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“Crossing the Bar”

**An investigation of some dynamic processes which contribute to
broaching while crossing a bar.**

Joost F. Besier

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CROSSING THE BAR

An investigation of
some dynamic processes which contribute to broaching
while crossing a bar.

Occasional Paper

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Mariri

November 2005

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INTRODUCTION

In November 2001 the Maritime Safety Authority (MSA) of New Zealand issued a Marine Notice (for) Boats 10/2001 promulgating the “National Code of Practice” for crossing a bar or river entrance. Subsequently the Seafood Industry Training Organisation (SITO) released a training video called “Crossing the bar” which has received favourable comment. However, it was felt that further investigation of broaching and/or capsizing while crossing the bar is justified. It must be emphasised that it is not the intent of this paper to offer a contrary view to the guidelines provided in these and other publications, indeed it is the recommendation that the National Code of Practice be heeded at all times.

Existing stability standards are intended to provide significant capsize resistance for a vessel in extreme waves but compliance with the IMO Torremolinos criteria for fishing vessels *does not* provide the ability to survive a direct hit by an extreme breaking or plunging wave.(1) To date, safety regulations are principally based on static stability concepts and static stability criteria are still being used in relation to extreme ship behaviour such as capsize or broaching despite these being dynamic phenomena.

A considerable amount of research has addressed different scenarios of ship behaviour (Vassalos, Umeda, Renilson, Grim, de Kat, et al) and of particular interest are Umeda and Renilson (1994) and Spyrou and Umeda (1995). Nevertheless, the complexities of ships’ behaviour when approaching and crossing a river or harbour bar and thereby encountering a range of wave conditions has, to our knowledge, not yet been addressed. It can be said that there is no common and accepted procedure of crossing a bar and after an analysis of some of the factors and dynamic processes involved it becomes clear that perhaps there cannot be a set procedure in regard to ship handling and/or seamanship.

What then, is the reason why so many, generally very experienced, seamen have lost their lives while crossing a bar? For example 23 lives have been lost since 1985 on the Greymouth and Westport bars in New Zealand. Perhaps a clue can be found in the last part of the SITO video, where every skipper interviewed admits to having made a mistake. Or perhaps in the phrase “when in doubt, stay out”.

The final paragraph of the Code of Practice states: “It is ultimately the skipper’s responsibility to determine whether or not to cross a bar.” If a conscientious and experienced skipper admits to having made an error then it was, most likely, not an error in ship handling or seamanship or preparation or a lack of seaworthiness of the vessel. It seems very obvious but maybe the only major error was that the wrong decision was made. *The vessel should have stayed out.* A correct decision can only be made after a rational analysis and this can only take place if one is sufficiently informed and acquainted with all the factors and circumstances of the situation.

The conditions conducive to broaching or capsize on a river or harbour bar depend on a number of factors:

- The location of the bar or bars
- The size and direction of the swell
- The size and direction of the sea
- The strength and direction of the wind

- The gradient or rise of the seafloor
- The depth of water and the state of the tide
- The longshore current or “set”
- The rate and volume of the fresh water “run” down the river.

It is the purpose of this paper to investigate and identify some dynamic processes which contribute to, or are the cause of broaching and capsizing of a vessel when crossing a bar and perhaps thereby aid the decision making process.

SAND BARS/RIVER BARS

It is very seldom that swell waves or deep-water waves propagate parallel to a shoreline. Most often swell waves hit a shoreline at an angle and since an earlier part of a wave that reaches the shore slows down considerably, the rest of the wave seems to bend towards the shore. The angle at which waves strike the shore causes water to flow parallel to the shoreline in a longshore current. It is the main force for transport of sediment and beach migration (See Figure 1). The more prevalent steeper waves on an exposed coast, especially in winter, tend to create a strong backwash, dragging sediment off the beaches which is subsequently carried offshore and deposited on spits or bars. If the bar is located near a river or delta system the position of the bar is subject to continuous change. The position of a bar or bars is therefore subject to seasonal variations, depending on prevailing weather.

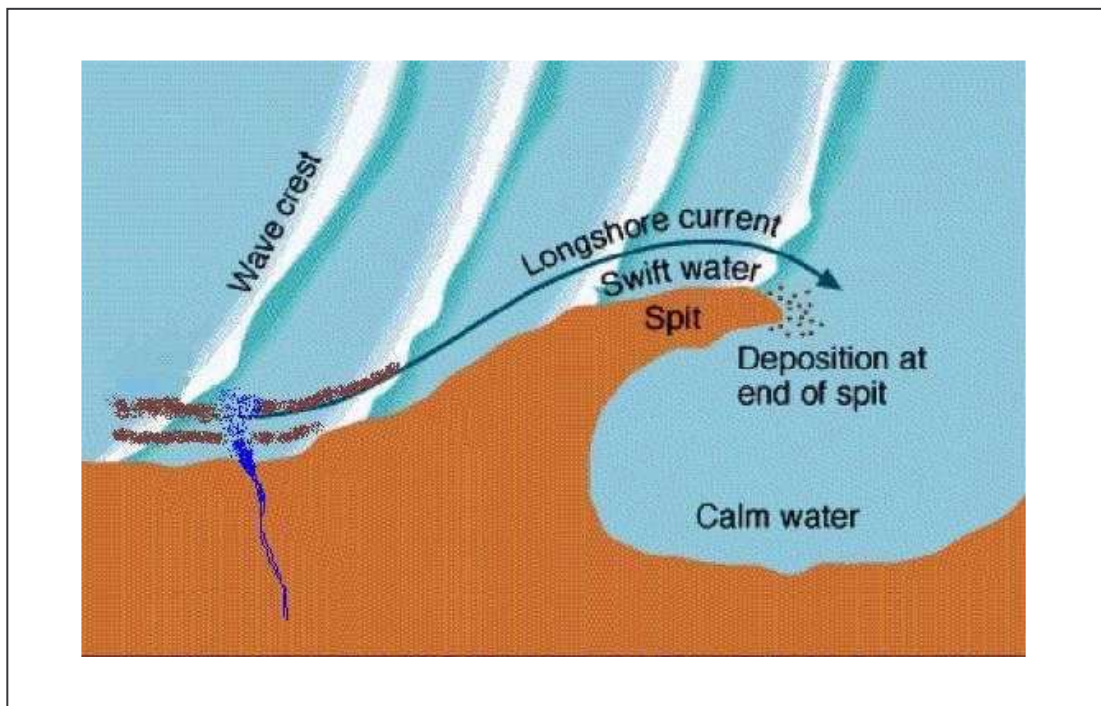


Figure 1: Sediment flow

WIND, SEA and SWELL

Wave speed (Celerity)

The three-dimensional behaviour of surface water waves as they interact with wind, bottom, obstructions, currents, and each other is very complex. Figure 2 defines the terms

most commonly used in discussions of water waves in regard to two-dimensional progressive waves using the so-called small amplitude wave theory.

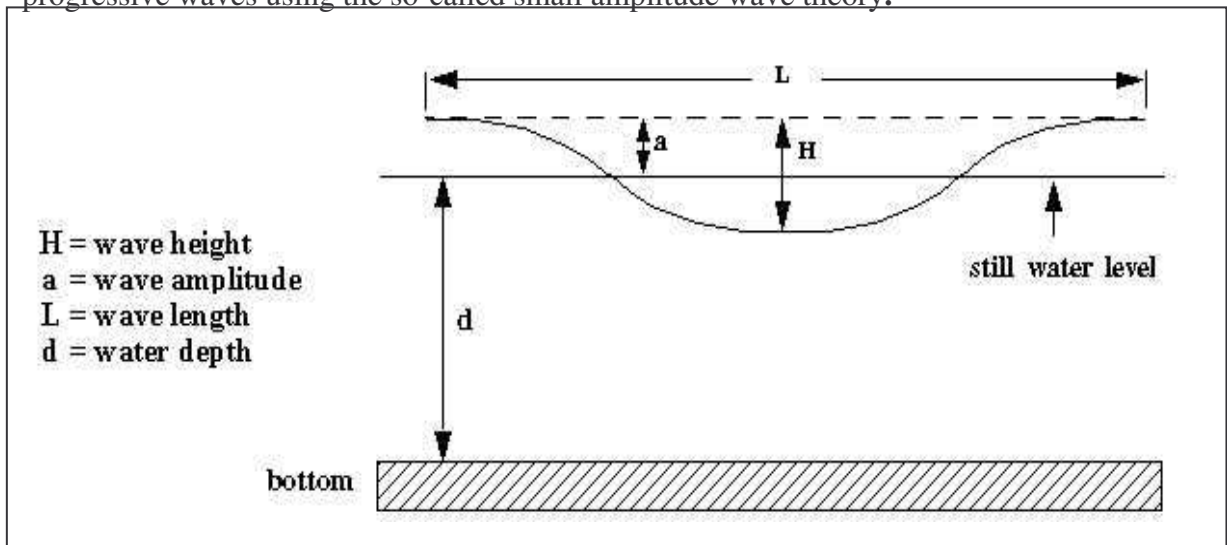


Figure 2

As waves pass some fixed point, the time between consecutive crests is the wave period T . The speed of the wave, or its celerity, C , is the distance travelled by a crest per unit time, or $C = L/T$

$$C = L/T \quad \text{Equation 1}$$

The small amplitude theory requires that both a/L and a/d be small. Using this assumption and solving the equation of motion for small amplitude waves yields the following expression for the wave celerity:

$$C = \sqrt{\frac{gL}{2\pi} \tanh\left(2\pi \frac{d}{L}\right)} \quad \text{Equation 2}$$

where g is the gravitational acceleration.

It is clear from Equation 2 that the wave celerity is a function of both the wave length (L) and the water's relative depth d/L .

Relative Depth d/L	Wave Type	Wave Celerity	Wave Length
$d/L < .05$	Shallow water wave	\sqrt{gd}	$\sqrt{gd}T$
$.05 < d/L < .50$	Intermediate depth wave	$\sqrt{\frac{gL}{2\pi} \tanh\left(2\pi \frac{d}{L}\right)}$	$\frac{gT^2}{2\pi} \tanh\left(2\pi \frac{d}{L}\right)$
$d/L > .50$	Deep water wave	$\sqrt{\frac{gL}{2\pi}}$	$\frac{gT^2}{2\pi}$

Deep-water waves

When d exceeds $\frac{1}{2} L$, ocean waves are not affected by the depth of water, *and the speed of the waves is proportional to the wave length or wave period*. This implies that waves with longer periods travel faster across the ocean surface than waves with a shorter period.

Shallow-water waves

When d is less than $\frac{1}{2} L$ ocean waves are being controlled by the water depth (the orbits of the water particles now become elongated ellipses with their major axis in a horizontal direction) and *the wave speed is now proportional to the water depth*.

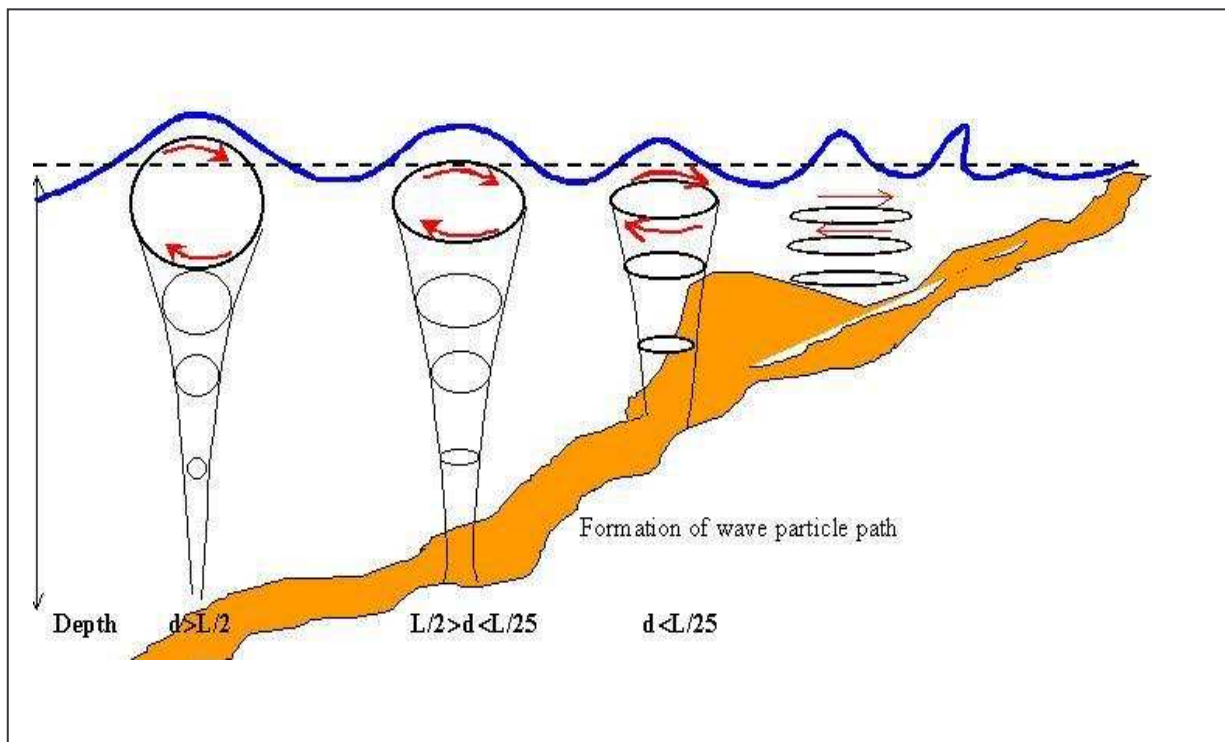


Figure 3: Orbital change as water depth decreases

Wind waves are generated when momentum is transferred from the wind to the water: *kinetic energy is transferred to potential energy*. In relation to energy distribution in waves it must be understood that the generating and restoring forces change as the wave period increases. As wind moves across the surface of the water energy is transferred and friction between air and water causes the surface to stretch. An individual water particle is dragged along a horizontal path, internal friction causes the particle to move downwards, it slows down, returns to the surface and this spiral motion is repeated. The small wavelets thus formed are known as capillary waves.

Capillary waves are created by momentum and restored by surface tension. As the wind continues to blow, the wave starts to develop and the motion of the water particle becomes more and more circular and as more energy is transferred *gravity waves* are formed. These are the most common waves, with periods between 1 and 30 seconds, they are created by momentum and restored by gravity.(2)

If the wind continues to blow then, theoretically, equilibrium is reached where the wave speed is equal to the wind speed. This is called a “fully developed sea”(FDS).

The water particles in a linear wave travel at maximum velocity at the surface and the velocity decreases as the depth increases.

The direction of the movement of the water particles is related to the direction in which the wave moves: At the crest of a wave the particle travels at maximum velocity in the direction of the wave travel. At the trough the motion is reversed.

At the leading edge of the wave, at still water level, the direction is vertically downward and at the trailing edge at the still water level the motion is vertically upward.

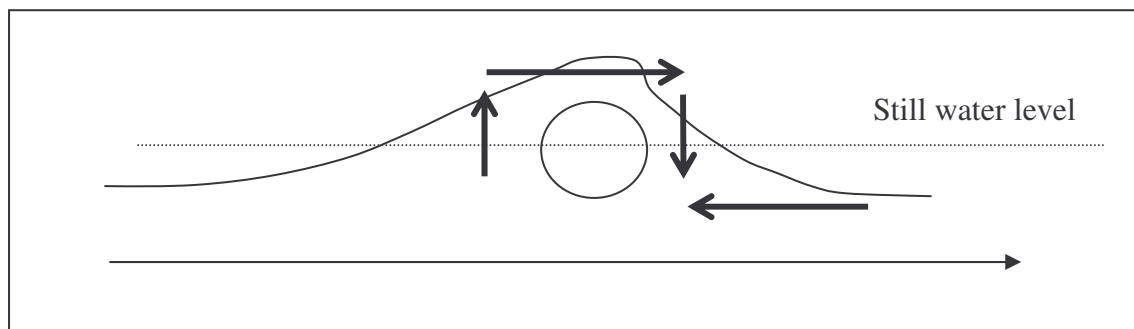


Figure 4: Movement of water particles

The steepness of a wave is determined by the relationship between wave length and wave height.

The steepness parameter or H/L increases as the height increases or the length decreases. When the ratio becomes larger than $1/7$ or 0.14, waves become unstable and break. If the wavelength was, for example, 28 m and the height 4 m the breaking criteria would have been met and an increase in H or a decrease in L would cause the wave to break.

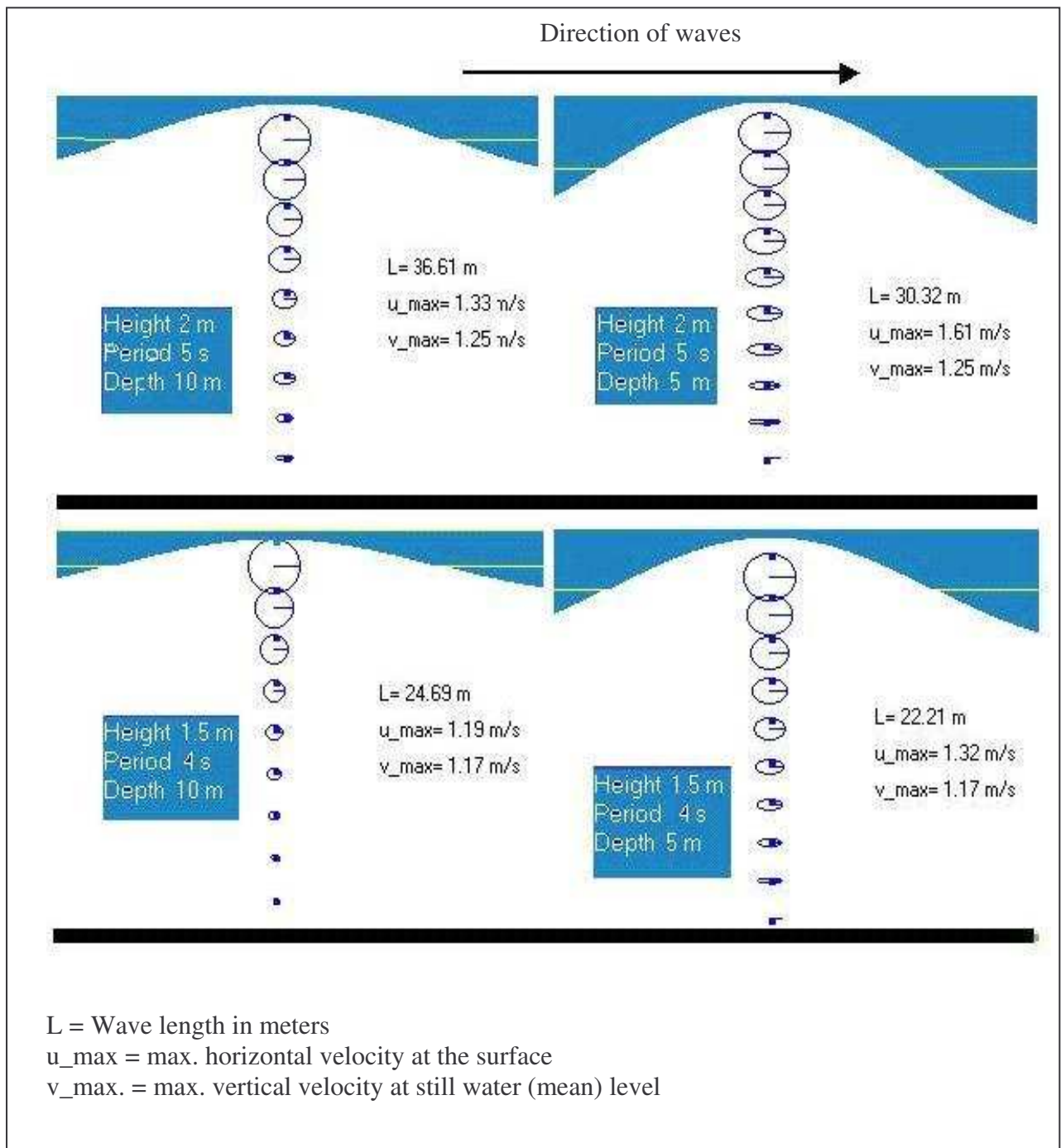


Figure 5: Relationship between height, depth and wave speed

The calculations are based on progressive linear water waves (3) and a Java applet for an animation can be found at: <http://www.coastal.udel.edu/faculty/rad/linearplot.html>

SEA and SWELL



Photo 1: Breaking Wave

The state of the sea and swell depends on the fetch, the distance over which the wind can blow without hindrance, and the duration of the wind. A fully developed sea is one where no further growth occurs despite an excess of fetch or duration. Wind input is balanced by energy loss through breaking.

Even after wind waves are fully developed, the wind continues to transfer momentum to the ocean but because the wave cannot grow any larger (H/L is maximum) the excess energy must go elsewhere. The excess energy dissipates when the waves break and through “*turbulent dissipation of energy*” whitecaps are being created.(4) In an area where waves are being generated the sea surface appears jumbled and confused with all kinds of waves of different heights and periods and, depending on how long the generating force exerts its influence, this assortment of waves will radiate out from the area where they were created.

Waves with longer periods and wavelengths travel faster and will move ahead of the shorter waves; eventually the field is sorted, the longest waves in front, the shortest waves closest to the wave generating area. This is called dispersion. Eventually we see groups of regular swell waves, known as wave trains or packets, travel across the ocean. A careful observation will show that waves are constantly being formed on the inside of the wave train as it moves along. As each wave joins the train a wave is lost on the outside. The outside wave’s energy is lost in advancing the wave from undisturbed water. Each individual wave moves twice as fast as the wave train, the group speed (group velocity of the wave) is half the speed of the individual wave (phase velocity of the wave).

Swell waves can travel for thousands of miles, losing their considerable (potential) energy very slowly. As a train of deep water waves begins to shoal (move into shallower water) the leading wave will start to “feel the bottom”, and tends to refract or bend towards a position parallel to the beach. More importantly, the wave will progressively slow down as the depth decreases. The waves that follow are catching up and also slow down resulting not only in a decrease in wave speed but also in wave-length. The waves are “bunching up” as the water becomes more and more shallow. A decrease in wave-length

and wave-speed means that the H/L ratio must increase therefore the waves must become steeper. Shoaling causes the wave height to increase and this makes the wave steeper as well.

Increase in Wave Height for Shoaling Wave

According to linear wave theory, the total amount of energy in a wave (TE) is equally partitioned between kinetic energy (KE) and potential energy (PE) in deep water. KE is the energy of motion, and in an ocean wave it is directly proportional to wave celerity (c). PE is the energy of position (think of water behind a storage dam) and is directly proportional to wave height (H). Therefore:

$$TE = KE (c) + PE (H).$$

Waves slow when they shoal, and because KE is directly proportional to c, KE will decrease. Since TE is conserved (held constant), the decrease in KE is reflected in a comparable increase in PE, so wave height (H) is increased.

H/L will increase doubly (remember H/L also is being increased because L decreases), and when the breaking criteria ($H/L > 1/7$) is exceeded, the wave will break.

Incident Band Processes - Breaking Waves

Wave breaking, perhaps the most visible near-shore phenomena, has long been a subject of research. Peregrine(5) and Battjes(6) provide reviews of work to date including discussion of the onset of breaking (breaking criteria), types of breaking waves, details of the plunge process and the consequences of natural wave fields having a random distribution of wave heights.

Several observations have motivated further research on the details of wave breaking. Traditionally, it was assumed that the process of wave breaking was accompanied by an instantaneous transfer of momentum from the coherent wave motion to the water column, forcing mean flows and pressure gradients. However, it has recently been realised that the turbulent kinetic energy (TKE) produced by wave breaking continues to carry momentum and that it is only with TKE dissipation that mean-flow forcing finally occurs.

Svendsen(7) originally proposed the concept of a wave roller, a region of intense turbulence that lies on and is transferred with the steep face of the breaking wave. Advection of the turbulent roller can cause shoreward shifts in current forcing patterns that may be most apparent in barred beach profiles. Since TKE production is primarily within this upper region of the water column,(8) vertical shears in cross-shore flows (undertow) can occur. Roller modelling is an important aspect of active research, focusing on consequences to vertical and horizontal mean flow structures and to the injection of turbulence into the water column.(8)

Lader, Myrhaug and Pettersen made detailed measurements of breaking-wave kinematics. One conclusion they arrived at is that the particle-velocity near the surface, in the crest of a plunging breaker, increased dramatically just before breaking. The wave energy becomes highly concentrated in the crest above the still water line.(9)

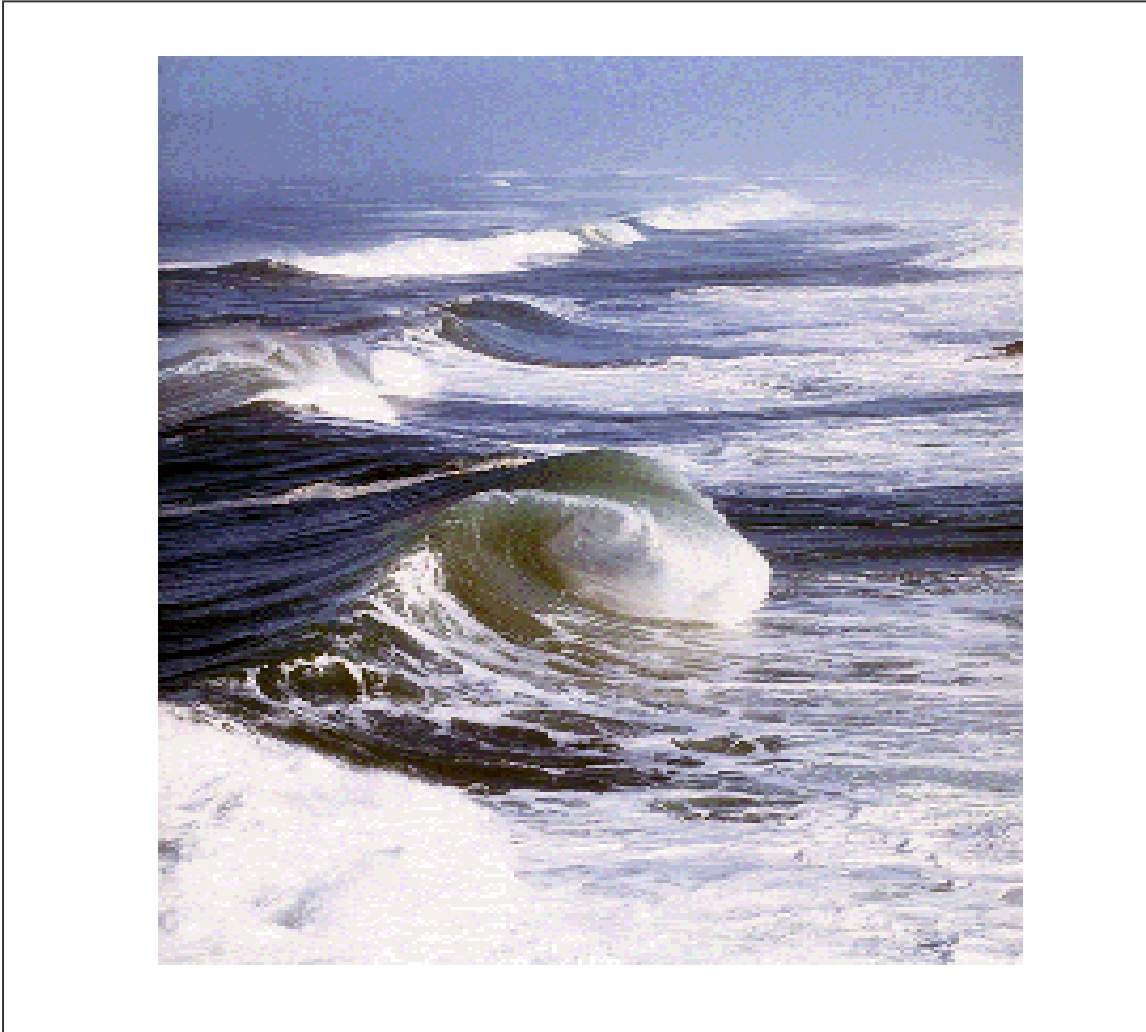


Photo 2: Breaking wave – near Westport

TIDES

Waves propagated into a tidal inlet, river or delta will shoal because of changes in water depth and as a result of interactions with an opposing ebb current or river flow. Such a flow will decrease the wavelength thereby increasing the height and the steepness. A wave steepening intensifies the wave breaking, and if induced by an opposing current the height to depth criterion may significantly underestimate wave-breaking and over estimate wave-height. A regular tidal variation of water depth over a bar will have a significant effect on the wave height and, more importantly, on the velocity of the crest of a breaking wave.

Example. A wave travels across the bar with a height of 3 m, a period of 5 sec and with a depth on the bar of 5 m.

This wave has a wave length of 30 m and the particle velocity at the crest is 4.7 knots but the wave does not break. The potential energy will remain in this wave while travelling across the bar at high tide. The same 3 m wave but now the tide has fallen by 2.5 m reducing the wave length to 23m. This reduction makes the wave break at a height of 2 m, and the running breaker it produces has a speed of 4.12 knots while a considerable amount of potential energy has been transformed to (destructive) kinetic energy.



© Mike Smith

Photo 3: The “Corsair” at Greymouth



© Peter Maich

Photo 4: The “Neptune” at Greymouth

FRESH WATER “RUN”

On an ebbing current or when there is a fresh water flow down-river, waves become steeper because their height increases and their length decreases. When there is a significant downflow the interaction between waves and current is very strong. The shortening of the wave length is significant. At a mean wave height of 2.5 m, a period of 5 seconds and an opposing current of 3.5 knots the waves are nearly blocked by the opposing current. Blocking occurs when the downflow is so strong that it stops waves from propagating further (up river).

A wave with height 2 m, length 36 m and a period of 5 sec travels at an approximate speed of 14 knots through water with a depth of 10 m. This same wave will slow down and steepen not only as a result of shoaling but also due to the opposing current. Once the fresh “run” attains a velocity of about 3.7 knots this wave will stop altogether. Once the wave is blocked the wave energy is dissipated by breaking and/or reflection offshore.(10) The shortening of the wave length is about 50 percent.

INTERNAL WAVES

Waves are periodic movements at an interface. If the water column consists of an upper layer and a denser lower layer, the interface between the layers can undergo wave motion. This motion, which does not affect the surface and which usually cannot be observed on the surface, is an example of an internal wave. Internal waves can often be observed in the atmosphere, where they travel on the interface between warm and cold air.



Photo 5: “Lenticularis” cloud

Density interfaces in the ocean are created by differences in salinity or temperature and therefore have far smaller gradients than those between the sea’s surface and the overlying air. Thus, internal waves are far more subdued in frequency than surface gravity waves.(11) On the other hand, a result of the small difference in density is that internal waves reach far greater amplitudes than those at the sea surface. Internal waves occur in a great variety of wavelengths. The most obvious are those with wavelengths from two to six kilometres, as measured from crest to crest. Where the waves are the result of daily tidal forcing, they occur in packets of four to eight waves, the lead wave being most dominant.

Where the density interface is shallow enough to permit the internal wave crests to interact with the sea surface, the waves can be seen, and photographed resulting in a textural change of the surface ocean.(12)



Photo 6: Internal wave, Hobart

Photo 6 shows an internal wave travelling up the Derwent River estuary in Hobart, Tasmania. The effect of the wave is visible by streaks of smooth water produced by the convergences above the wave troughs.(13)

If the interface on which the wave travels is very shallow, ships may sometimes find themselves in a situation that most of the energy put into the propeller goes into driving the circular particle motion of the internal wave at the interface, with the ship making little or no progress through the water. This phenomenon is known as “dead water” and is common in fjords, where the interface is produced by a shallow layer of freshwater from glacier runoff overlying oceanic water underneath.(13)

If there is a sufficient outflow of fresh water from a river through the heads of the breakwater(s) and across the bar an interface is created with a very pronounced gradient. The fresh water flows outward on the surface while the salt water lies underneath, the interface being very clearly defined not only by the difference in density but also a difference in motion which could be up to 5 or 6 knots or more. The far more pronounced internal wave(s) thus created will move independently from the swell or sea waves and can therefore be in-phase, out-of-phase or anywhere in between.

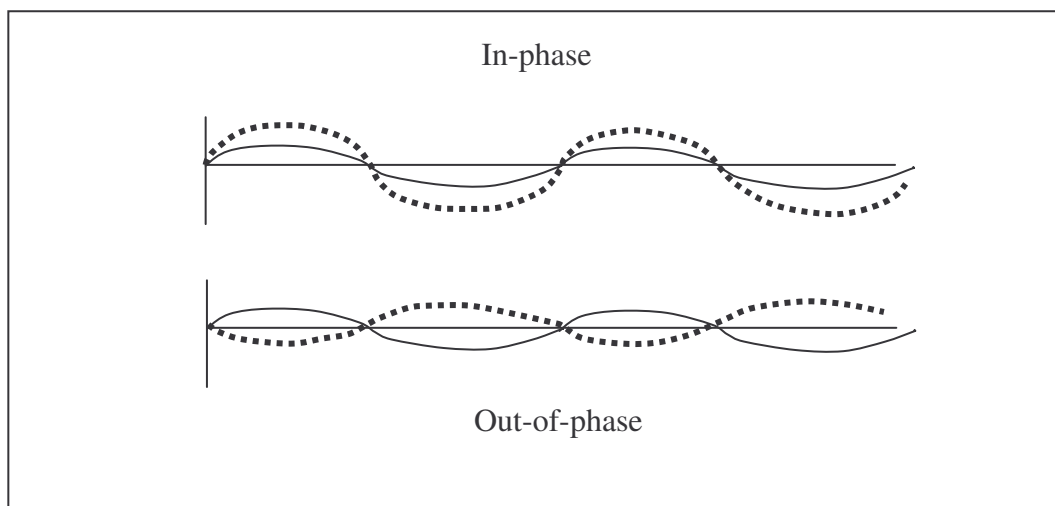


Figure 6: Waves in- or out of phase

When an internal wave on a sufficiently shallow boundary layer is in-phase with a surface wave, it can significantly increase the height of the waves and the depth of the troughs and when out of phase the heights and depths will be significantly decreased. In the context of this argument, these are totally random events and could account for the unpredictable appearance of "rogue" waves and troughs.

SHIP'S LENGTH versus WAVELENGTH versus SHIP'S SPEED

In 1995 the Maritime Safety Committee of the IMO issued a "Guidance to the Master for avoiding dangerous situations in following and quartering seas"(14), (15) and dealt in general terms, with situations like broaching and/or surf riding, the reduction of intact-stability, synchronous rolling and parametric rolling etc. The advice offered is valid for any kind of vessel, be it large or small, and applies to deep water conditions which are, or remain, relatively constant. "On the approach of the coast and perhaps a subsequent crossing of a bar, however, the sea/swell/wave conditions change continuously and adversely. The extremely dangerous combination of phenomena as mentioned in 3.1.5 which may cause a ship to capsize cannot be avoided." (Appendix I)

Two separate critical conditions of encounter waves are met, either

- a) When the ship speed approaches to the phase velocity of the wave.

"When the ship speed is so high that its component in the wave direction approaches to the phase velocity of wave, the ship will be accelerated to reach surf-riding and broaching-to (paragraph 3.1.1). The critical speed for the occurrence of surf-riding is considered to be $1.8/L$ (knots), where L is ship length. It should be noted that there is a marginal zone ($1.4/L \sim 1.8/L$) below the critical speed, where a large surging motion may occur, which is almost equivalent to surf-riding in danger. In these situations, a significant reduction of intact stability (paragraph 3.1.2) may also be induced with longer duration." (Appendix I 3.2.1) or
- b) When the ship speed is nearly equal to the group velocity of the waves.

"When the ship speed component in the wave direction is nearly equal to the wave group velocity, that is a half of the phase velocity of the dominant wave components, the ship will be attacked successively by high waves. The expected maximum wave height of the successive waves can reach almost twice the observed wave height of the sea state concerned. In this situation, the reduction of intact stability (paragraph 3.1.2), synchronous rolling motions (paragraph 3.1.3),

parametric rolling motions (paragraph 3.1.4) or combination of various dangerous phenomena (paragraph 3.1.5) may occur and create the danger of capsizing.” (Appendix I 3.2.2)

In this case we argue that it is not the ship’s speed which varies but the phase velocity of the wave which is inexorably slowing down as it feels the bottom and eventually breaks on or near the shore or "tip" heads (breakwater). Also, the wave group velocity, which is half the rate of the phase velocity of the wave, is slowing down at the same rate as the wave velocity and must therefore catch up with the speed of the vessel and will eventually also be reduced to zero.

When the mariner is confronted with a potentially dangerous condition in relation to a wave period or a wave direction or bad weather while navigating in deep water an alteration of course or speed or indeed the appropriate application of proper seamanship, would limit the chance of encountering a combination of extremely dangerous phenomena. When approaching the coast and eventually entering a port or river, the mariner travels from deep water through an area where:

- a) The wavelength continuously decreases
- b) The phase velocity of the wave continuously decreases
- c) The wave height continually increases.

A ship’s behaviour in following and quartering seas is dependant on the length of the vessel (L) in relation to the wave length (λ) and optimum conditions for surf riding and/or broaching exist when $\lambda / L = 1.0$ or less.(14) A water depth of 10 m at a particular location suggests an average wavelength of around 35 m with a height of about 2 m and a period of 5 seconds.(3) Hence a vessel with a length of 35 m or more will not seriously be affected by the conditions, indeed, upon approaching the shore the wave lengths continue to decrease and the safe navigation for such a vessel is now a matter of negotiating the shallows, allowing for the "set" or cross-currents etc. Dangerous conditions at that particular location would be limited to vessels of less than about 35 m.

We can come to the following conclusion:

- When sailing in following or quartering seas a vessel is likely to encounter various kinds of dangerous phenomena.
- The susceptibility of a vessel to such dangerous phenomena will depend on the ship’s speed and size as well as the shape of the hull. (Given compliance with stability parameters covered by IMO instruments.)(14)
- When a vessel of a certain (smaller) size approaches a coast from seaward, the encounter of extreme and optimum dangerous conditions cannot be avoided regardless of prevailing conditions except when there is no significant swell.
- The extent of the area of extreme and dangerous conditions depends on the rate of shoaling.
- The location of the area depends on:
 - a) The depth under the keel (the state of the tide)
 - b) The size of the swell
 - c) The rate of the fresh water “run”.
- The presence of one or two bars will increase the area considerably and makes the location of the area unpredictable.
- Most importantly, the location of the area depends on the length of the vessel and the water depth, i.e. for every vessel there exists a different area.

BROACHING

“Broaching” is an unintentional change in the horizontal-plane kinematics of a ship. Broadly, it may be described as the “loss of heading” by an actively steered ship that is accompanied by an uncontrollable build-up of large deviation from the desired course. Broaching more commonly occurs in waves that come from behind and propagate in a direction forming a small angle, say 10-30 deg, with the longitudinal axis of the ship. Although the inception of broaching represents a problem of instability on the horizontal plane, capsize may be incurred at the post critical stage due to development of large heel as energy is transferred into the roll direction.

Broaching could happen to small as well as to larger ships. It is notable however that the dynamics involved do not seem to fit always into a single pattern. Frequently, broaching is manifested as a sudden divergent yaw, which peaks within a single wavelength. Control is lost when the middle of the ship lies somewhere on the down-slope and nearer to the trough. In other cases there is a gradual, oscillatory-type build-up of yaw as successive waves impinge on the ship from behind. In moderate sea states a ship is more likely to broach-to if it runs with a high speed and is slowly overtaken by the waves. Broaching may also occur at lower speeds if the waves are very steep.” (18)

THE PROGRESSION FROM DEEP WATER TO AND ACROSS THE BAR

Assume our vessel to be 16 m long and it complies with all IMO/MSA imposed and recommended Rules and Regulations, particularly in relation to seaworthiness and stability. The vessel adheres to the “National Code of Practice” and takes particular note of “prudent practice”(16). The vessel is proceeding with caution and reduced speed toward the deepest sections of the bar, as indicated by the most recent bar chart. The vessel is now entering the area where the dangerous conditions particular to the length of this vessel are approaching optimum. Assume an average swell, height of 1.5 m and a period of 5 s over a water depth of 10 m giving a wave length of 36 m. The lookout, watching astern, warns the skipper that some waves are approaching from astern which seem to gain in height.



© Peter Maich

Photo 7: Going In

The skipper reduces speed, with the intent of letting the wave overtake him thus reducing a chance of surf riding and also thereby increasing the reserve power in case this is needed for a later manoeuvre. The wave approaches the stern of the vessel and the skipper has placed his vessel parallel to the line of advance.

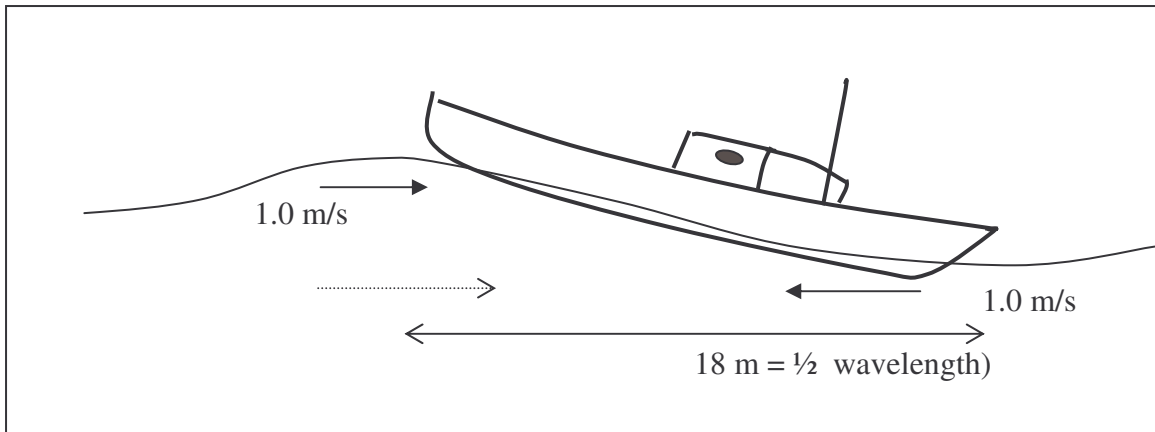


Figure 7: Travelling down-slope

As a result of the orbital velocity of the wave the velocity of the water particles accelerate from zero to maximum in one quarter of the wavelength. On the advancing slope of the wave, the water particles near the bow and in the trough travel in the *opposite* direction to the wave, in this case with a speed of about 1.95 knots. The water particles near the stern are travelling in the *same* direction as the wave also with an approximate speed of 1.95 knots. (Refer page 6.) It puts the stern of the boat in water that is moving in the opposite direction than the water surrounding the bow.

This creates two opposing forces that form a turning couple or torque if the direction of travel of the vessel is not exactly parallel to the advancing wave. The water flow past the rudder blade has decreased and steering becomes more and more difficult, the vessel shows an increasing tendency to veer sideways as a result of the increased pressure on the bow.

The speed of the vessel increases as it progresses down the face of the wave but the skipper manages, with rudder and engine manoeuvres, to maintain steerage and prevent “surfriding”. If the vessel is still at the seaward side of the “extreme” area the wave will travel a bit faster than the vessel, the crest will pass underneath the vessel and if the wave does not break it will move ahead toward the shore.



© Peter Maich

Photo 8: On the crest of the wave

When riding on the wave crest the stability will decrease substantially as a result of a loss in moment of inertia due to the change in area of the waterplane. Since the vessel and the wave travel in the same direction at nearly the same speed, this period of decreased stability is greatly prolonged and could easily precipitate a capsize.(14)

Although a very dangerous situation, this is not the cause of broaching.

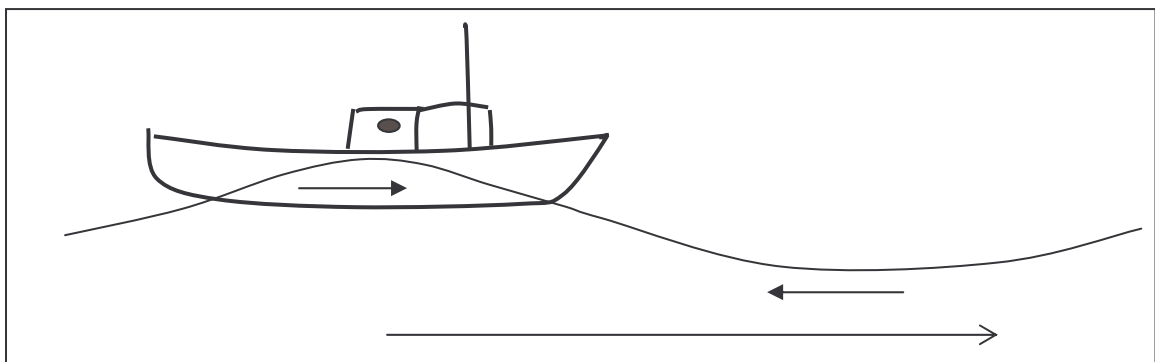


Figure 8: On the crest of a wave

Thus far the vessel has been able to be kept under control, but she advances a little further into the area of extreme danger and now the conditions for broaching are becoming near optimum for the size, speed of travel and the draught/water under the keel of the vessel. (Refer page 17.) By applying good seamanship and “good practice” the skipper angles for the best approach towards the heads of the breakwaters, taking into account the location of the bar(s) and the amount and direction of the set.

The speed of the fresh water run, the state of the tide, the change of phase in relation to an internal wave and the rise of the sea bottom all contribute to making the progression of the waves quite irregular. The wave train is difficult to detect and the prediction of on-coming waves becomes very difficult. Another set of waves approaches and the vessel is again lifted on the advancing wave. This time the wave is near its maximum height. The speed of the advancing wave is approximately 6 to 8 knots over the ground and the speed of the vessel is similar. If the river flows at a rate of 2 knots, the vessel's speed would be about 8 to 10 knots through the water.

A same, average wave has now increased to a height of 1.7 m in a water depth of 7 m, the period is 4 seconds and the wavelength has been reduced to about 23 m. The water speed at the crest has increased to 2.7 knots and in the trough also to 2.7 knots going in opposite direction. The vessel is lifted stern first and starts to accelerate down the wave. The loss of steering is unavoidable, if the skipper increases the water flow past the rudder by increasing the power, some steerage might return but the vessel would probably begin to ride the surf. There are now three possible scenarios.

Scenario One

The lack of steerage causes the vessel to veer sideways, and once this has begun the turning couple thus created quickly reaches maximum. In a matter of seconds the vessel is twisted beam-on to the advancing crest of the wave.

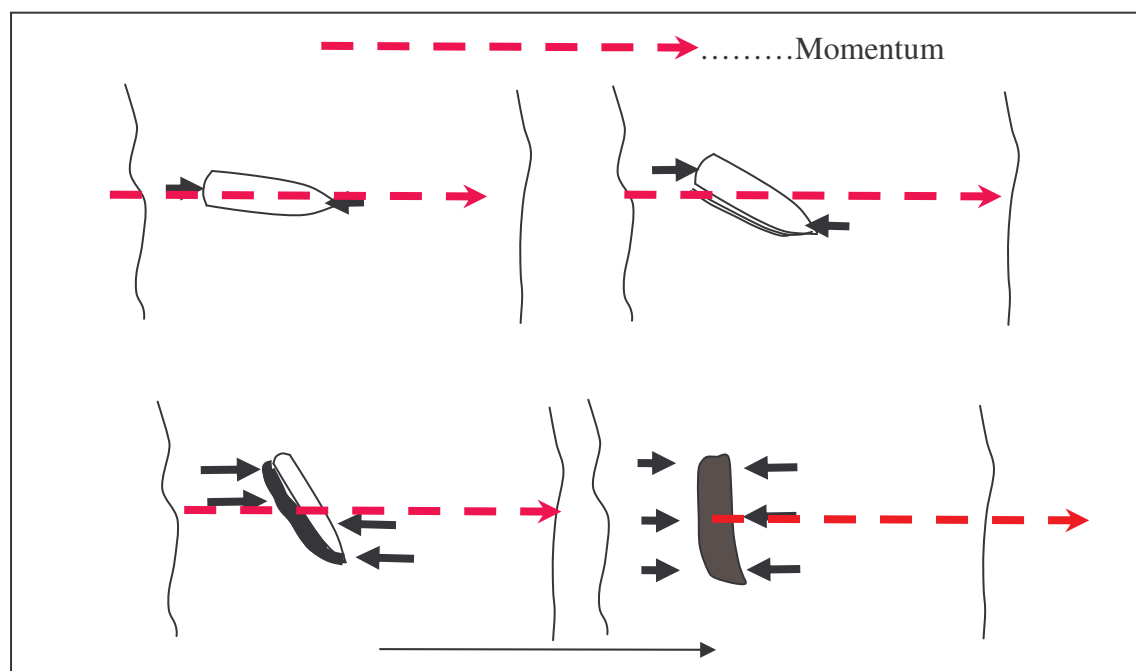


Figure 9: A broach

The vessel, with a mass of 60 tonne, has made a violent turn of 90 degrees with the result that linear momentum ($m \times v$) is converted to a substantial and prolonged capsizing torque, a capsizing is unavoidable. This situation can be likened to a 60 t. locomotive travelling at 8 knots suddenly being forced to turn 90 degrees. The body will turn, twist and roll over until all kinetic energy is expended.

A broach followed by a capsize does not necessarily involve the presence of large waves. It is the momentum created by the speed of travel through the water which provides most of the capsizing moment.

Any amount of positive stability is of little or no relevance and cannot prevent such a calamitous outcome. Factors like preparedness, ship's husbandry or seaworthiness only determine to what degree the vessel and crew can survive such a disaster.

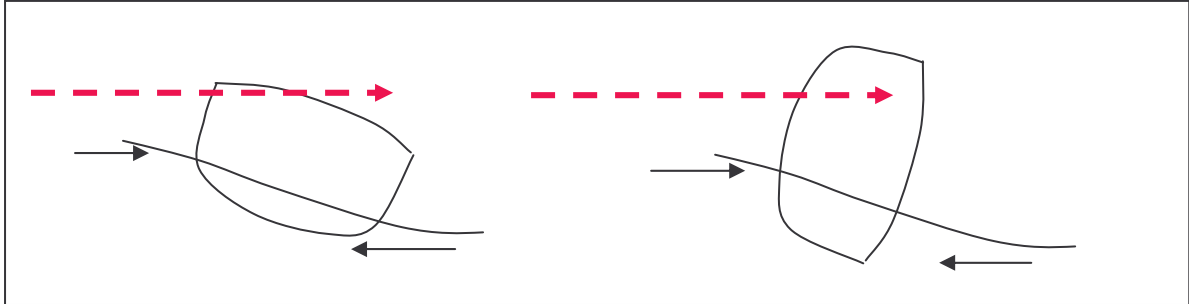


Figure 10: Capsize due to momentum



Photo 9: The “Katana” at Greymouth

Scenario Two

The skipper is able to maintain steerage by using the engine and as a result the speed of the vessel is approaching the speed of the advancing wave. This prolongs the time the vessel spends on the face of the wave and while the wave height is increasing, the wave length and the wave speed is decreasing. If this situation continues then, at some time, the after part of the vessel will be positioned underneath a developing plunging breaker. The very efforts of the skipper to maintain steerage and position promotes the chance of the stern of the vessel being buried (pooped) under an avalanche of water. If this happens the vessel will be partly or completely overwhelmed and loses all available positive stability, either instantly or when the remainder of the advancing crest critically reduces the area of the waterplane. The advancing breaker is capable of considerable destruction when its kinetic energy is being released and the watertight integrity might instantly be compromised with a similar result. It is the only considerable skill of the experienced skipper which allows a successful crossing of this hazardous area.

Scenario Three

The vessel is in the centre of the danger area and a wave approaches from astern. The skipper slows down and tries to maintain steerage with the intention to let the wave pass. The wave speed decreases and the wave height increases, the water particles in the crest move faster than the wave itself and the crest disintegrates. The breaking wave now hits the stern of the vessel. The magnitude of this impact should not be underestimated. If we assume the total area of the stern to be 20 m², the force would be about 17.6 tonnes and this force would only slowly dissipate. (Refer pages 9 and 10 and Appendix II.)

As a consequence the vessel (displacement 60 t) is literally picked up and thrown forward. The acceleration and twisting motion is sometimes of such violence that the vessel is sliding over the surface of the underlying water. The opening minutes of the SITO video show a perfect example of such an event. The vessel can be seen to literally skid over the surface for about 50 metres.



Photo 10: “Hildaron” Westport

CONCLUSION

For a smaller vessel the crossing of a harbour or river bar is a very hazardous undertaking even if conditions seem very favourable. It is likely that when crossing a bar with a swell or sea of any size a vessel will encounter a combination of the dynamic processes discussed in this paper.

The creation of dangerous conditions on a bar depends on many factors and when all factors are combined it is possible to determine where the most hazardous area is located. This location is directly related to the wave length and the length of the vessel. Every vessel has therefore its own most dangerous area when approaching the bar. This implies that what seems reasonable and possible for one vessel in a given area is quite dangerous for a shorter vessel in the same area. Consequently the successful crossing of a certain area of one vessel could easily be disastrous in the same area for a vessel which is a little shorter.

The location of the most dangerous area changes continuously partly due to the fact that the internal wave created by fresh water flowing down river is randomly in- or out-of-phase with the wave(s) above. Obtaining and analysing relevant information necessary to make decisions in relation to crossing a bar is essential in order to make a well-founded decision.

There is no doubt that the situation on the bar is most accurately assessed from the heads of the breakwater(s) but, in light of the preceding arguments, conditions are extremely changeable and unpredictable and this should be kept in mind. As stated earlier, the state of preparedness in relation to stability, watertight integrity and not the least the expertise and experience of the Master is very important but sometimes have a reduced influence on what happens when the vessel is subjected to the dynamic processes while crossing the bar. Moreover, the unpredictability of the situation and the most “unnatural” behaviour of the vessel will sometimes even leave the most prudent and experienced Master with very little defence.

It must therefore be remembered that at no time, even in the most favourable conditions, should the Master be less than alert or become complacent.

REFERENCES

- (1) Bruce Johnson U.S. Naval Academy. "Capsize resistance and survivability when smaller vessels encounter extreme waves". Abstract for Rogue waves 2000 workshop, Brest, 29 - 30 November 2000
- (2) Robert M. Sorensen, "Basic Wave Mechanics for Coastal and Ocean Engineers" Chapter 2. John Wiley & Sons, 1993
- (3) Dean and Dalrymple, *Water Wave Mechanics for Engineers and Scientists*, World Scientific Press
- (4) Duxbury & Duxbury, *Fundamentals of Oceanography*, 1993
- (5) Peregrine, D. H., Breaking waves on beaches, *Annual Review of Fluid Mechanics*, 15, 149-178, 1983
- (6) Battjes, J. A., Surf-zone dynamics, in *Annual Review of Fluid Mechanics*, pp. 257-293, 1988
- (7) Svendsen, I. A., Wave heights and set-up in a surf zone, *Coastal Engineering*, 8, 303-329, 1984
- (8) U.S. National Report to IUGG, 1991-1994 Rev. Geophys. Vol. 33 Suppl., 1995 American Geophysical Union
- (9) Pal F. Lader, Dag Myrhaug and Bjornar Pettersen Department of Marine Hydrodynamics, Norwegian University of Science and Technology, Trondheim, Norway
- (10) Smith, J.M., "Wave breaking on an opposing current," Coastal Engineering Technical Note CETN IV-17, U.S. Army Engineer Research and Development Centre, Vicksburg MS. 1999
- (11) LaFond, E. C., Internal waves. In *The Sea* (M. N. Hill, Ed.). Vol. 1, Pt. 1, 731-751, InterScience Publications, John Wiley and Sons. New York, N.Y., 1962
- (12) Basovitch, A. Y., Transformation of the surface spectrum by the action of internal waves. *Fizika Atm. Okeano* 15, 655-662, 1979
- (13) Tomczak M. *An Introduction to Physical Oceanography*, 1999 - 2001
- (14) MSC/ Circular 707 "Guidance to the Master for avoiding dangerous situations in following and quartering seas", 15 October 1995
- (15) Agenda item 17, 44th session, Sub-committee on Stability and Load Lines and on Fishing Vessels Safety
- (16) MSA Marine Notice Boats 10/2001 November National Code of Practice

(17) Umeda N. & Renilson M.R. Broaching of a fishing vessel in following and quartering seas – a non-linear dynamical system approach. 1994

(18) Spyrou K.J. & Umeda N. From surf riding to loss of control and capsizing. A model of dynamic behaviour of ships in following/quartering seas. 1995.

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APPENDIX I

Ref. T1/2.04

GUIDANCE TO THE MASTER FOR AVOIDING DANGEROUS SITUATIONS IN FOLLOWING AND QUARTERING SEAS

1. The Maritime Safety Committee, at its sixty-fifth session (9 to 17 May 1995), approved the annexed Guidance to the master for avoiding dangerous situations in following and quartering seas, with a view to providing masters with a basis for decision making on ship handling in following and quartering seas, thus assisting them to avoid dangerous phenomena that they may encounter in such circumstances.
2. Member Governments are invited to bring the Guidance to the attention of shipmasters and other interested parties of the shipping industry as they deem appropriate.
3. The Maritime Safety Committee has decided to review the Guidance in the future with a view to improving it, in particular with respect to large ships, on the basis of new technical developments and in the light of experience gained from its application.

MSC/Circ.707 I:\USCG\IMOLONDON\CIRC1\MSC.0\707

ANNEX

GUIDANCE TO THE MASTER FOR AVOIDING DANGEROUS SITUATIONS IN FOLLOWING AND QUARTERING SEAS

1 GENERAL

- 1.1 When sailing in severe following or quartering seas, a ship is likely to encounter various kinds of dangerous phenomena, which may lead to capsizing. Although the dynamic behaviour in following and quartering seas is not yet covered in present stability standards, much progress has been made in recent years towards understanding the physics of capsize mechanisms and identifying potentially critical conditions.
- 1.2 The sensitivity of a ship to dangerous phenomena will depend on the actual stability parameters, hull geometry, ship size and ship speed. This implies that the vulnerability to capsizing and its probability of occurrence in a particular sea state may differ for each ship.
- 1.3 The guidance aims at giving seafarers caution on dangerous phenomena that they may encounter during navigation in following and quartering seas, and providing the basis for a decision on ship handling in order to avoid such dangerous situations. It provides advice on safe and unsafe combinations of ship speed and course relative to waves, in a simplified form of a polar diagram. The diagram does not take into account the actual stability and the dynamic characteristics of an individual ship, but provides a general unified boundary of safe and unsafe combination of the operational parameters for all types of conventional ships covered by IMO instruments.

- 1.4 For the ships which are equipped with an on-board computer, the Administrations are encouraged to use a specially developed software which would take into account the main particulars, actual stability and dynamic characteristics of the individual ship in the real voyage conditions. Such software should be approved by the Administration.

2 PRECAUTIONS

It should be noted that the operation guidance is not the criteria to guarantee the safety absolutely. A ship could be unsafe even outside the dangerous zone defined in this guidance if the stability of the ship is insufficient and several dangerous phenomena characteristic for following and quartering seas happen simultaneously. Therefore, the ship master should pay attention that the ship maintains a good state of stability and do not carelessly navigate in severe following and quartering seas.

3 DANGEROUS PHENOMENA FOR SHIPS IN FOLLOWING AND QUARTERING SEAS

- 3.1 Dangerous ship responses in following and quartering seas The period with which a ship travelling in following and quartering waves encounters the waves becomes longer than in head or bow waves, and principal dangers caused in such situations are as follows:

3.1.1 Surf-riding and broaching-to

When a ship is situated on a steep forefront of high wave in following and quartering sea condition, the ship can be accelerated to ride on the wave; this is known as surf-riding. When a ship is surf-ridden, the so-called broaching-to phenomenon may occur, which endangers the ship to capsize as the result of sudden change of ship's heading and unexpected large heeling.

3.1.2 Reduction of intact stability caused by riding on the wave crest at midship

When a ship is riding on the wave crest, the intact stability will be decreased substantially according to the ship form. The amount of stability reduction is nearly proportional to the wave height and the ship may lose the stability when the wave length is one to two times of ship length and wave height is large. This situation is especially dangerous in following and quartering seas, because the duration of riding on wave crest, i.e. the time of inferior stability, becomes longer.

3.1.3 Synchronous rolling motion

Large rolling motions may be excited when the natural rolling period of a ship coincides with the encounter wave period. In case of navigation in following and quartering seas this may happen when the transverse stability of the ship is marginal and therefore the natural roll period becomes longer.

3.1.4 Parametric rolling motion

Unstable and large amplitude roll motion will take place if the encounter wave period is approximately equal to half of the natural roll period of the ship. This type of rolling can occur in head and bow seas where the encounter wave period becomes short. In following and quartering seas, this can occur particularly when the initial metacentric height is small and the natural roll period is very long.

3.1.5 Combination of various dangerous phenomena

The dynamic behaviour of a ship in following and quartering seas is very complex. Ship motion is three-dimensional and various detrimental factors or dangerous phenomena such as additional heeling moment due to deck in water, water shipping and trapped on deck or cargo shift due to large roll motions, may occur in combination with the above-mentioned phenomena simultaneously or in a sequence. This could create an extremely dangerous combination which may cause ship capsizing.

3.2 Dangerous navigation conditions in following and quartering seas

There exist two kinds of critical conditions of encounter waves under which the dangerous phenomena as above-mentioned are excited:

3.2.1 When the ship speed approaches to the phase velocity of wave

When the ship speed is so high that its component in the wave direction approaches to the phase velocity of wave, the ship will be accelerated to reach surf-riding and broaching-to (paragraph 3.1.1). The critical speed for the occurrence of surf-riding is considered to be $1.8/L$ (knots), where L is ship length. It should be noted that there is a marginal zone ($1.4/L \sim 1.8/L$) below the critical speed, where a large surging motion may occur, which is almost equivalent to surf-riding in danger. In these situations, a significant reduction of intact stability (paragraph 3.1.2) may also be induced with longer duration.

3.2.2 When the ship speed is nearly equal to the group velocity of wave

When the ship speed component in the wave direction is nearly equal to the wave group velocity, that is a half of the phase velocity of the dominant wave components, the ship will be attacked successively by high waves. The expectable maximum wave height of the successive waves can reach almost twice of the observed wave height of the sea state concerned. In this situation, the reduction of intact stability (paragraph 3.1.2), synchronous rolling motions (paragraph 3.1.3), parametric rolling motions (paragraph 3.1.4) or combination of various dangerous phenomena (paragraph 3.1.5) may occur and create the danger of capsizing.

APPENDIX II

Assume speed of wave crest = 1.9 knots

Speed of approach in relation to stern of vessel = 1 knot

Speed of impact 2.9 knots

$$F/f = 1025 \times (20 \text{ m}^2) \times 2.9^2 = 172405 \text{ Newtons}$$

$$172405 \div 9800 = 17.6 \text{ tonnes}$$

APPENDIX III

Boat Notice - 10/2001 November

National Code of Practice for Bar Crossings

This code addresses widespread concerns over fatalities, mainly to the crew of fishing vessels, on bar harbours. A group comprising bar harbour Harbourmasters, fishing industry representatives and the Maritime Safety Authority has developed the code after extensive consultation with all sectors of the maritime industry.

1.0 PURPOSE

- 1.1 The purpose of the 'National Code of Practice' is to provide clear guidelines to the skipper and crew of all vessels regarding safe and prudent practice when attempting to cross any bar or river entrance.

2.0 CAUTIONS

- 2.1 Extreme caution must be exercised when crossing bars. Conditions prevailing on a bar or in river approaches may cause unusually sudden steep and often breaking seas. Conditions change quickly and unpredictably. The skipper's experience and the vessel type should be taken into account when a bar crossing is considered. However, no amount of experience or boat type makes crossing a bar SAFE when the conditions are marginal or adverse. No situation warrants taking the risk, so if in doubt "STAY OUT".
- 2.2 Before leaving harbour a skipper must assess conditions on the bar. Skippers must be aware that a rapid change in conditions might prevent a safe return to harbour. Craft unable to weather adverse seas outside the bar should not leave port. Those vessels leaving for longer trips should ensure they have adequate reserve fuel and provisions to enable the vessel to remain at sea and/or divert to another port should adverse bar conditions prevail on their return.

- 2.3 Ensure that your vessel has sufficient stability. All vessels must be in a stable condition. Skippers should be aware of all the factors that determine a vessel's stability including:
- The free surface effect of liquids and loose fish.
 - Additional weights on deck, including portable ice slurry bins and fuel containers.
 - The loss of stability that occurs if deck enclosures or bins suddenly fill with water.
 - Modifications to a vessel may be detrimental to its stability. The vessel's static stability should have been calculated after such alterations.
 - The movement of weights within the vessel including people.
- 2.4 Skippers should be aware that:
- All bars have areas of broken water containing air, which can severely reduce the stability and handling of a vessel;
 - In marginal conditions, night time crossings are more hazardous; and
 - Vessels attempting to cross a bar at or near low water are more likely to experience adverse conditions than at high water.
- 3.0 PRUDENT PRACTICE
- 3.1 Effective communication must be established before attempting a crossing between the skipper and the Harbourmaster or if unavailable, another responsible person.
- 3.2 All skippers operating to and from bar harbours should obtain relevant up to date information and a weather report pertinent to the area before crossing the bar, and take into account that information.
- 3.3 Stay at a safe distance offshore until a report on the prevailing bar conditions has been obtained from the Harbourmaster or, if unavailable, another responsible person inside the harbour. If in doubt "STAY OUT".
- 3.4 Skippers should ensure that all deck openings, hatches and doors are securely battened down or closed, particularly off-centre line hatchways. Freeing ports should be checked that they are clear and operating. Loose gear on deck including ice-slurry bins and their lids should be secured.
- 3.5 Before crossing any bar entrance, skippers should ensure that everyone on board is awake and dressed.
- 3.6 Ensure lifesaving equipment is easily accessible and ready for immediate use. Every person should wear a Personal Flotation Device (PFD) of an appropriate size, particularly children. There are many approved inflatable lifejackets that are easy and comfortable to wear.
- 3.7 Approaches should be made at a moderate speed in order that a skipper might increase or slacken speed in order to steer out of trouble.

- 3.8 A lookout watching astern should be posted to keep the helmsman informed of the approach of dangerous building swells.
- 3.9 In the interests of safety and manoeuvrability the skipper should ensure the preceding vessel is well clear of the bar before preceding.
- 3.10 Once across the bar, the skipper should confirm successful crossing with the Harbourmaster or, if unavailable, another responsible person.

A “responsible person” is a person with relevant experience and/or expertise, in whom the skipper has confidence, who is accountable for the provision of advice regarding local bar conditions and/or prudent practice to skippers intending to cross the bar.

IT IS ULTIMATELY THE SKIPPER’S RESPONSIBILITY TO DETERMINE WHETHER OR NOT TO CROSS A BAR