OPERATIONAL PROCEDURES
RICHARDS BAY HARBOUR

by

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ABSTRACT

The new port of Richards Bay on the east coast of South Africa (Figure 1), was officially opened in April 1976 and was mainly built for the export of bituminous coal. Exports increased from an initial 2,5 million tons per annum to 26,5 million tons per annum in 1981. Extensions are now under way to increase this further to 44 million tons per annum by 1987.

Fig. 1 Richards Bay Harbour

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Because near-beam long swells occur frequently at Richards Bay, special care was taken with the design of the entrance channel. These swells cause much greater vertical ship motions than normally occur in other ports around the world and a 24 m deep outer channel was therefore provided for the 17 m draught design ship (40 per cent underkeel allowance, based on physical model tests).

Vertical motions recorded at Richards Bay as part of a comprehensive research project into ship motions in shallow water confirmed that this large underkeel allowance is realistic. Experience with ship manoeuvring also indicated that the channel width (300 to 400 m) and the stopping length (6,1 km) are adequate, probably for ships up to about 250 000 dwt.

To assist the port operating staff in deciding whether a particular entry or departure of a loaded vessel under adverse conditions is safe, particularly with regard to underkeel clearance, a **Port Operation Manual, Mark I,** was prepared. This manual describes the procedures for collecting ship and environmental data and contains diagrams from which the limiting wave height or the minimum required tide level can be read off as function of wave direction and the ship's draught.

This manual has been in use since October 1981 and has already been found very valuable in the operation of the port. As the research into ship motions progresses, the manual will be updated.

INTRODUCTION

Richards Bay harbour was officially opened to traffic on 1 April 1976. The harbour was built for the handling of bulk cargoes, initially, mainly the export of bituminous coal. Situated on the Zululand coast between Durban and Maputo, it was the nearest suitable site to the Transvaal and the Orange Free State coal fields. Total cargo handled during 1981 was 29,4 million tons of which 26,5 million tons was coal.

A detailed description of the design and construction of the harbour was given by Campbell and Zwamborn (1977).

Layout

The overall harbour layout is shown in Figure 2. The relevant dimensions of the **entrance channel** are as follows:

length,	outer channel	~ 3,5 km
	inner channel	6,1 km (available stopping length)
width,	seaward end	400 m
	tapering to	300 m (inside breakwaters)

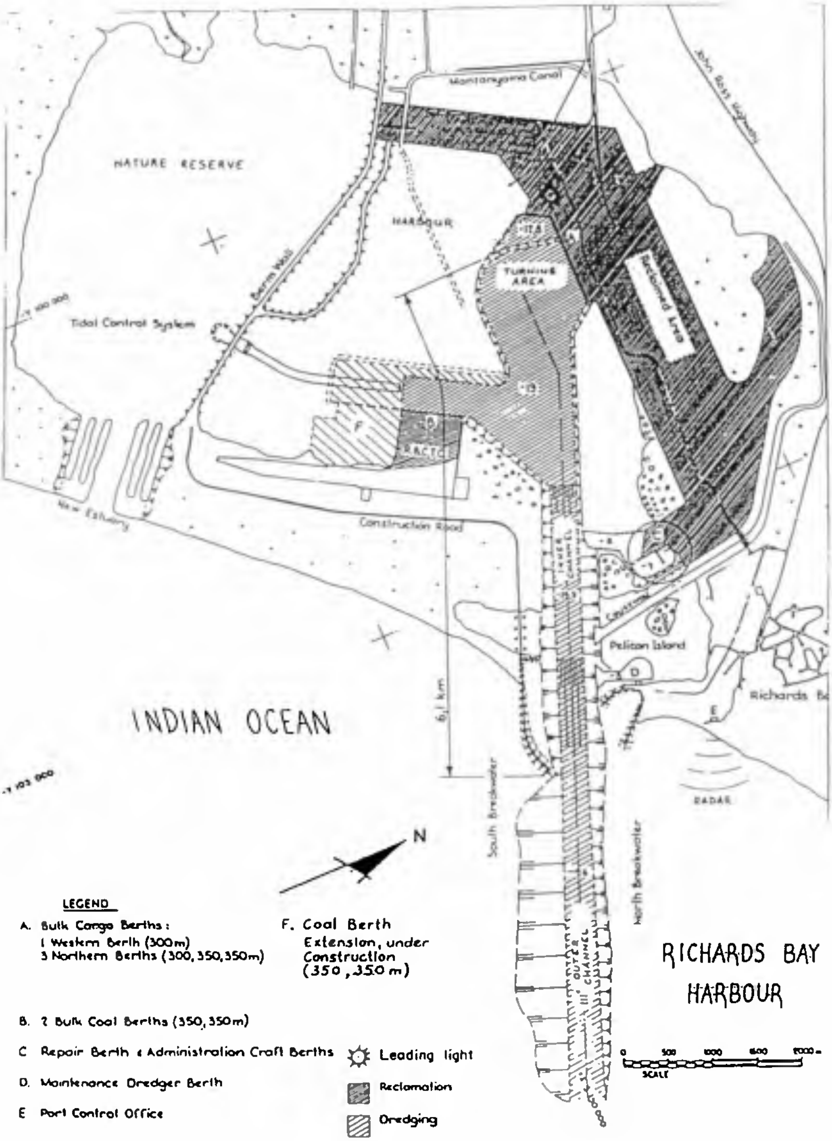

Fig. 2 Harbour layout

depth,	outer channel	- 24 m CD (Chart Datum ≈ LWOST)
	transition area	- 22 m CD
	inner channel	- 19,5 m CD
	turning and mooring area	- 19 m CD.

The foundation level of the coal quays was set at -23 m CD. A turning area with a diameter of 1000 m was provided.

Design Criteria

The channel dimensions were originally determined to allow the entry and departure of 17 m draught ships (about 150 000 dwt) for 99 per cent of the time, with a tide level assumed to be at 0,0 CD (Campbell and Zwamborn, 1977). However, the possibility of handling larger ships, up to 20 m draught (about 250 000 dwt), was taken into account throughout the design stage. For this reason, the coal quays were founded at -23 m, to allow for possible future dredging to -22 m CD and the breakwaters were placed in such a way that the entrance channel could be widened and/or deepened if necessary.

Design Studies

The harbour design was assisted by a detailed programme of field measurements, sediment model studies, breakwater stability tests, wave penetration studies and physical ship model tests (Campbell and Zwamborn, 1977; Zwamborn and Grieve, 1974).

The latter were undertaken to assist in the determination of the entrance channel dimensions. They were carried out in the 1 in 100 scale wave penetration model using a self-propelled radio-controlled model of a 150 000 dwt, 17 m draught bulk carrier (Hoppe, 1972). Most tests were carried out with near-beam regular waves of near-resonance frequencies, conditions, which occur frequently at Richards Bay. The test results indicated that:

- a maximum overdraught ('sinkage') of 6 m is to be expected for the 1 per cent occurrence SSW'ly swell, indicating a minimum channel depth of 24 m, allowing 1 m underkeel clearance (thus underkeel allowance is 7 m or 40 per cent of the design draught);

- a channel width of 300 to 400 m would be sufficient for single-lane traffic during all but the SSW design waves for entry speeds of 3,5 to 4 m/s (7 to 8 kn) and for ships leaving under design conditions at a speed of 3,5 to 4,5 m/s (7 to 9 kn);

- an approximately 150 m wider entrance channel would be necessary for entry under the SSW'ly design wave condition, alternatively the entry speed would have to be increased to 4,8 m/s (9,5 kn) to avoid transgression of the 300 to 400 m wide channel bounderies.

Based on information on stopping distances available at the time, it was accepted that 150 000 to 250 000 dwt loaded ships entering the harbour at $\leq$ 4 m/s (8 kn) could be stopped within the available 6,1 km stopping length, provided powerful tugs could attach and assist when the ship was moving at a speed of $\leq$ 2 m/s (4 kn).

A group of 20 pilots who were also asked to operate the model concluded that the handling of the model ship was generally realistic but they thought that its movements were somewhat excessive and initially they were reluctant to enter at speeds much in excess of 1,5 to 2 m/s (3 to 4 kn).

Future Expansion

The first-phase development at Richards Bay was mainly based on a 2,5 million tons per year export contract of bituminous coal and anthracite, as from April 1976. As a result of the oil crisis in the early seventies, the demand for coal increased dramatically and the export rate increased rapidly to the present (1981) figure of 26,5 million tons per year.

Extensions to the coal berths and loading facilities (Figure 2) are under way at present to increase the export capacity to 44 million tons per year. These extensions are scheduled to be completed by 1987. Moreover, the South African Government has approved export permits up to a total of 80 million tons per year and further extensions to the harbour must therefore be expected in the future.

The harbour was originally designed for 17 m draught ships. From the start the official draught restriction was 17,1 m (10 per cent underkeel clearance in the inner harbour) although draughts up to 17,3 m were allowed at certain times to assist with the ship motion monitoring programme. Shipping agents approached the harbour authority during 1980 for use of 17,6 m draught ships for early 1983 (about 185 000 dwt). This increase of draught to 17,6 m could be achieved by using the tide, but any further increase would require a certain amount of dredging in the turning/mooring areas and in the inner channel.

Finally, as mentioned above, allowance was made in the foundation level of the coal quay for 20 m draught ships (250 000 dwt) and studies are underway at present to determine the dredging depths in the outer and inner entrance channels required to accommodate these ships for 99 per cent accessibility.

EXPERIENCE IN THE OPERATION OF THE PORT

A maximum degree of flexibility was aimed at in the design of the entrance channel because it was realised that, as experience was gained in the operation of the port, particularly with regard to negotiating the entrance channel, adjustments in the channel dimension or in the limiting operational conditions might have to be made at a later stage. It was, therefore, important to gather any information on possible problems experienced during operation related to the channel depth, width and length.

Ship Statistics

Because Richards Bay is mainly an export port for coal, large bulk carriers normally enter the port light (about 10 to 12 m draught) and leave loaded (up to 17,1 m draught). This reduced the entry problem for this traffic because light ships are much easier to stop than a fully loaded ship although the ship's larger freeboard could cause additional manoeuvring problems during strong SW or NE wind (a 150 000 dwt bulk carrier has a displacement of about 180 000 t when fully laden but only 110 000 t when in full ballast).

However, there are occasions on which fully or near-fully laden bulk carriers come in to 'top up' their coal load or for bunkers and these occurrences were of particular interest in checking the design.

The use of the port by VLC's in excess of 100 000 dwt can be summarised as follows (1981 data):

Ship size (dwt)	< 50 000	50-100 000	100 - 150 000	> 150
Number of ships	367	106	160	29

This gives a total of 662 ship movements (compared with 522 in 1979 or a growth rate of 13,5 per cent per year).

The deepest draught for a **sailing** VLC in 1981 was 17,37 m.

During the year eight ships **entered** in almost fully loaded condition (to 'top up') with a deepest draught of 16,8 m.

Port Control

Apart from the usual lights on the ends of the breakwaters the centre line of the channel is marked by leading lights situated at 6,7 and 9,2 km from the end of the main breakwater at 27 and 50 m above CD, respectively (Figure 2). The lights consist of sealed beam units with the following light power:

- front light, red: 4 800 000 candelas during the day (fixed) and 57 200 candelas at night (flashing);

- rear light, white: 3 600 000 candelas during the day (fixed) and 57 200 candelas at night (flashing).

Radar Responder Beacons (Racons) have been provided on the leading light towers to mark the channel centre line on the ship's radar should the leading lights become obscured by rain or mist (radar particulars: 9 300 to 9 500 MHz, 72 s sweep, 360° coverage, 20 km range, continuous transmission).

The port control office is situated 1,5 km north of the harbour entrance at 55 m above sea level. Apart from the usual radio equipment, 30 and 100 mm wavelength radar sets are installed in the operating room. The pilots and the Assistant Port Captain are also stationed at the port control office (Figure 2, E).

Tugs and Pilotage

The following tugs are available at Richards Bay to assist with entry/departure manoeuvres:

Type	Number	Power HP/kW	Bollard Pull (t)	
			Ahead	Astern
Kort-Nozzle	2	4400/3200	52	28/32
Voith-Schneider	1	4000/2940	40	34

Compulsory pilot service is provided by the South African Transport Services, at present only during daylight hours, extended to 21h00 on special request for unberthing loaded coal vessels.

For entry, the pilot boards 5 to 9 km offshore, depending on whether the ship is light or fully laden. A 21,5 m long pilot boat is used for this purpose; it goes alongside the ship which makes a lee from the wind and sea. It is virtually always possible for the ship to provide a lee to the pilot boat but during heavy swell and sea conditions (winds exceeding about 40 kn or 20 m/s) the pilot boat itself becomes difficult to handle.

For departing ships, the pilot boards at the coal quay and normally disembarks just before the ship leaves the protection of the main breakwater. Thereafter, further advice is provided by port control on the basis of the ship's radar image which is carefully monitored as the ship passes through the outer channel.

Entry Manoeuvres

Typically, an entry manoeuvre of a VLC at Richards Bay goes as follows (Figure 3, a):

- pilot boards 7 to 9 km offshore
- ship lines up with leading lights, speed 6 to 8 kn
- approaches entrance with engines slow to dead slow, speed 5 to 7 kn
- enters between breakwaters with engines dead slow to stopped, speed 4 to 6 kn
- tugs attach in inner channel, one or two for'd and one aft
- ship turns to port towards coal quay, reverse power
- starboard turn, reverse towards coal quay
- pilot leaves the ship at the coal quay.

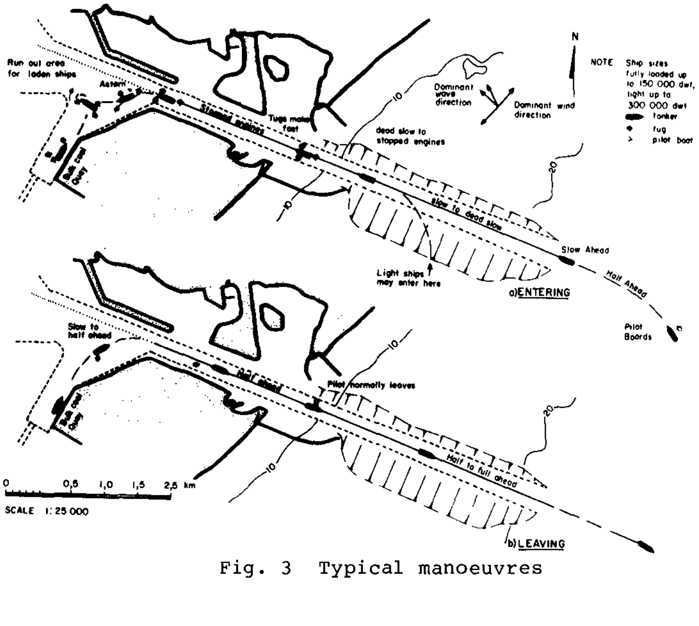

Fig. 3 Typical manoeuvres

Departure Manoeuvres

Normally, the departure manoeuvre goes as follows Figure 3, b):

- pilot boards at the coal quay
- ship lifts off and turns into inner channel, slow to half ahead, one tug in attendance
- ship moves through inner channel, half ahead, speed 5 to 8 kn
- pilot leaves ship between breakwaters
- ship moves through outer channel half to full ahead, speed $\geq$ 9 kn
- progress and position is monitored on radar at port control from where advice is given on course adjustments, if necessary.

Discussion and Comparison with Model Predictions

Ships enter Richards Bay at minimum speeds of between 4 to 6 kn (2 to 3 m/s), depending on the conditions. Entering at these speeds allows, mostly, light ships of the 150 000 dwt class to be stopped and turned in the coal berth area which means a stopping length of 4 to 4,5 km. Further data on the entry of laden vessels under near-design conditions will be collected but, based on present experience, there is little doubt that the 6,1 km available stopping length will be sufficient for up to 250 000 dwt loaded vessels entering at speeds of up to 8 kn (4 m/s), perhaps even 9 kn (4,5 m/s).

Also, tugs can make fast at virtually any manoeuvring speed but only tractor-type tugs can start to assist with steerage at speeds of 4 to 5 kn (2 to 2,5 m/s); conventional tugs cannot 'open-up' at speeds above 2 to 3 kn (1 to 1,5 m/s) and can thus only assist a little by reducing the ship's speed. Thus, when tractor tugs are available (at present there is only one tractor tug, the Voith-Schneider tug), relatively higher entry speeds will be possible, if required, for the control of the ship during adverse conditions; alternatively, larger ships could probably be stopped within the available stopping length.

Finally, the available channel width was found to be adequate in most circumstances. However, it is imperative that under southerly wind and wave conditions (near-beam conditions) sufficient speed be maintained to ensure control of the ship, as indicated by the model tests (that is, 7 to 8 kn for entry and 7 to 9 kn for departure). This is borne out by an occurrence where a departing loaded VLC was forced over the north channel bank under these conditions while travelling at only 5 kn (2,5 m/s) and two recent occurrences where similar ships leaving at a speed of about 9 kn were able to remain in the channel although leaving under near-design conditions (measured wave height, $H_S \approx$ 2,7 m, wave period, T_Z = 10 s, wave directions, ϕ = 160°, 25 kn, SSW wind). Both ships first took a sharp turn to port (north) just outside the breakwaters, probably due to a local northbound current. After nearly 'locking' into the waves (heading parallel to the waves) the ships took a very strong 'sheer' to starboard. Although these manoeuvres included course changes of + and -15°, the ships remained in the channel.

SHIP MOTION STUDIES FOR RICHARDS BAY HARBOUR

A programme of free moving ship motion studies has been undertaken for Richards Bay, including prototype measurements, mathematical modelling and physical modelling. The diagram given in Figure 4 shows all the elements of the studies, and also the various interactions between the 'three-legged' approach (the moored ship studies are done for Saldanha Bay harbour and are not discussed here).

Purpose of Studies

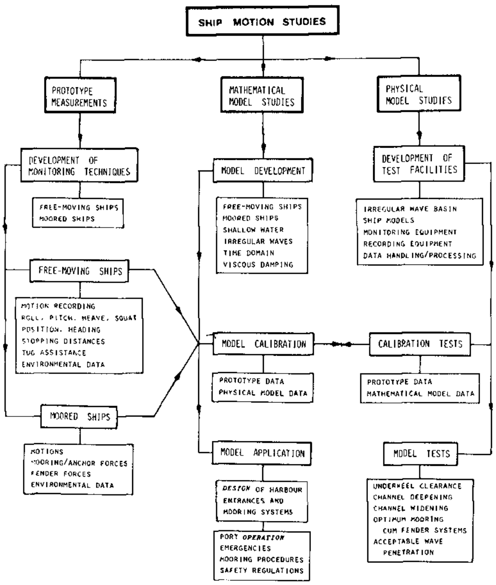

Fig. 4 Ship motion studies flow diagram

The above studies were undertaken for Richards Bay:

(a) to confirm the predictions based on the original hydraulic model tests,

(b) to determine the conditions under which 18 m draught ships could use the present entrance channel safely,

(c) to determine minimum required dredging depths to allow 20 m draught ships to use the port with a maximum downtime of 1 per cent (regarding underkeel clearance), and

(d) to develop guidelines to assist with the safe operation of the port, particularly with regard to required underkeel allowance under various conditions.

Prototype Measurements

A photographic technique has been developed which enables the accurate monitoring of the course, speeds and vertical motions of all ships using Richards Bay harbour (Zwamborn and Van Wyk, 1981). Since August 1978, 175 ships with a dead weight tonnage exceeding 100 000 dwt have been monitored and some of the results are presented in another paper to this conference (Van Wyk, 1982). The results of these measurements provided valuable data with regard to entry and departure speeds vis-à-vis stopping distances and ship handling (discussed above) and they indicated that the adopted underkeel allowances are of the right order.

More data on near-design conditions (small underkeel clearances) are, however, required and arrangements have been made to charter loaded bulk carriers when these conditions occur, to carry out special monitoring runs.

Mathematical Modelling

To determine the required channel depths for ships larger than those using the port at present, a mathematical model will be used. This model will first be calibrated against available prototype data obtained from the measurements. A deep-water strip-theory model was tried first but the results were not satisfactory. A shallow-water version and a shallow-water three-dimensional source technique model are therefore being used at present.

Once properly calibrated, the mathematical model will be invaluable in the operation of the port.

Physical Modelling

As soon as a fully-irregular wave basin becomes available, model runs will be made reproducing typical prototype measuring runs, to check possible scale efffects. Thereafter, the physical model will be used to provide additional **calibration data** for the mathematical model, particularly regarding different wave directions, as well as for a final check on the required dredging depths to accommodate ships up to 250 000 dwt.

APPLICATION OF SHIP MOTION STUDIES TO PORT OPERATION

The large underkeel allowances at Richards Bay, reducing from 7 m in the outer channel to 2 m inside (at low water), were dictated by the regular occurrence of long waves with near-beam directions. These long waves cause considerably greater sinkages than those due to the squat and trim, which are determinative in many other ports. It was therefore considered necessary to use available information on ship motions due to waves, to determine the expected overdraught during the passage of the ship through the outer and inner entrance channels in order to decide under what heavy weather conditions vessels would be permitted to negotiate the channel. This procedure also requires knowledge of the environmental conditions at or near the time of passage.

Wave Directions

Vertical ship motions are greatly influenced by wave direction and it was therefore necessary to determine the wave directions,preferably those in the entrance channel. This is done by using radar, wave clinometer or by pilot boat observations.

Wave direction in the channel can be read off the **radar** screen, provided there is sufficient backscatter from the water surface,that is, a wind chop superimposed on the swell. For better definition, the short wave length (3 cm) or X band is used. Wave direction is observed in the channel about 1 to 2 km out to sea.

If no radar direction can be observed, a **wave clinometer** direction reading is used. The wave clinometer is an inclined (3^{o}) graduated telescope directed onto a buoy anchored in 13 m water depth at about 800 m offshore and 1600 m north of the entrance channel.

If both methods were to fail or when conditions are such that confirmation is advisable, the **pilot boat** can be used to record/check the swell directions in the channel by heading into the swell and reading the compass direction.

Wave Height

Vertical ship motions are generally assumed to be proportional to wave height. Preferably, the wave heights should again be measured in the entrance channel but this is impracticable. The measurements are normally made with a **waverider buoy,** anchored in 20 m water 1 km south of the channel and about 1,5 km out to sea, and with a receiver at the port control station.

Available data on ship motions, that is, the maximum expected sinkage during passage through the channel is related to the significant wave height, H_s. A quick estimate of H_s can be made by reading off the waverider chart the maximum wave heights for three consecutive 3 min records and calculating the mean, that is, $H_s \approx H_{rep} = \frac{H_1+H_2+H_3}{3}$.
This wave height, H_{rep}, is a conservative value.
Assuming Rayleigh wave height distribution and considering that a ship will on average be 20 min in the channel, $H_{rep} \approx H_{s\text{-}20\ min}$ (Longuet-Higgins, 1952).

In the event of waverider failure, an estimated wave height is obtained from the **wave clinometer.** The average vertical movements of the anchored buoy, relative to fixed graduations in the telescope, is determined over a period of three to five minutes.

Wave Period

Vertical ship motions are also very dependent on the **wave periods.** Because of the regular occurrence of long-period swells, near-resonance conditions normally occur, particularly under moderate to heavy swell conditions. Although wave period records are available from the waverider and the wave clinometer, these are not used in the present operational procedures, which assume that most of the wave energy is concentrated near the natural roll/pitch periods of the ships.

Tide Levels and Water Depths

The lowest tide level, Z_o, during the passage of a ship through the channel (on average 20 min) must be used to determine available water depth relative to the proclaimed channel bottom level (taking into account possible siltation, ΔZ).

Tide levels are read from an automatic **tide recorder** or, in the absence thereof, from the tide tables.

Ship Motions in the Outer Channel

Because of the lack of sufficient directional spread in the conditions during prototype monitoring, the first version of an 'operational model' was based on the results of model tests with a 200 000 dwt tanker (Koelé and Hooft, 1969) and a 150 000 dwt bulk carrier (CSIR, 1976).

Figure 5 gives the expected maximum sinkages as functions of wavedirection for a 18,9 m draught ship, proceeding at 4 m/s (8 kn) in a 10 km long channel of various depths, under irregular swell with H_S = 1,5 m and T_Z = 10 s (zero-crossing wave period). The sinkages also include squat, linearly extrapolated for greater underkeel clearances (CSIR, 1979).

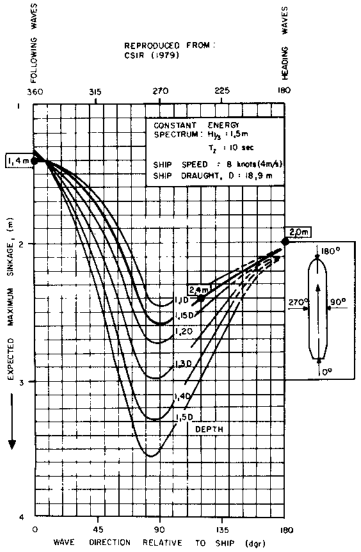

Fig. 5 Sinkage of 200 000 dwt model tanker as function of wave direction and water depth

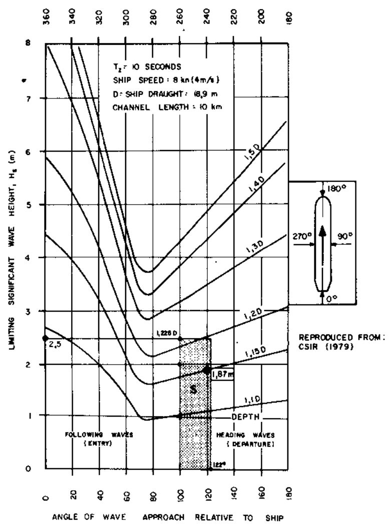

Fig. 6 Limiting significant wave height for which a ship may touch the bottom

Figure 5 was converted into Figure 6 giving the limiting significant wave heights as functions of wave direction and underkeel allowance. In this conversion, linearity was assumed between (a) sinkage due to waves and wave height and (b) sinkage due to squat and trim and underkeel allowance; the latter reduces from 0,7 m for 10 per cent to 0,0 m for 50 per cent underkeel allowance. For example, for a wave direction of 240° and 15 per cent underkeel allowance, Figure 5 gives a total sinkage of 2,4 m of which 0,65 m is due to squat and trim. The limiting H_s then follows from $0,15\ D = \frac{H_{s-lim}}{1,5}\ (2,4 - 0,65) + 0,65$ or, since $D = 18,9$ m, $H_{s-lim} = 1,87$ (see Figure 6).

Using Figure 5 and assuming linearity between sinkage and wave height the expected maximum sinkages for the 200 000 dwt model ship in the Richards Bay channel are compared with the maximum sinkages measured in the original Richards Bay tests using a 150 000 dwt model in Figure 7 (CSIR, 1979). The results are seen to be compatible with a maximum sinkage for beam waves of about 6 m and Figures 5 and 6 were therefore considered to be a safe basis for determining maximum sinkages for bulk carriers up to about 250 000 dwt passing through the Richards Bay outer entrance channel.

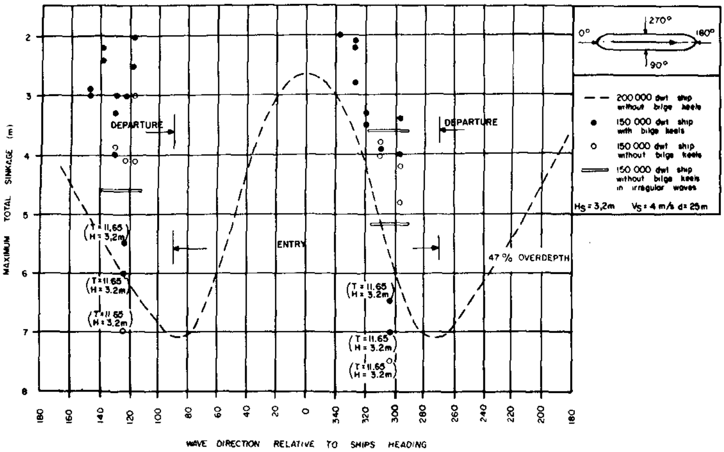

Fig. 7 Comparison of maximum sinkages of 150 000 dwt and 200 000 dwt ships

Ship Motions in the Inner Channel

The waves entering the harbour will run parallel to the channel axis and will therefore be either following (0°) or heading (180°) waves for entering and leaving, respectively (see Figure 6). To determine the ship motions in the inner channel the local wave heights must be known. These were obtained from the results of the Richards Bay physical model tests which showed maximum wave penetration for the deep-sea wave direction of 146° and very low penetration for ESE, the direction parallel to the channel axis (Zwamborn and Grieve, 1974).

Two specific areas were chosen for ship motions determination, namely, the 'top of slope', where the channel depth changes from -22 m to -19,5 m CD and 'Sandy Point', just before the channel widens into the coal berth area (-19,5 m CD). Figure 8 shows the relationships between wave penetration and wave direction for these two areas using wave refraction data to convert deep-sea to entrance channel wave directions (Moes and Van Niekerk, 1981). Accepted penetration values for the entrance channel directions are also shown in this figure. For example, for the direction sector SE, the penetration factor is 0,6 at 'top of slope' and 0,2 at 'Sandy Point'.

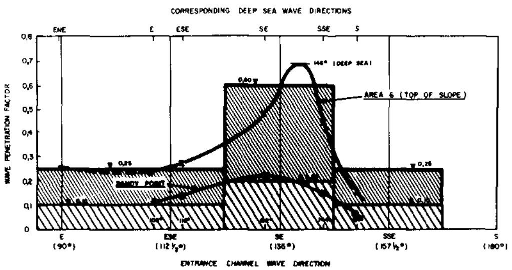

Fig. 8 Wave penetration at 'top of slope' and 'Sandy Point' versus wave direction

On the basis of the above and using Figure 5 (following and heading waves), the limiting wave heights at the positions in the inner channel could be found. For example, taking the available depth at the 'top of slope'at -20 m CD and allowing a minimum underkeel clearance of 1 m, the available depth at low water in this area is 19,0 m. For a ship **entering** under SE'ly waves, the wave penetration factor is 0,6 while the total sinkage for 1,5 m high waves is 1,4 m. Assuming 0,5 m squat and trim the sinkage due to waves is thus 0,9 m. Now the maximum permissible sinkage z_{max} = $19{,}0 - D = 0{,}5 + \frac{0{,}9}{1{,}5} \times 0{,}6\ H_{s-lim} = 0{,}5 + 0{,}36\ H_{s-lim}$ or $H_{s-lim} = \frac{18{,}5-D}{0{,}36}$, which is a linear relationship between draught D and H_{s-lim}. For a ship **leaving** under SE'ly waves, the total sinkage for heading waves must be used, namely, 2,0 m for 1,5 m high waves. Thus the sinkage due to waves is 1,5 m (0,5 m squat). This leads to the following relationships:

$$z_{max} = 19{,}0 - D = 0{,}5 + \frac{1{,}5}{1{,}5} \times 0{,}6\ H_{s-lim} = 0{,}5 + 0{,}6\ H_{s-lim}$$

or $H_{s-lim} = \frac{18{,}5-D}{0{,}60}$.

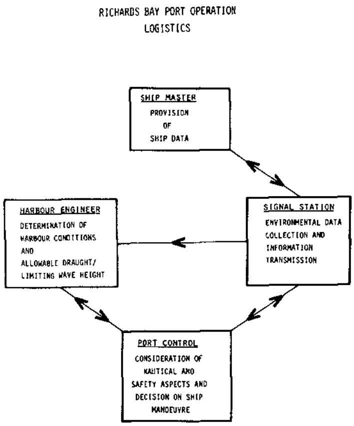

Fig. 9 Port operation logistics

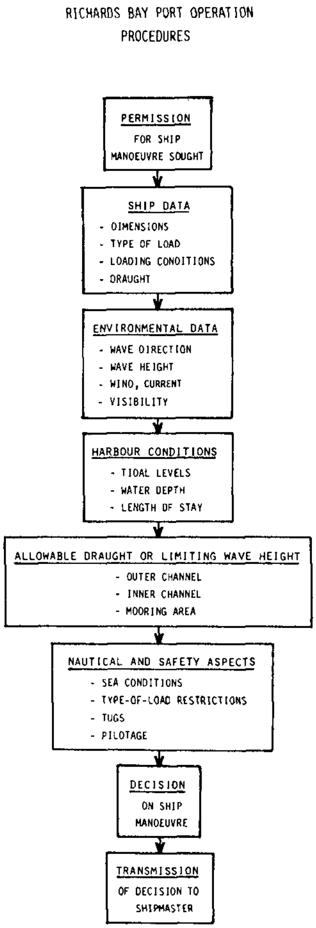

Fig. 10 Port operation procedures

PORT OPERATION MANUAL, MARK I

The first version of a port operation manual (CSIR, 1981) was drawn up on the basis of the data and assumptions discussed above. It is realised that the data are limited and that the problems have been over-simplified; this is the reason for a conservative approach throughout. The main purpose of Operation Manual, Mark I was to provide the nautical operating staff at Richards Bay with a first tool to assist in their decision making, with regard to under-keel clearance, on acceptable conditions for entry/departure of VLC's under severe conditions.

Logistics and Procedures

Port operation logistics are shown diagrammatically in Figure 9. Although for routine operations Port Control can apply the operation manual directly, it is the Harbour Engineer's responsibility to ensure that the manual is correctly interpreted, kept up to date and amended when necessary. The Harbour Engineer should also be consulted on special cases (e.g. emergency entry of larger then design vessels) and he is responsible for providing up-to-date information on possible channel siltation.

Operation procedures are shown diagrammatically in Figure 10. Operation Manual, Mark I, forms an important part of these general procedures. It contains the following steps/instructions:

(i) Obtain details on the ship's draught, D (maximum stationary value), from the ship's master;

(ii) record environmental conditions, including wave direction, $\emptyset$, wave height, H_{rep}, and tide level, Z_o;

(iii) check available water depths in the area concerned and calculate the equivalent draught ($D_{eq} = D - Z_o$); and

(iv) determine the limiting wave height, $H_{rep,lim}$, for a ship with equivalent draught D_{eq} and angle of wave approach, $\emptyset$, and check whether the recorded wave height is equal to or smaller than the limiting wave height, that is, $H_{rep} < H_{rep,lim}$;
alternatively
determine the minimum tide level, $Z_{o,min}$, required for a ship with a draught, D, angle of wave approach, $\emptyset$, and wave height, H_{rep}, and check whether the actual tide is equal to or higher than the limiting tide level, that is, $Z_o > Z_{o,min}$.

Specific instructions on how to determine the environmental and other data are included in the Manual (CSIR, 1981).

Draught Allowance Criteria

To facilitate step (iv) above, easy-to-read coloured draught allowance diagrams were prepared and are also included in the manual, one for entry and one for departure (the latter is shown in Figure 11). These diagrams allow for a minimum underkeel clearance of 1 m anywhere in the harbour or entrance channel. The straight lines in Figure 11 represent the conditions in the inner channel (example equations derived in the above), the dotted vertical line is the limit for the turning and mooring area (see Figure 11, maximum D_{eq} = 19 - 1 = 18 m) and the curved lines represent the limiting conditions in the outer channel.

The latter are obtained from Figure 6. For example, taking the S direction sector (169° to 191°), the wave angles relative to a leaving ship travelling on the channel centre line (111° to north, corresponding to 180° relative to the ship) will be 122° to 100°. Considering the limiting wave height of 2,5 m, the largest required depth for this wave height in the S direction sector is 1,225 D (Figure 6). With a channel depth of 24 m and 1 m underkeel clearance, the allowable draught follows from 1,225 D = 24 - 1 or D = 18,7 m. This gives one point of the curve for S'ly waves (see Figure 11).

It is clear from Figure 11 that a ship with D = 18,7 m would be able to be in the port only when its equivalent draught, D_{eq} = 18 m or with a minimum tide of 0,7 m. This brings out the interesting point that, with the present channel depths, the inner channel forms a greater limitation to large draught ships than the outer channel, particularly for SE'ly waves (see Figure 11).

Example Applications

Example 1: Loaded carrier to leave port

Ship draught	D	=	17,0 m
Recorded wave direction	Ø	=	169°
Recorded representative wave height	H_{rep}	=	3,8 m
Tide level at time of manoeuvre	Z_o	=	0 m

Can this ship leave the port?
Determine $D_{eq} = D - Z_o$ = 17,0 - 0 = 17,0 m.
For S direction sector, Figure 11 yields $H_{rep,lim}$ = 3,45 m.

Since this is 0,35 m less than the recorded value, the ship cannot leave the port.

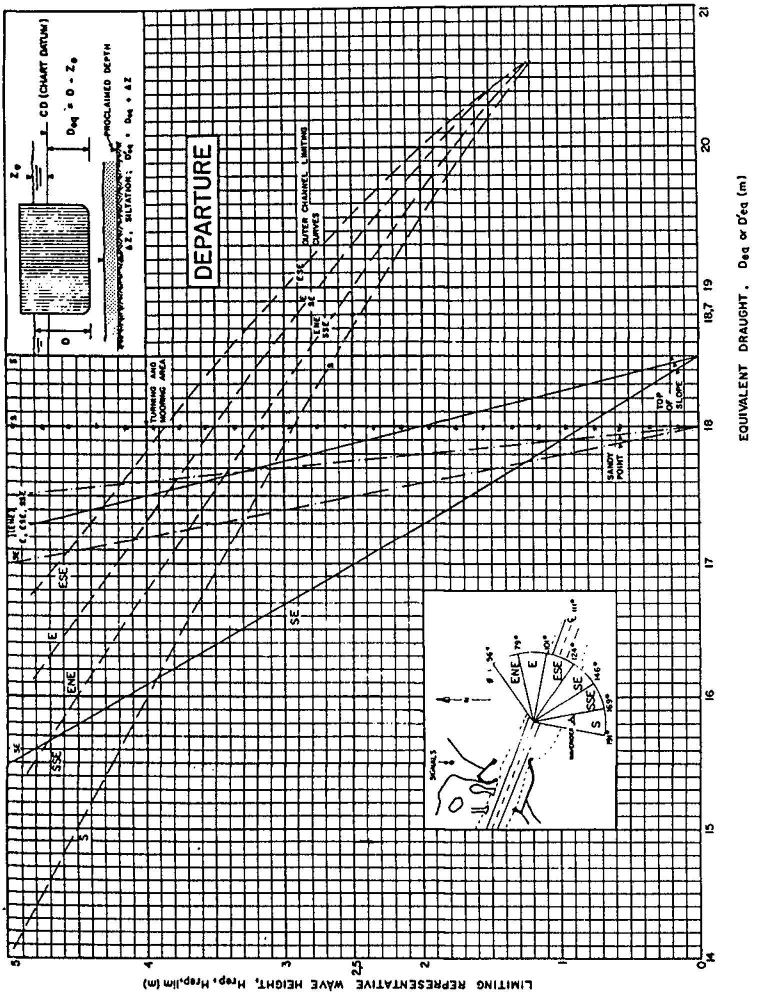

Fig. 11 Allowable draughts during departure

Example 2: Loaded carrier to leave port
Taking the same ship as in Example 1 and assuming that the sea conditions remain the same, what is the minimum tide required for the ship to leave?

For H_{rep} = 3,8 m, D_{eq} = 16,4 m (Figure 11, S direction sector).
Thus, $Z_{o,min}$ = 17,0 - 16,4 = 0,6 m.

Under these severe conditions this ship will thus have to wait until a minimum tidal level of + 0,6 m CD is reached.

Practical Experience in Using the Manual

The "Richards Bay Harbour Port Operation Manual, Mark I" has been in use since October 1981. Records of ships in excess of 100 000 dwt which enter or leave the port under fairly rough conditions are kept on special record sheets provided to 'port control'. These records include information on the ship, its loaded condition, recorded wave direction and height during passage through the channel and tide records. The calculated equivalent draught (D_{eq}) and the limiting wave height ($H_{rep,lim}$) read from the draught allowance diagrams and the decision taken are also recorded on these sheets.

So far (August 1982), 97 departures and one entry of loaded coal carriers between 101 600 dwt and 169 080 dwt have been recorded on the special record sheets (maximum draught up to 17,3 m). Of these there were six occasions on which ships had to be held back, either for the high swell to subside or until the tide level had increased. In one case, the swell height was more than 1 m too high.

Future Improvement to the Manual

It is expected that the manual will be improved in two ways, firstly, by improving the recording system of the environmental data and, secondly, by improving the techniques for determining maximum expected vertical motions.

Wave heights are already recorded on magnetic tape and it is intended to replace the present graphic technique to determine H_{rep} by a spectral analysis technique. Provided the response functions of the ships are known (these will be determined from the prototype measurements), the effect of wave period can then also be included. Since ship motions are very dependent on wave direction, it is also expected that an automatic wave direction recording system will be used in the future.

The results of the present prototype measurements of vertical ship motions and additional physical model tests will be used to calibrate available mathematical ship motion models. The final aim would be to replace the present draught allowance diagrams by a simplified version of such a model, which would predict the maximum expected vertical motions for a given ship under various wave and tide conditions.

CONCLUSIONS

The main cargo through Richards Bay harbour consists of coal exports using bulk carriers up to about 170 000 dwt, loaded to 17,1 m draught (in certain cases, 17,3 m was allowed).

Experience with the operation of the port indicates that the available stopping distance (6,1 km) is more than adequate for ships, presently calling at Richards Bay, entering at 6 to 8 kn (3 to 4 m/s) although further data on loaded design ships is still needed. Provided outer channel speeds of at least 7 to 8 kn (3,5 to 4 m/s), indicated by the hydraulic model test, are maintained, there is no serious problem in holding the ships in the 300 to 400 m wide channel.

Ship motion research is aimed at determining the minimum required dredging depths for ships up to 20 m draught (about 250 000 dwt) and at developing guidelines to assist in the safe operation of the port. The results of the prototype measurements showed that the underkeel allowance of 7 m accepted in the original design is of the right order of magnitude.

Because of the lack of sufficient direction coverage in prototype data, the Port Operation Manual, Mark I, was based on physical model tests with a 200 000 dwt and a 150 000 dwt model ship. Data on these test results were used to draw up easy to apply draught allowance diagrams which relate equivalent draught and limiting wave height for various wave directions. These diagrams allow for a minimum underkeel clearance of 1 m in the outer channel, the inner channel and the turning/mooring areas. To apply these diagrams to port operation, reliable data on wave heights and directions, tide levels and channel depths must be available.

The manual has been in use at Richards Bay port control since October 1981 and has been found to be of great value in assisting in the safe operation of the port.

The success of this project depended largely on the understanding and co-operation of the various disciplines involved, namely, those of the harbour engineers (civil engineering), the nautical staff and the research engineers (civil and mechanical/naval engineering).

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REFERENCES

CAMPBELL, N P and ZWAMBORN, J A (1977). Special features in the design and construction of the new harbour for bulk cargoes at Richards Bay, Republic of South Africa. Proc. 24th PIANC Congress, Leningrad.

CSIR (1976). Manoeuvring tests with a 150 000 dwt model ship in the recommended final Richards Bay harbour entrance. CSIR Report C/SEA 7603, Stellenbosch.

CSIR (1979). Conditional allowance criteria for deeper draught ships using Richards Bay harbour. CSIR Report C/SEA 7906, Stellenbosch.

CSIR (1981). Richards Bay Harbour Port Operation Manual, Mark I. CSIR Report C/SEA 8104, Stellenbosch.

HOPPE, K G (1972). Scale effects in manoeuvring tests with small ship models. Proc. ECOR Symposium, S71, Stellenbosch, RSA.

KOELé, L A and HOOFT, J P (1969). The behaviour of a 200 000 dwt tanker in shallow water. Rijkswaterstaat Report No. W69-074, Wageningen.

LONGUET-HIGGINS, M S (1952). On the statistical distribution of the heights of sea waves. Journal of Marine Research, Vol. XI, Number 3.

MOES, J and VAN NIEKERK, M (1981). Refraction studies for Richards Bay using the Wale program. CSIR Report T/SEA 8105, Stellenbosch.

VAN WYK, A C (1982). Wave induced motions in harbour entrances: a field study. Proc. 18th International Coast. Eng. Conf., Cape Town.

ZWAMBORN, J A and GRIEVE, G (1974). Wave attenuation associated with harbour approach channels. Proc. 14th International Coast. Eng. Conf., Cophenhagen.

ZWAMBORN, J A and VAN WYK, A C (1981). Monitoring of ship motions in the Richards Bay harbour entrance channel. Proc. 25th PIANC Congress, Edinburgh.