I.O.S.

WAVE-CURRENT INTERACTIONS: A REVIEW OF SOME PROBLEMS

BY
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WORMLEY

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ABSTRACT

This report reviews the methods available for calculating the interaction of waves with a vertically varying current which is steady and uniform in the horizontal plane. These methods are assessed in the light of experimental evidence on wave-current interactions and recommendations are made for further research in this area.

CONTENTS

1. Introduction

This report arises out of an earlier study (Carter et. al. 1985) which reviewed methods of estimating wave parameters for engineering applications. Chapter 5 of that study was concerned with wave kinematics and discussed, among other problems, wave-current interactions. One particular aspect of wave-current interactions will be considered in detail in this report; that of the interaction of waves with a current which is steady and uniform in the horizontal plane but varies with depth. This is a problem of some importance for the design of offshore structures where the combined effects of extreme currents and waves need to be understood.

Beiboer (1984) has discussed wave-current interactions in relation to engineering design applications. He too has noted the need for a better understanding of wave-current interactions for design purposes. He also notes the need for a better statistical description of the joint probability of occurrence of extreme waves and currents, but this aspect of the problem will not be pursued here. His paper discusses some of the problems involved in combining waves and currents to obtain the kinematics of the flow; necessary for the calculation of the forces acting on a structure. We will not repeat his discussion here but refer the reader to his paper.

The aim of this report is to outline the methods that exist for calculating the interactions of waves with a current that varies only with depth. The methods available will be assessed in the light of such experimental evidence that exists at present and some of the outstanding theoretical and practical difficulties that exist in applying the methods will be highlighted. On the basis of this review of our present understanding suggestions for further research in this area will be given.

As this report deals with only a small area of the subject of wave-current interactions we will mention here some references which may fill in details and give further information on this topic. Reviews of work on wave-current interactions have been made by Peregrine (1976) and Peregrine & Jonsson (1983). Peregrine, Jonsson & Galvin (1983) give an annotated bibliography of papers on wave-current interactions. Dalrymple (1973) describes various methods for calculating wave-current interaction and gives more details than it is possible to do here. For background reading in relation to wave kinematics Carter et. al. (1985) may be consulted and in relation to wave forces Sarpkaya & Isaacson (1981).

2. Basic assumptions and equations

Before discussing the various methods for calculating wave-current interactions for waves on a depth varying current, we will outline the assumptions and equations that underlie all the methods. It is assumed that we are considering the motion of an inviscid, incompressible fluid (water) under the action of gravity. The velocity field $\underline{u} = (u, v, w)$ at any point (x, y, z, t) then satisfies the momentum equation

$$\frac{\partial \underline{u}}{\partial t} + \underline{u} \cdot \nabla \underline{u} = -\frac{1}{\rho} \nabla p - g \underline{k} \qquad (1)$$

and the continuity equation

$$\nabla \cdot \underline{u} = 0 \qquad (2)$$

where ρ is the density of the fluid

p is the pressure

g is the acceleration due to gravity

$\underline{k}$ is a unit vector in the z -direction (vertically upwards, see figure 1).

In addition to the above equations it is necessary to specify the boundary conditions on the fluid domain. On any rigid boundary (such as the sea bed - asssuming that it is impermeable) the normal velocity is zero

$$\underline{u} \cdot \underline{n} = 0 \qquad (3)$$

where $\underline{n}$ is the unit normal to the boundary. At the free surface, neglecting the effects of surface tension, the pressure p must be constant and equal to the atmospheric pressure which can be taken to be zero

$$p = 0. \tag{4}$$

In addition, if the free surface is given by

$$z = \eta(x, y, t)$$

then

$$\frac{\partial \eta}{\partial t} + u\frac{\partial \eta}{\partial x} + v\frac{\partial \eta}{\partial y} = w. \tag{5}$$

This is the kinematic boundary condition which states that no fluid can cross the boundary.

In what follows it will be assumed (unless otherwise stated) that the waves are monochromatic (hence periodic), steady and propagate in the x-direction only on water of uniform or infinite depth. These assumptions allow considerable simplification of the problem. Furthermore if the current is at an angle θ to the waves

$$\underline{U}(z) = (U(z)\cos\theta, U(z)\sin\theta, 0)$$

the problem need only be solved for the case

$$\underline{U}(z) = (U(z)\cos\theta, 0, 0)$$

as the momentum equations in the x and z directions, the continuity equation and the boundary conditions remain unchanged. This reduces the problem from three to two dimensions (x and z). The motion in the y-direction can be found from the y-momentum equation once the two-dimensional solution is known (see Benny, 1966). Therefore we will restrict our attention to two-dimensional problems (in x - z coordinates).

3. Waves on a uniform current

The simplest situation to consider in wave-current interactions is the case of waves on a uniform current $U(z) = U_o$. The primary effect of a uniform current is to change the frequency of the waves due to a Doppler shift. Thus if the radian frequency of the waves in a frame of reference moving with the current speed is σ and they have wavenumber k then their frequency ω in a fixed frame of reference is given by

$$\omega = \sigma + kU_o \tag{6}$$

If U_o is positive (wave and current travel in the same direction) then the frequency of the waves is increased over that which they would possess in still water. If U_o is negative (waves and current travel in opposite directions) then the frequency is reduced. For sufficiently high opposing currents the waves cannot propagate against the current. As, for practical purposes, the currents are small compared to the phase speed of the waves the reader is referred to the review of Peregrine (1976) for a discussion of this point.

In the case of a uniform current it is clear that any solution for waves on still water may be combined with the current by the simple addition of the uniform velocity to the wave solution. However, in the fixed frame of reference allowance has to be made for the change in wave frequency given by (6). If this Doppler shift in frequency is not correctly taken into acount errors can result in the interpretation of experimental results (see Peregrine, 1976).

The simplification of the problem assuming a uniform current is not always possible. If waves propagate from a region of no current to one with uniform current then account has to be taken of changes in the wave amplitude and wavenumber. As we are concerned with vertical rather than horizontal variations in the current this aspect of the problem will not be discussed here. See Carter et. al. (1985), Peregrine (1976) and Peregrine & Jonsson (1983) for further details.

4. Small amplitude waves

Having considered the simple case of a uniform current the next simplification to consider is that of small amplitude waves. Under the assumption of small amplitude the waves can be regarded as a perturbation of the current and this allows the equations of motion to be linearised by neglecting terms which contain the square and higher powers of the wave amplitude.

Following Thomas (1981) we may write

$$\eta(x,t) = a \cos(kx - \omega t) \tag{7}$$

$$\left.\begin{aligned} u_T(x,z,t) &= U(z) + u(z)\cos(kx-\omega t) \\ w_T(x,z,t) &= w(z)\sin(kx-\omega t) \end{aligned}\right\} \tag{8}$$

and

$$p_T(x,z,t) = -\rho g z + p(z)\cos(kx-\omega t) \,. \tag{9}$$

Here the subscript T has been used to denote the total fluid velocity and pressure. $U(z)$ is the depth varying current and the perturbation due to the waves is assumed to be sinusoidal. Substitution into the momentum and continuity equations (1) and (2) and linearisation leads to the following relationships

$$\left.\begin{aligned} u &= k^{-1} w' \\ \frac{p}{\rho} &= k^{-1}\left[w U' - (U-c) w'\right] \\ \frac{p'}{\rho} &= k\,(U-c)\,w \end{aligned}\right\} \qquad (10)$$

where $'$ = d/dz and c = ω/k is the phase speed of the waves. These equations can now be combined to yield a single equation for the function $w(z)$

$$w'' - \left[k^2 + \frac{U''}{U-c}\right] w = 0 \; . \qquad (11)$$

This is the "inviscid Orr-Sommerfeld equation" or "Rayleigh equation" of hydrodynamic stability theory (Drazin & Reid, 1981). Once a solution to this equation has been found (10) allows the functions $u(z)$ and $p(z)$ to be determined.

In addition to (11) it is necessary to specify boundary conditions for the function $w(z)$. At the free surface linearisation allows these to be applied at the mean level z = 0, thus the dynamic boundary condition (4) gives

$$(U-c)^2 w' = \left[g + (U-c)\,U'\right] w \quad \text{on } z = 0 \qquad (12)$$

while the kinematic boundary condition (5) gives

$$w = a\,(\omega - kU) \quad \text{on } z = 0 \, . \qquad (13)$$

The bottom boundary condition (3) becomes

$$w = 0 \quad \text{on } z = -h \tag{14}$$

Clearly equation (11) does not possess a simple analytic solution for an arbitrary current profile $U(z)$ but analytic solutions exist for the linear profile

$$U(z) = U_o + \zeta_o z \tag{15}$$

for which

$$w(z) = a(\omega - kU_o) \sinh k(z+h) / \sinh kh \tag{16}$$

This gives the following dispersion relationship for waves on a linear shear flow

$$(\omega - kU_o)^2 = [gk - (\omega - kU_o)\zeta_o] \tanh(kh) \tag{17}$$

For no current (U_o = ζ_o = 0) this reduces to the linear dispersion relationship for waves on water of depth , while for a current with no shear (ζ_o = 0) it reduces to the Doppler shifted linear dispersion relationship for waves on a uniform current (see previous section). Note that ζ_o is the vorticity of the flow, which is constant. This solution was originally given by Thompson (1949).

Thompson (1949) also suggested how more complex profiles $U(z)$ could be approximated by a piecewise linear profile with appropriate matching conditions on $w(z)$ at the "joins" in the profile. The appropriate conditions (Peregrine, 1976) are that normal velocity and pressure

$$w/(U-c) \qquad \text{and} \qquad (U-c)\,w' - U'w$$

be continuous across the "join". For the case of a particular bilinear profile Thompson (1949) gives results for water of finite depth while Taylor (1955) gives results for water of infinite depth. Dalrymple (1973) has given results for the most general form of the bilinear profile. The resulting dispersion relationships are considerably more complicated than (17) and will not be given here.

For arbitrary $U(z)$ Burns (1953) considered the case of long waves ($k \to 0$), while Dalrymple (1973) gives results for short waves ($k \to \infty$) using the WKB approximation. If the waves are stationary, ($c = 0$) Lighthill (1953), Fredsoe (1974), Peregrine & Smith (1975) and Peregrine (1976) give results for a variety of profiles $U(z)$. As these various special cases are not of great significance oceanographically they will not be discussed further here.

More importantly we note that (11) can be solved numerically for an arbitrary given profile $U(z)$ and wavenumber k to obtain the combined wave-current interaction. Fenton (1973) gives a method that is applicable when $U(z)$ is specified analytically, while Thomas (1981) describes a method that can be used when $U(z)$ is specified at a number of points over the water depth, for example from measurements. Shemdin (1972) and Plant & Wright (1980) have solved the equation to consider the effect of wind drift on the phase speed of the waves.

Problems arise in the solution of (11) if at some level in the flow $z = z_c$ a critical layer occurs with

$$\left(U(z_c) - c\right) = 0$$

Under oceanographic conditions the phase speed of the dominant waves is generally greater than the current speed so that this problem will not arise. Methods of dealing with it when it does occur are discussed by Peregrine (1976) and, in the context of hydrodynamic stability theory, by Drazin & Reid (1981).

5. Finite amplitude waves

It is clear that the methods discussed in the previous section will be inadequate to model the interaction of large (finite) amplitude waves with a current, as they essentialy treat the waves as a small perturbation of that current. Here we will describe some methods that are applicable to finite amplitude waves on a vertically varying current.

Peregrine (1976) discusses various special solutions for waves on currents, such as Gerstner's rotational waves and the highest wave on a current with uniform vorticity (that is, one with a linear profile). He also discusses the effect of finite amplitude waves on the mean level and mass flux (Stokes drift), which are important for waves on water of finite depth. We will not pursue these issues here, more details may be found in his paper.

The first approach that can be used to study finite amplitude waves on a current is to use a Stokes type expansion in powers of some small parameter (for example, wave steepness). The linear theory of the previous section provides the first order solution to the problem and successive approximations may, in principle, be calculated (Dalyrymple, 1973; van Ninh, 1984). However, as analytic solutions exist in the linear case only for a very restricted class of profiles $U(z)$, higher order analytic approximations cannot be calculated for a general $U(z)$. Results have been given by various authors for linear and bilinear profiles (Tsao, 1959; Brevik, 1978; Brink-Kjaer & Jonsson, 1975). These solutions are only to second or third order of the small parameter, for even in these "simple" cases the expansion procedure rapidly becomes very complicated.

Peregrine (1976) gives the following results for waves on deep water with $U(z)$ given by (15) with U_o =0,

$$\eta(x,t) = a\cos(kx-\omega t) + \frac{1}{2}a^2k\left(1+2S+\frac{1}{2}S^2\right)\cos 2(kx-\omega t) \qquad (18)$$

where $S = \zeta_o/\omega$

and the dispersion relationship is

$$\omega^2 = gk - \zeta_o\omega \, . \qquad (19)$$

The usual second order Stokes solution is obtained by setting $\zeta_o = 0$ ($S = 0$). We note that for $\zeta_o > 0$ the waves are peakier at the crest and flatter at the trough than the corresponding waves with no current, while for $\zeta_o < 0$ the waves are more nearly sinusoidal. In fact, for

$$S = -2 + \sqrt{2}$$

the second order term in (18) vanishes identically and the profile is sinusoidal to second order. Figure 2 illustrates these effects schematically (see Peregrine, 1976, for more details).

In order to obtain higher order solutions it is helpful to recast the equations of motion in stream function form. In a frame of reference moving with the wave, at the phase speed c , the motion is steady and the stream function $\psi(x,z)$ is defined by

$$\left.\begin{aligned} \psi_z &= U(z) + u(x,z) - c \\ \psi_x &= -w(x,z) \end{aligned}\right\} \qquad (20)$$

so that the continuity equation is automatically satisfied. From (20) and the momentum equations it can be shown (Dalrymple, 1973) that

$$\nabla^2 \psi = f(\psi) \tag{21}$$

which expresses the fact that for an inviscid, incompressible fluid the vorticity is constant along a streamline ($-\nabla^2\psi$ being the vorticity). The boundary conditions can also be expressed in terms of the stream function (see Dalrymple, 1973).

For general $f(\psi)$ equation (21) cannot be solved easily, however for the linear profile (15) $f(\psi) = -\zeta_o$ (constant) and results can be obtained by an extension of Dean's stream function (Dalrymple, 1973, 1974a). For a piecewise linear profile $f(\psi)$ is constant over each section of the profile and again a stream function approach can be employed to solve the problem (see Dalrymple 1974b, for the bilinear case). Results can also be obtained for $f(\psi) = \pm \gamma^2 \psi$, which lead to exponential or sinusoidal profile $U(z)$ (Dalrymple & Cox, 1976), but these do not allow the exact current profile to be specified in advance (it is found as part of the solution procedure). Dalrymple's (1973, 1974a, 1974b) results show that considerably different fluid velocities can occur for waves of the same height and period depending on whether a zero, linear or bilinear current is present.

One of the difficulties in solving finite amplitude wave problems is that the position of the free surface is unknown and this leads to difficulties in applying the boundary conditions at the free surface. In order to solve equation (21) for more general values of $f(\psi)$ Dalrymple (1973, 1977) transforms the equation by interchanging the dependent and independent variables ψ and z, thus

$$z = z(x, \psi) \tag{22}$$

This allows (21) to be written as

$$z_\psi^2 z_{xx} - 2 z_\psi z_x z_{x\psi} + (1 + z_x^2) z_{\psi\psi} = z_\psi^3 f(\psi) . \tag{23}$$

Although this equation is more complicated than (21) it is valid over a known (rectangular) region in $x - \psi$ space (rather than an unknown region in $x - z$ space) as the stream function ψ is constant on both the free surface and the bottom. This enables the equation to be solved by a finite difference method (Dalrymple 1973, 1977). Dalrymple gives results for both linear and one-seventh power law current profiles and finds large differences in the resulting wave velocities.

A problem that arises with the above formulation is the relationship between the current profile $U(z)$ and the function $f(\psi)$. Dalrymple (1973, 1977) specifies $f(\psi)$ and then solves the problem to obtain $U(z)$. Preferably one would like to specify $U(z)$ rather than $f(\psi)$. Benjamin (1962), in a study of solitary waves, introduces a new height variable s , equal to the value of z in the undisturbed flow (current only); thus

$$\left.\begin{aligned} \psi &= \Psi(s) \\ \text{and} \qquad U(s) - c &= \frac{d\Psi}{ds} \end{aligned}\right\} \tag{24}$$

in the undisturbed flow (no x-variation). Equation (21) may now be written as

$$(U(s) - c)\left\{ z_s^2 z_{xx} - 2 z_s z_x z_{xs} + (1 + z_x^2) z_{ss} \right\}$$

$$+ \; U'(s) \left\{ z_s^3 - z_s (1 + z_x^2) \right\} = 0 \qquad (25)$$

where $$f(\psi) = \Psi''(s) \qquad (26)$$

Here $U(s)$ appears explicitly, but this equation has only been studied in the solitary wave case (Benjamin, 1962) and not for periodic waves.

This concludes our survey of methods used to calculate the interaction of waves with a vertically varying current. We will now discuss the methods in relation to experimental results on wave-current interactions.

6. Comparisons with experiment

To determine which of the theoretical methods discussed above can be applied practically to the calculation of wave-current interactions, and under what circumstances, requires that theory be compared with experiment. Few such commparisons exist and, to the author's knowledge, none of these are based on field data. Such field studies as have been carried out (see, for example, Lambrakos, 1981; Gonzalez, 1984) assume that the currents are uniform with depth and vary only in the horizontal plane. As we are concerned with vertically varying currents, none of these field studies are of help in assessing the applicability of the theoretical methods discused herein. We are therefore forced to restrict our attention to a limited number of laboratory studies which have a bearing on the problem under consideration.

A number of laboratory studies of waves on a vertically varying current have been carried out. Four of these (Shemdin, 1972; Mizuno & Mitsuyasu, 1973; Thomas, 1981; Ismail, 1984) have compared measurements with the small amplitudes theories outlined in section 4. Shemdin (1972) and Muzuno & Mitsuyasu (1973) compare the measured phase speed of the waves on a wind drift currrent with those calculated from equation (11). Shemdin (1972) uses a logarithmic wind drift profile, while Muzuno & Mitsuyasu (1973) use a parabolic profile fitted to data. In both cases allowance is made for the effect of airflow by use of Miles (1957) theory. The agreement between theory and experiment for the phase speed is found to be good. No comparison is made in either case for the velocities beneath the waves.

Thomas (1981) and Ismail (1984) compare the velocities beneath the waves with theoretical predictions and find good agreement. Thomas (1981) uses equation (11) together with the current profile $U(z)$ measured in the absence of waves to obtain theoretical results. Ismail (1984) compares measurements with results based on theory for linear superposition of waves and current, waves on a uniform (depth-averaged) current and waves on a linear shear current (fitted to data). The conclusion to be drawn from these comparisons is that models that include the effects of shear can accurately reproduce the results of experimental measurements if the waves are of small amplitudes. Approximating the current profile by a linear profile is better than neglecting the effect of shear by using a depth-averaged current. Ismail (1984) shows that linear superposition (simply adding wave and current velocities) can underpredict the particle velocities in following currents by up to 30% and overpredict them by up to 10% in opposing currents. Both authors find that a depth-averaged current (which includes the effect of the Doppler shift - see section 3) can yield a good approximation if the shear in the current is small.

There appear to be only three attempts (Plant & Wright, 1980; Kemp & Simons, 1982, 1983) attempts to allow for finite amplitude wave effects in comparisons between theory and experiment. Plant & Wright (1980) consider waves on a wind drift current and find that the incorporation of finite amplitude effects does not improve agreement between theory and measurements for the phase speed. Their work is similar to that of Shemdin (1972) and Mizuno & Mitsuyasu (1973).

Kemp & Simons (1982) note that their experimental results for waves on a following current are consistent with Dalrymple's (1974a) theoretical predictions that the waves will have sharper crests and flatter troughs. However, no direct comparison of wave profiles or velocities are made. In a later paper (Kemp & Simons, 1983) on waves on an opposing current they compare their results with Brink-Kjaer & Jonsson's (1975) second order theory for waves on a linear shear current. For the wave profile they find good agreement (better than for linear wave theory) while for the velocities beneath the waves

Brink-Kjaer & Jonsson's (1975) theory gives good agreement (better than Stokes second order theory for no current) except near the bottom where boundary layer effects become important.

Although other experimental results exist for wave-current interactions (Sarpkaya, 1957; Brevik & Aas, 1979; Brevik, 1980) these authors do not make any comparisons with the theories discussed in this report. Sarpkaya (1957) does however show that linear superposition of waves and current is inadequate to describe his experimental results.

It should be noted that several of the studies (Ismail, 1984; Kemp & Simons 1982, 1983) show that the presence of waves affects the mean current profile. This is because of the mass transport (Stokes drift) due to the waves. In a laboratory situation the current profile $U(z)$ can be determined by making measurements in the absence of waves. However, observation of the mean current in the field will contain a contribution from the waves. This will make any comparison between field data and theory difficult as all the theoretical methods require as input the current profile $U(z)$. In practice an inverse problem will have to be solved to obtain the current profile $U(z)$ and the velocities beneath the waves.

7. Discussion and conclusions

This review has shown that, while a number of different methods exist for calculating wave-current interactions for waves on a vertically varying current, the question of which is the best method to use in a given case remains open. For small amplitude waves the theory of section 4 has been found to give good agreement with laboratory measurements (see section 6). However, for large amplitude waves the comparisons between theory and experiment do not allow any definite conclusions to be drawn. Dalrymple's (1973, 1977) numerical results do suggest that the accurate modelling of current shear is important as different current profiles with the same total vorticity (a measure of shear, in this case) can lead to significantly (30%) different velocities beneath the waves. A further problem in calculating finite amplitude waves or currents is the correct specification of the current profile in the numerical calculations. In this respect Benjamin's (1962) formulation would appear to be better than Dalrymple's (1973, 1977), but it has not, as yet, been employed to investigate wavetrains (only solitary waves).

Another area in which there is a lack of results is that of field measurement of waves on vertically varying currents. Even if such measurements existed the difficulties highlighted at the end of section 6 would still make comparison with theory difficult. Despite this difficulty such comparisons are necessary if the theories are to be used for practical problems.

From the above it is perhaps possible to draw the following conclusions:

(a) the effect of current shear is important in determining the kinematics for the waves.

(b) linear superposition of waves and currents is generally inadequate to describe their interaction. At the very least allowance should be made for the Doppler shift in wave frequency due to the current.

(c) for small amplitude waves the perturbation theory of section 5 gives good agreement with laboratory measurements.

(d) for finite amplitude waves further comparisons between theory and experiment need to be carried out to check the theoretical results. The correct specification of the current profile in the calculations needs to be investigated.

(e) there is a need to compare theoretical results and laboratory measurements with field experiments to verify the practical applicability of the various theoretical formulations. (In order to be able to combine the 50 year wave and current with a view to predicting forces on structure, points (d) and (e) need to be pursued).

Finally it is perhaps worth noting that this report has only considered steady, monochromatic waves on vertically varying currents. Other aspects of the problem, such as the generation of waves on a vertically varying current (Kato & Tsuruya, 1978), wave breaking, turbulence (Kitaigorodskii & Lumley, 1983) and the effect of the current on a spectrum have not been considered. We have also assumed that the current is uni-directional throughout the depth, but in practice Ekman spiral effects may be important (Weber, 1983), where the current direction as well as magnitude varies with depth. All these aspects are also important and deserve further study.

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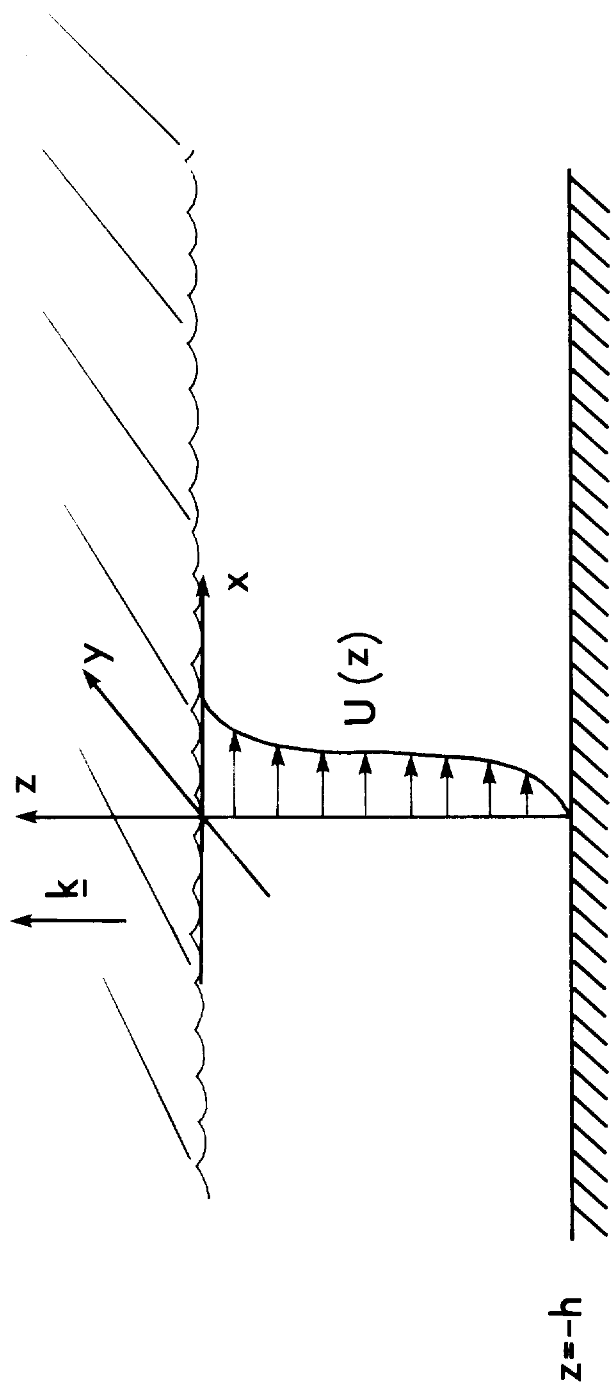

Fig. 1 Coordinate system

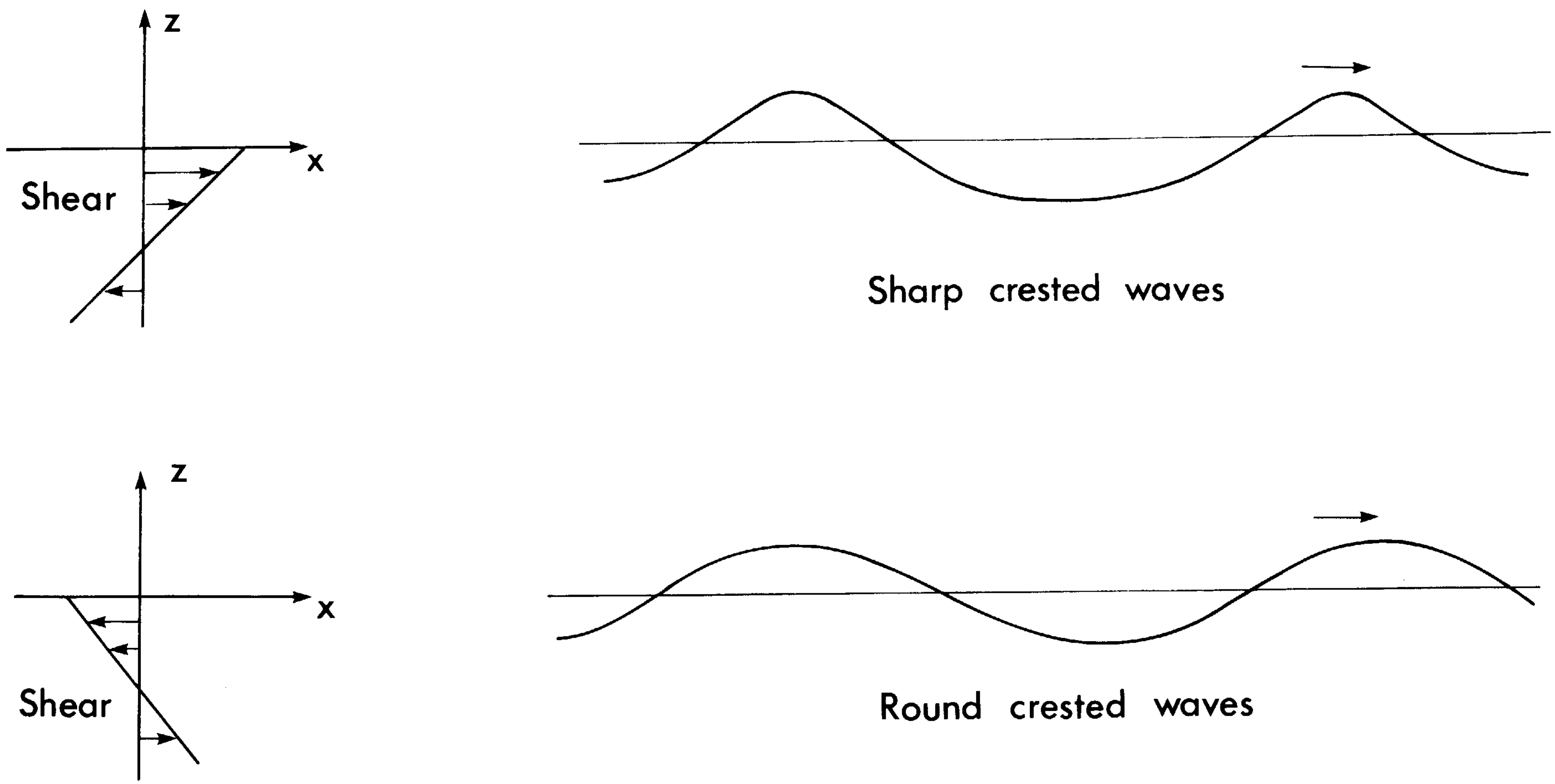

Fig. 2 Schematic illustration of the effects of shear on the wave profile (after Peregrine & Jonsson, 1983).