a consequence of this rather haphazard "flip-flop" process of sediment transfer.

The Jade sandwaves appear to be nourished by two sources of sediment: material eroded from the trough areas and material eroded from the edges of the channel. On the basis of the foregoing discussion, it is evident that the trough areas provide the most ready source of material, particularly for the mid-channel sections of the sandwaves. The channel margins will provide material only slowly to the central crest areas, hence the marginal crests tend to be higher. There is some evidence that the fully transverse sandwaves may have originally formed partly by outward growth of sandwave "fingers" from either side of the channel, which then met in the middle.

5-IMPLICATIONS FOR FUTURE CONTROL OF SANDWAVES

One of the obvious consequences of the re-interpretation of the 1987 Wing trial data is that neither:

- Displacing material from the crests into the adjacent troughs, i.e. by means of jetting, nor
- Removing material from the crests, i.e. by conventional dredging,

can be considered efficient solutions to the problem of recurring crestline build-up of the Jade sandwaves. The dredging solution is particularly inefficient because, in the long run, all that it serves to achieve is an increase in the depth of the trough areas and/or an increase in the overall width of the shipping channel. To consider either method as a basis for long-term control would be futile. The question is whether there is a more efficient long-term solution. This question remains to be answered, but within the framework of the foregoing discussion there is the basis for a solution.

It has already been mentioned that flattening the sandwaves, to more than half their current height, would not be practicable, except for local areas. Deep trenching through the sandwaves, however, to cut them up into a number of sections would be practicable, as would a certain amount of controlled displacement of the crestlines by selective cutting and filling. Deep trenching can be seen as a way of disrupting the lateral continuity of the residual current flows that are responsible for the 2-D form of the sandwaves and more importantly their upward crest building capability. In effect, the severed ends of the trenched sandwaves would lose contact and not spontaneously rejoin because there is no natural repair mechanism. This is seen as being in marked contrast to asymmetrical and flat symmetrical sandwaves, where diagonal trains of mega-ripples will migrate to rapidly infill a trench cut transversely across the sandwave (see for instance the description by Barber et al 1999). The upward building propensity of the individual segments will also be suppressed, because the latter is linked to the overall dimensional scale of the circulating currents, which will also be disrupted.

The material excavated by trenching (using the Wing) would be displaced into the adjacent trough areas, where it would not immediately be available for re-building onto the sandwave. It would, however, influence the pattern of residual flow by creating cross partitions and dividing the troughs into smaller cells, in effect creating a 3-D flow pattern. It is essentially the breakdown of the 2-D sandwave pattern into a stable 3-D pattern that is seen as the key to controlling the upward crest-building tendency and thereby the navigation hazard. With a 3-D pattern not only would more of the trough areas be occupied by bedforms, hence a more even distribution of sediment, but the discretisation of residual current flow and sediment movement would mean that there is less opportunity for organised up-building.

CONCLUSIONS

The symmetrical trochoidal sandwaves of the Jade shipping channel are sessile, upwardly mobile bedforms, which are considered to be a discrete class of sandwave. Their morphology and hydrodynamics is well displayed by

oblique imagery derived from multi-beam swathe bathymetry. The Jade sandwaves show many features, which would accord with a Hulscher-type of building mechanism. The tendency for their crests to build up and create a navigation hazard is an on-going process, but is greatly accelerated by any removal or displacement of material from the crest. This up-building repair mechanism will operate spontaneously, provided that the crests are not excessively reduced in height or the lateral continuity of the sandwaves disrupted. Active re-building highlights the futility of trying to manage the navigation hazard by conventional dredging or displacement of material from the crests. The trial with the Wing Excavator has not only offered an insight into the dynamics of these sandwaves, but holds out the possibility of a more efficient long-term solution for managing the sandwave hazard.

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Figure 8. Method 1 cut and fill areas.

Figure 9. Method 2 and 3 cut and fill areas.

Figure 10. Contour plot of post-survey of trial area.

Figure 11. Sandwave geometrical properties.

Figure 12. Residual currents in Hulscher-type sandwave building mechanism.

(Note: figures not attached)