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TOE SCOUR AT SEA WALLS SUBJECT TO WAVE ACTION
A literature review

K A Powell

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Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

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ABSTRACT

Wave induced scouring at the foot of sea walls is now accepted as the major cause of sea wall damage in the UK. It is however a problem that historically has received very little attention and, as a consequence, minimal research funding. It is not surprising therefore that at present this form of scouring is virtually impossible to predict. In recognition of this it has been proposed that a major research study should be set up to:

1. examine the underlying causes of toe scour, and
2. develop methods for predicting both its onset and extent for various types of sea wall, and beach sediment.

This report, which represents the first phase of the study, lays down the framework for subsequent experimental investigation, based upon a critical review of the available literature and a re-appraisal of previous understanding.

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1 INTRODUCTION

1.1 The problem

The scouring, or erosion, of mobile beach sediments under wave action, at the foot of sea walls, has long been one of the major banes of Coastal Engineers. Only recently a comprehensive survey of sea walls in the UK (Ref 1) concluded that toe scour represented the most serious and prevalent form of damage, directly accounting for over 12% of the case histories studied and indirectly responsible for up to a further 5% of cases, including collapsing/breaching of sea walls and washing out of fill materials.

Problems with toe scour are not however confined to UK sea walls. Smith and Chapman (Ref 2) describe Australian experience with sloping rock revetments and conclude that failure is generally initiated by toe scour. In particular, they note one section of wall, originally located in 0.3m of water at low tide, which suffered in excess of 3m of toe scour in the space of 2 years, during which wave heights seldom exceeded 1m. In Japan, Hotta and Marui (Ref 3) reported scour depths of up to 2m at detached breakwaters, in a 3m depth of water, off the Nigata coast. This pales into insignificance however when compared to the typhoon initiated scour damage described by Ichikawa (Ref 4) at the toe of the vertical breakwaters in the Japanese port of Tagonoura. On two occasions waves with a height of up to 8m and a period of between 14 and 17 seconds scoured out up to 6m of the sea bed; a depth of erosion which seriously endangered the stability of the caisson breakwaters.

Whilst in the UK we are thankfully rarely afflicted by typhoons, toe scour is still a serious and costly problem. Moreover, it is one which is not limited to any particular environment nor generally to any particular type of sea wall. Suggestions that porous sloping structures may be less susceptible are not borne out by Australian experience (Ref 2), and this, as much as anything, serves to emphasise the paradox of toe scour; that is, that despite the acknowledged seriousness of the problem very little research effort has been directed towards it. It is not surprising therefore that we cannot yet claim to understand fully the causes and mechanisms of toe scouring under wave action, let alone predict its occurrence or extent.

In an attempt to remedy this situation, it is proposed that a major programme of systematic research into the 2 and 3 dimensional aspects of wave-induced toe scouring at sea walls should be undertaken. This report, being a review of the available literature, represents the first stage of this research.

1.2 Purpose and extent of review

This review aims to draw together, critically appraise, and summarise, available knowledge relating to the causes and prediction of wave-induced scour at sea walls. For the purpose of the report the term 'sea wall' is considered to include both permeable/impermeable and vertical/sloping structures. No mention is made of the various scour prevention techniques nor the calculation methods related to them; these aspects are however covered in detail by Hales (Ref 5), to whom the interested reader is referred. Also outside the scope of this report are the natural processes of sediment transport, which will occur as much on a free standing beach as on one backed by a sea wall. It should however be noted that the distinction between these natural quasi-cyclic trends of erosion and accretion, and the processes of localised scour is often blurred, and has been the subject of much confusion amongst previous researchers. This has resulted in a number of definitions of sea wall related scour, the two most notable of which are:

1. the maximum localised erosion of sediment at the wall, and
2. the distance-averaged erosion of sediment normal to the wall.

In an attempt to avoid these inconsistencies, this report, unless otherwise stated, will consider toe scour to be the process of localised erosion adjacent to the sea wall; and the scour depth to be the maximum depth of localised erosion relative to a natural bed level without the wall.

1.3 Outline of report

Chapter 2 briefly introduces and outlines the hydraulic processes responsible for toe scour. These include both the wave aspects, such as breaking and reflection, which initiate scouring, and the generation of longshore and onshore-offshore currents, which help to maintain and prolong the scouring process. References to more detailed reviews are given where necessary.

Previous experimental studies are described and critically assessed in Chapter 3. Particular emphasis is placed upon potential scaling effects and the extent to which these might distort subsequent results. Attempts are made to correlate the findings of various researchers, given the recent improvements in our understanding of the scaling problems.

Chapter 4 summarises the methods presently available for predicting scour depths. The implications of the formulae are assessed and an appraisal of their validity, and hence usefulness, is given. The additional uncertainties involved in the prediction of scour depths are also discussed.

The final chapter of this report seeks to draw together the conclusions arising from the review, and to identify those remaining areas of uncertainty. General recommendations are made for further research.

2 WAVE - SEA WALL INTERACTION

2.1 Wave and current processes

As waves propagate from deep to shallow water they are subject to a number of effects, such as shoaling and refraction, which result in the waves both steepening and swinging round to approach the coast more normally. This steepening of the waves increases up to a critical limit at which the waves break. For waves breaking on a slope several different breaker types can be distinguished depending upon the wave steepness and the gradient of the slope. These are spilling, plunging, collapsing and surging breakers. These breaker types will differ both in their energy dissipation characteristics and in the loads they exert on the slope. The behaviour of such breaker types is discussed by many authors. For further details the interested reader is referred to Peregrine (Ref 6).

Under shoaling waves fluid particle velocities tend to be slightly greater in the landward direction, at the top of their orbits, than in the seaward direction at the bottom of the orbits. This imbalance, which is due to viscosity effects (Ref 8), results in the formation of a low velocity mass transport current. This current acts in the direction of wave propagation, at least in the immediate vicinity of the bed (Fig 1), and therefore tends to transport sediment onshore. This tendency is opposed by rip and turbidity currents and by the downslope component of gravity. In a closed system with the wave conditions held constant the beach would eventually reach an equilibrium profile for which these various factors balance. In real life, however, conditions are constantly changing and the beach is rarely in equilibrium with its incident wave field.

Because of refraction, waves usually arrive on a beach at a fairly small angle to the normal. In doing so, they will have a longshore component of radiation stress which is capable of generating and maintaining a wave induced current along the beach. This current, although relatively mild, can transport considerable quantities of sediment tossed into suspension by the turbulence associated with breaking waves. It is usually, however, incapable of suspending sediment of its own accord.

2.2 Sediment transport

The interaction of waves, sediment and currents is an extremely complex topic, which is largely beyond the scope of this review; a detailed account of the subject is however given by Sleath (Ref 7) to whom the interested reader is referred. It is nevertheless worth noting that, depending on its size, sediment may be transported either in suspension or as bed-load, and that suspended sediment is the more susceptible to current transport. The highest transport rates will occur under the combined action of waves and currents, that is currents provide the most efficient transport mechanism, and waves the most efficient suspension mechanism. Generally the distances covered by suspended sediment will be a function of the current velocities and the sediment fall velocity.

2.3 Beach processes

Undisturbed beaches, by their very nature, tend to be in a constant, quasi-cyclic state of flux under wave action. This process can continue even when the beach fronts a solid sea wall provided that there is a sufficient volume of material to prevent the waves acting on the wall, either directly or as wave run-up. However, should the beach be depleted to a level such that wave action can reach the wall, then there will follow a pronounced, accelerating and usually permanent reduction in beach levels. This process of depletion is caused by the sea wall interrupting the flow of water within the beach, forcing up the water table and hence increasing the volume of backwash. This results in an increased offshore transport of beach material and the subsequent lowering of the foreshore levels.

If these processes are unchecked the beach will eventually be lowered to a level sufficient to allow waves to impinge directly on the sea wall. Erosion of the foreshore will then proceed much more rapidly in response to both the reflection of wave energy from the wall and an accelerated littoral drift.

2.4 Wave reflection

Once waves can reach a sea wall they will be reflected to some extent, depending upon the properties of both the wave and the structure. The degree of reflection will be much greater for unbroken waves than for broken, or breaking waves. Following reflection, standing wave patterns may be produced by the interaction of incident and reflected waves; these patterns will lead to a very confused sea state in front of the wall, with very steep waves momentarily occurring as the two trains merge. These standing wave patterns will be much more pronounced under regular waves in the laboratory than they will in the real, random sea situation, though they will of course become more evident as the degree of reflection increases.

One of the more important side-effects arising from this energy-enhanced sea state in front of the wall, will be an increase in the scouring of the sea bed. This is likely to be most pronounced at the immediate toe of the sea wall and unless prevented, or allowed for in design, could seriously compromise the structural stability of the wall itself.

3 REVIEW OF EXPERIMENTAL STUDIES

3.1 General

Although the study of wave-induced toe scour at sea wall structures has spanned several decades, the format of the various model tests has remained remarkably consistent. In each case the researchers have used regular waves, and have obtained qualitative rather than quantitative results (this latter constraint arising from the lack of any consistent scaling philosophy in the studies). Nevertheless, between them, these studies have covered a wide range of conditions, detailed in Table 1, and have managed to assess the effects of, amongst others, wave steepness, breaker type, beach gradient, sediment properties, and sea wall slope and position, on the scouring processes.

3.2 Two-dimensional tests

One of the earliest studies of toe scour at sea walls was that conducted by Russell and Inglis (Ref 9) in 1953. This study is unique in that it is still the only investigation of toe scour to have utilized a varying water level and hence reproduced tidal conditions. The tests themselves confirmed that a vertical wall constructed at the top of a beach (in the run-up zone), increased turbulence, through the reflection of energy previously dissipated on and within the beach, and hence lead to a depletion of the beach immediately in front of it. Although the ultimate scour depth was not determined the authors concluded that, in the model, scouring would probably cease at a level about one wave height below low water.

Herbich and Ko (Ref 10), following on from the work of Herbich, Murphy and Van Weele (Ref 11), considered the case of scouring under non-breaking waves. A series of tests were run, using sloping sea walls sited on flat, sand beaches. From the results of these tests a mathematical model for the prediction of scour was developed. Unfortunately the predicted scour - the 'ultimate scour depth' - was defined as the constant average depth towards which the scouring tended, over a distance of 15 feet normal to the sea wall, in the physical model. Because of this definition the mathematical model is unlikely to be able to predict toe scour. The model is, nevertheless, discussed further in Chapter 4.

Herbich and Ko (Ref 10) also concluded, perhaps somewhat surprisingly, that the distance-averaged scour was not a function of the reflection coefficient. This claim was later re-iterated by Herbich et al (Ref 12) in a review of the earlier work. In this review the authors went on to explain that the sea wall slope was observed to have little or no effect on the distance-averaged scour for sea walls inclined between 45° and 90°. However, for walls flatter than 45° the scour depth was observed to decrease with decreasing slope. Such an observation can be explained by considering the response of wave reflections to sloping walls, as theoretically demonstrated by the formula of Miche (Ref 13). This implies that there is a constant reflection of energy from inclined walls, provided their slope is greater than some critical value, and a decreasing level of reflection when the slope drops below that critical value. The precise sea wall slope at which the reflection behaviour changes is dependent on the steepness of the incident waves. Thus for conditions similar to those used by Herbich et al this change would occur for walls angled at about 30° to the horizontal, ie compatible with their scour/sea wall slope findings.

Ichikawa (Ref 4) carried out a series of tests to investigate the scouring of sloping beds under breaking waves. He observed that scouring at the foot of vertical walls was always a maximum under 'curling' breakers. In general these scour depths were equivalent to the offshore wave heights but there was some indication of a bed slope effect, with steeper slopes suffering slightly greater scour for the same set of wave conditions than shallow slopes. Further analysis of Ichikawa's results suggests that maximum scour, S, occurs when the initial water depth at the sea wall is in the region of $1.5H_o$, where H_o is the offshore regular wave height. For water depths either side of this value, scour depths appear to reduce quite rapidly.

Sato, Tanaka and Irie (Ref 14) examined the processes of scouring at the foot of vertical and inclined sea walls, and at the base of composite breakwaters, located at different positions on a beach. They identified 5 types of scour behaviour, the occurrence of which depended on the location of the wall relative to the initial breaking point. These scour types were classified as:

Type 1 - rapid initial scouring followed by a gradual accretion of material
Type 2 - rapid initial scouring leading to beach stability
Type 3 - rapid initial scouring giving way to slower but more prolonged erosion
Type 4 - continuous gentle scouring
Type 5 - continuous gentle accretion.

For vertical walls and step type beach profiles (ie low steepness waves), the maximum relative scour depth at the toe of the wall, S/H_o, occurred when the wall was located at or about the wave plunge point (see definition sketch - Fig 2). For steeper waves and the storm or bar type beach profile, maximum relative scour occurred when the wall was sited at either the shoreline or just landwards of the break point. In all cases the maximum scour was of type 3 classification.

The scour behaviour for inclined sea walls under storm conditions differed slightly from that outlined above in that maximum scour occurred at only one position - just landward of the break point - rather than the two locations noted with vertical walls.

For all wall locations offshore of the original break point, the scour depth was found to decrease with sea wall slope. The difference was however small for slopes in the range 60°-90°, a feature that would tend to agree with the reflection considerations of Miche (Ref 13). Such a trend was also observed for walls located at the original shoreline.

From the results of their tests Sato et al (Ref 14) concluded that the relative maximum scour depth was inversely proportional to the offshore sea steepness. However, such a trend may only be applicable for walls located seaward of the shoreline. Indeed similar tests by Hattori and Kawamata (Ref 15), with sea walls in the run-up zone, gave just the opposite results - the scouring under steeper waves reverting to accretion under shallow waves.

One final, important, result from Sato et al's tests was the suggestion that, for waves with a steepness of between 0.02 and 0.04, the maximum scour depth was approximately equivalent to the deep water wave height. This was subsequently confirmed by field data obtained from the Port of Kashima (Fig 3) which, in agreement with Ichikawa's findings (Ref 4), showed the maximum scour depth under storm conditions to be nearly equal to the maximum H_s (significant wave height), during the storm, and on the assumption of $H_s \approx S$, to occur in initial water depths of around $1.5H_s$. On this basis, Sato et al concluded that under normal storm conditions ($0.02 < H/L < 0.04$) the maximum scour depth could be expected to be less than or equal to the deep water wave height, but that in calmer conditions the scour depths could be very much greater than the corresponding wave heights.

Song and Schiller (Ref 16) undertook a study of toe scour along similar lines to that of Sato et al (Ref 14) but with the emphasis predominantly on the effects of sea wall location and wave reflection. Despite considerable scatter in the results they found that low reflection coefficients generally corresponded to greater scour depths. This, they concluded, was due to the low reflection coefficients coinciding with waves breaking at the sea wall. Responsibility for the scouring would then lie with the turbulent nature of wave breaking, rather than any reflection of energy. This hypothesis appears perfectly reasonable and may well account for some of the discrepancies previously noted in the reflection related scour trends. Such an explanation does not appear likely however to account for the difference between Song and Schiller's, and Sato et al's, findings regarding the effect of sea wall location on the scour depths. These are in direct contrast, with Song and Schiller finding that, for all wave conditions, maximum toe scour occurred with the wall at or about the wave plunge point, while minimum scour always occurred when the wall was at the break point.

On the basis of their results Song and Schiller derived, through regression analysis, an expression relating relative scour depth, S/H_o, to sea wall location and wave steepness. This is examined more closely in Chapter 4. From it the authors concluded that for small values of the standing wave steepness ($H/L < 0.02$, perhaps non-breaking waves), S/H_o was virtually independent of the position of the sea wall on the beach. This however appears to be an over-simplification and is perhaps a rather optimistic conclusion.

Hotta and Marui (Ref 3) extended the study of toe scour to vertical permeable structures. In doing so they highlighted one of the major problems in any study of toe scour, and that is that localised toe scour is always likely to be superimposed on much larger scale natural beach movements. Thus, for new sea wall structures, it could prove extremely difficult to predict toe scour alone, without reference to the fundamental changes that occur in beach levels in response to the incident wave conditions. This is particularly a problem in model studies where scour may be measured from either a plane initial slope (Refs 3, 4, 10 and 17) or a pre-formed equilibrium profile (Refs 14 and 16).

Although Hotta and Marui were unable to fit their results with permeable walls to the scouring classification suggested by Sato et al (Ref 14), they did find several interesting similarities between the scouring characteristics of permeable and solid walls. First, in line with Song and Schiller's results (Ref 16), the scouring depths were observed to be a minimum at the break point but a maximum at or about the plunge point. This held regardless of the bed materials or the hydraulic properties of the walls tested. Secondly the maximum scour depths were found to be of the order of the deep water wave height. Subsequent analysis of Hotta and Marui's results also suggests that for walls located seawards of the plunge point, the maximum depth of scouring occurs when the water depth is in the region of $1.6H_o$. This again is compatible with previous findings.

Sawaragi (Ref 17) conducted a series of tests specifically to investigate the relationship between the void ratio of permeable structures and their reflection coefficient, K_r, and hence the relationship between reflections and scour depth. He found that although K_r was fairly constant for void ratio's greater than 20% it increased rapidly for smaller values. He also observed that for a particular void ratio the reflection coefficient increased with increasing sea wall slope; a result comparable with the findings of Miche (Ref 13).

For breaking waves, Sawaragi, in common with Sato et al (Ref 14), noted that the scour depth does not always increase in time and that the scouring process is often interspersed by periods of accretion or infilling of the scour hole. It was also observed that the relative scour depth, S/H_o, increased with the reflection coefficient, albeit at a decreasing rate. Sawaragi suggested that a reflection coefficient of 0.25 marked the boundary between a rapid increase in scour (< 0.25) and the more gentle increase (> 0.25). No scouring was observed at the toe of the permeable walls for values of $K_r < 0.10$.

Lastly, in contrast to previous studies, the maximum scour depth under breaking waves was perceived to occur in water depths of the order of $0.5H_o$. It should however be noted that this conclusion was reached on the basis of only one set of wave conditions.

The most recent study of toe scour appears to be that by Irie and Nadaoka (Ref 18) who attempted to determine whether prototype scour behaviour could be reproduced in laboratory models, and, if so, the requirements to be fulfilled. Tests were carried out on composite breakwater models, in both 2 and 3 dimensions, using regular waves. For particles on a roughened bed under standing waves, two types of sediment movement were identified:

1. N-type: transport from beneath the antinodes to the nodes of the standing waves
2. L-type: transport from standing wave nodes to antinodes.

L-type movement was found to occur when suspended sediment transport dominated. It could be characterised by the parameter u_b/ω, where u_b is the amplitude of the near-bed water particle velocities for incident waves and ω is the sediment fall velocity. N-type movement was considered to depend on the non-linearity of the waves as expressed by the Ursell number $U = HL^2/h^3$, where H, L and h are wave height, length and water depth respectively.

In the 2-dimensional tests, it was found that for a particular set of conditions accretion or erosion under the nodes of the standing wave envelope, and hence N or L-type movement, depended both on the characteristics of the bed material and the wave height. Movement was observed to change from N to L-type as the wave height increased or as the sediment size decreased. The relative importance of these two mechanisms to the toe scour depended on whether an antinode or a node formed at the breakwater. If it was the latter then L-type movement would lead to scouring, whereas if it was the former, N-type movement would scour. However, it is worth noting that this differentiation is only likely to prove important in the case of regular waves, and will have minimal significance under random seas.

Irie and Nadaoka plotted the results of their model tests in terms of the relative velocity, u_b/ω, and Ursell's number. From the resulting graph they concluded that L-type scour occurred when $u_b/\omega > 10$, regardless of the value of Ursell's number. On this basis the authors suggested that as relative velocity would normally be much greater than 10 in prototype, correct reproduction of scour in the model would require $u_b/\omega > 10$. Therefore L-type scour occurred in nature, and as a consequence, for composite breakwaters, toe scour would be most intensive when the breakwater toe coincided with the node of the standing wave envelope. Interestingly enough, this is a direct contradiction of Sato et al's (Ref 14) findings for composite breakwaters and would therefore suggest that the scaling in the latter's study was sadly awry. It is also interesting to note that for typical UK inshore wave conditions, Irie and Nadaoka's criterion suggests that the change from L-type to N-type scouring occurs for a bed material of $d_{50} \approx 1\text{mm}$. It would appear therefore that sands

(d_{50} < 1mm) exhibit a different scouring behaviour to that of coarser materials.

Finally it is worth briefly mentioning the tests performed by Nishimura, Watanabe and Horikawa (Ref 19) in an attempt to simulate the scouring at the toe of sea walls caused by tsunamis. Single waves were allowed to break on a mobile slope, collide against the inclined sea wall, overtop, and then run-up on the gentle slope behind the wall. During this process only minimal scouring was observed. However when the overtopping water returned back over the wall a pronounced scouring of the beach material was evident. The depth of this scour was found to depend on the slope of the sea wall, the depth of water in front of it, and the velocity of the returning flow, as well as the specific gravity and size of the bed material. In general it was found that lighter and finer materials suffered greater scour.

3.3 Three dimensional tests

Very few studies into the 3-dimensional aspects of wave induced toe scour have been performed. Irie and Nadaoka (Ref 18) conducted tests with regular waves as a supplement to their earlier 2-dimensional work. As in the earlier work they found that scour occurred under the nodes of the standing wave envelope (L-type movement) with material being transported both to the antinodes and alongshore. Generally the longshore transport of suspended sediment followed the antinodes.

The major difference between the 2 and 3-dimensional tests was that in the latter the scour depth decreased downstream (ie along the longshore current), as the suspended sediment slowly settled out. This would suggest that there is a pronounced 3-dimensional aspect to scour at sea walls whereby the depth of scouring at any one point along the wall is dependent upon its overall position relative to the total length of the section of wall being scoured. Interestingly enough Irie and Nadaoka found reasonable agreement between model and prototype but concluded that this agreement could be improved by the use of random waves in the model.

Silvester (Ref 20) gives some details of work related to the reflection of waves approaching sea walls at an angle. In particular the incident waves interact with the reflected waves to produce a short crested sea with a range of particle orbits and directions. This effect can greatly increase the suspension of sediments which may then be transported along the coast by various currents. As the waves pass off the end of the wall boundary effects can result in the formation of vortices which may themselves erode the beach material.

3.4 Scale and model effects

It is clear from the preceding sections that there are considerable disagreements between the results from the various studies. In part these differences may be due to model effects, that is effects inherent in the particular test facilities and conditions used. In practice, however, many of the studies followed similar formats, used similar test conditions and were carried out in essentially similar facilities. It is difficult therefore to see model effects as accounting for the great variation in results, though they will almost certainly give rise to spurious conclusions and inhibit the transfer of model data to prototype. Instead, it is more likely that the contradictions between studies arise through scale effects resulting from the general lack of a systematic scaling philosophy for wave induced scour.

Incorrect scaling of the bed material would certainly account for the general confusion regarding the direction of sediment transport under standing waves, as confirmed by the findings of de Best, Bijker and Wichers (Ref 21), who carried out a series of tests on the scouring of a sand bed in front of a vertical wall. They found that both the direction of sediment transport and the resulting bed contours depended upon the size of sand particles used in the model. Thus fine material was moved in suspension and travelled from the node to the antinode of the standing wave envelope, whilst coarser material stayed as bed load and converged on the envelope node. These results agree generally with Irie and Nadaoka's (Ref 18) definitions of N and L-type scour. Re-analysis of data from the earlier investigations, in terms of sediment size and wave height, tends to resolve the previously noted discrepancies and confirms the correctness of the above scour mechanisms. Clearly however, a conformity of results can only be achieved if the size and specific gravity of the bed material is correctly reproduced, at model scale, in each of the studies.

Unfortunately the situation is further complicated where there is only a partial reflection of wave energy from the sea wall. Carter, Liu and Mei (Ref 22) theoretically demonstrated that the modes of sediment transport, outlined above, were a response to localised reversals of the mass transport current, prompted by the reflected waves. As such these transport modes exist only when there is a certain level of wave reflection. Carter et al calculated this critical level to be $K_r = 0.414$; above this value L and N-type sediment transport applied, while below it sediment transport would always be in the direction of incident wave advance, and under the jurisdiction of the mass transport current. Provided that $K_r << 0.414$ the transport current was theoretically of nearly uniform intensity and little or no scour/accretion of the bed occurred. For slightly higher values of K_r (but still less than 0.414) sediment transport, while in the direction of wave advance, was slightly retarded between the node and antinode of the partial standing wave envelope, allowing a slight accumulation of bed material in this region.

Carter et al then went on to extend their work to the case of waves obliquely reflected from sea walls (the 3D situation). When the angle of incidence of wave attack, relative to the normal, is very large, the incident wave crests will swing round, tending to become perpendicular to the wall. They then travel along the wall with their orthogonals parallel to it; a situation which permits no reflection of energy. This effect is known as a Mach stem and Wiegel (Ref 23) who provides a good description of it, suggests that it will occur for an angle of incidence greater than 70° to the normal. For angles of incidence between 45° and 70° some reflection and some Mach stem effect may occur. The consequence of this, as demonstrated by Carter et al, is that when the angle of incidence is within 45° to the normal the bed load will travel to the nodal lines and the suspended load to the antinodal lines (ie N and L-type movement). However, when the angle of incidence is greater than 45° the sediment transport converges, albeit at a reduced rate, on the antinodal lines.

Thus it is clear that the correct reproduction of wave-induced scouring processes in the model depends upon the accurate scaling of the bed material and upon a similitude of wave directions and sea wall reflection characteristics. Results from 2D models may not therefore be applicable to the 3D situation.

The complications outlined above are severe and represent a considerable hurdle, which future physical model studies of wave-induced scouring must overcome. They do, however, go a long way towards accounting for the discrepancies observed in the results of previous studies. It may also be possible to circum-navigate, or at least reduce, some of these problems by concentrating on random wave rather than regular wave modelling. Under random waves a clearly defined standing wave state cannot exist, therefore the series of offshore bars and troughs (deposition and scour) observed in regular wave studies is unlikely to form. Moreover the sediment transport processes will be less precise than under regular waves. It is probable therefore that the sedimentation trends observed in previous studies are purely academic and bear little relationship to the reality of the natural processes. If this is so, wave-induced scouring may be one of the areas of coastal engineering for which physical modelling is simplified by the use of random waves.

This argument is supported by the observations of Dean (Ref 24) who stated that "while reflection can cause offshore bars in the laboratory for the case of monochromatic (regular) waves, the existence of reflection bars in nature has not been convincingly demonstrated".

4 THE PREDICTION OF TOE SCOUR

The currently available prediction methods for wave-induced toe scour may be divided into two categories, that is:

(a) rule-of-thumb approaches, as expounded by the Shore Protection Manual (Ref 25) and Dean (Ref 24), and
(b) semi-empirical equations derived from small scale model tests (Refs 10 and 16).

These methods are outlined and assessed below:

1. The Shore Protection Manual (SPM) rule-of-thumb

In common with many other researchers (Refs 3, 4, 9 and 14) the SPM (Ref 25) suggests that "the maximum depth of a scour trough below the natural bed is about equal to the height of the maximum unbroken wave that can be supported by the original depth of water at the toe of the structure". Subsequent calculations, however, reveal that the orbital velocities at the bottom of the scour hole are still substantially higher than they would have been at the original beach level without the wall. This applies no matter which wave theory is used to perform the calculations, and as such suggests that this rule-of-thumb may under-estimate the actual scour depths. It has also been shown that the scour depths are dependent upon the size of beach material and the direction of wave advance (Chapter 3); factors which such a simple design rule cannot incorporate.

2. Dean's rule-of-thumb

Dean (Ref 24) proposed that for the 2-dimensional situation, with conditions conducive to the formation of a longshore bar, the volume of scour immediately fronting a sea wall will be less than or equal to that volume of material which would have been provided from behind the wall, had the wall not been present. This hypothesis is, however, unproven and is in any case difficult to apply not least because it requires the designer to accurately determine beach profiles for a given material size and incident wave conditions/direction, prior to calculating the volumes of material eroded and hence the depth of scour. At present the only means of accurately determining these profiles would be extensive and prolonged field measurements or a physical model, the use of which would tend to nullify the purpose of a theoretical design methodology.

3. The Herbich equation

Herbich and Ko (Ref 10) derived the following equation for the prediction of scouring at sea walls:

$$S = \left(h - \frac{A}{2}\right) \left\{(1 - K_r)\, u_* \left[0.75\, C_D\, \rho \frac{\cot \theta}{d_{50}\,(\gamma_s - \gamma)}\right]^{\frac{1}{2}} - 1\right\} \tag{4.1}$$

where	S	is a maximum distance-averaged scour depth
	h	is water depth at the wall
	A	is wave height at the wall = $H_i + H_r$ ie incident plus reflected wave heights
	K_r	is reflection coefficient (H_r/H_i)
	u_*	is horizontal velocity within boundary layer, under standing waves
	C_D	is sediment drag coefficient
	ρ	is fluid density
	θ	is the angle of repose of the sediment
	d_{50}	is effective median sediment diameter

γ_s is specific gravity of sediment, and
γ is specific gravity of fluid.

Although equation 4.1 was claimed to be in reasonable agreement with results from physical model tests, it is worth noting that there are several limitations to its usage.

1. There appears to have been little attempt to 'prove' the equation against anything other than a few limited results from small scale model tests, which were themselves severely affected by scaling errors.

2. The equation predicts a distance-averaged scour over a sea bed line normal to the wall, rather than the depth of toe scour.

3. The equation was derived only for non-breaking waves and flat sea beds. Care should therefore be taken if applying it to other situations.

Bearing these limitations in mind, the equation has been examined in more detail in Fig 4, where the predicted distance-averaged scour depths are plotted against reflection coefficient, sediment size, wave height and wave period. A number of interesting features are now apparent. First, the distance-averaged scour depth tends towards a constant value for sediments greater than 6mm in diameter and wave periods in excess of 6 seconds. Secondly, the assertion by several researchers (Refs 4, 14, 16) that scour depths are greatest when the waves are breaking at the wall is not refuted. Thirdly, and perhaps most surprisingly, the equation implies that contrary to previous results, the scouring decreases as the reflection coefficient increases. Clearly this latter point is a cause for some concern, suggesting that there may be errors implicit within the derivation of the equation. Even if this were not so, there are still too many uncertainties and limitations to allow the use of equation 4.1 for the prediction of the toe scour.

4. Song and Schiller's equation

Based on the results of small scale model tests Song and Schiller (Ref 16) obtained a semi-logarithmic regression equation for the prediction of scour depths at the toe of a sea wall. This equation, which was found to have a correlation coefficient of 0.84 when compared to the test data, may be written as:

$$S/H_o = 1.94 + 0.57 \ln (X/Xb) + 0.72 \ln (H/L) \qquad (4.2)$$

where S is the depth of toe scour

H_o is deep water wave height

X is horizontal distance from the original shoreline

X_b is horizontal distance from the original shoreline to the breaker point (ie original surf zone width)

H is deep water standing wave height

L is local wave length.

Further examination of equation 4.2 (Fig 5) indicates that toe scour increases as the wall location approaches the shoreline. This contradicts Song and Schiller's basic results unless there is a limited range of X/Xb for which the equation applies. Though this is not expressly declared by the authors it would appear from the test data that the range should be of the order of 0.5 - 1.0 X/Xb. For walls at any location within this part of the surf zone, equation 4.2 also implies that, for a constant wave height, the scour depths increase with decreasing wave steepness.

This is perhaps not surprising and may well be a response to an increased proportion of reflected energy from the wall at the lower wave steepness.

The major problems with equation 4.2 lie in its derivation from small scale model tests (that made no attempt to correctly reproduce prototype behaviour) and in its relative simplicity. For instance, the equation does not take account of the reflection characteristics of the wall, other than that implicit in the standing wave height; the 3-dimensional aspects of scour; or the beach sediment size. It is unlikely therefore to be of benefit to present day designers.

It has been shown that the methods and rules available for predicting wave-induced toe scour at sea walls are both limited in scope and compounded by serious errors in their derivation. However predicting toe scour accurately would be a difficult proposition even if there were well proven methods and equations available. The prediction accuracy of any equation can only be dependent upon the accuracy and reliability of its input data and, for toe scour, that data is likely to be considerable and difficult to measure. For instance, information would be required regarding:

1. the bed material characteristics and compaction
2. the wave climate
3. the local current field
4. the structure geometry, ie bed profile, sea wall slope etc
5. the wave/structure interactions, ie wave breaking and reflection.

Clearly obtaining or estimating this data would be a costly process which, given the present state of prediction methods, would be difficult to justify.

5 CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed the available published literature related to wave-induced toe scour at sea walls. During the review it became apparent that the results and conclusions from previous model studies, although mainly qualitative in nature, are often contradictory. These discrepancies appear to arise for a number of reasons:

1. There is usually no consistent scaling philosophy for the bed material. To a certain extent, it is the size of this material, in conjunction with the incident wave conditions, which determines the direction of particle motion, and hence the form of the bed profile.

2. Different researchers have used different measures and definitions of scour. Often the scour is measured relative to the initial beach line which, depending on the study, may be either a plane slope or a preformed equilibrium profile.

3. Waves breaking and plunging at the sea wall can cause an increase in the scouring of the sea bed over and above that which might be anticipated on the basis of wave reflection scour trends. Thus results from studies using breaking waves may not be consistent with those for non-breaking waves.

4. The reflection coefficient is not a linear function of sea wall slope. Thus, depending on the sea wall slopes used, some researchers have

reported no relationship between reflection and scouring whilst others have found consistent trends.

Taking these points into consideration allows a number of general conclusions to be drawn from the model studies.

1. For waves of steepness 0.02-0.04 the depth of scouring is approximately equivalent to the height of the incident unbroken wave.

2. Maximum scour occurs when the sea wall is located at, or about, the plunge point of breaking waves or in an initial water depth of 1.5H, where H is a nominal wave height.

3. The depth of scouring decreases with decreasing reflection coefficient.

4. Scouring is a 3-dimensional phenomenon which may have pronounced depth variations along a sea wall.

However, the fact that reasonably consistent conclusions can be shown to apply to previous model studies does not mean that they will also apply to the real situation. Indeed, the majority of the model tests suffered from 3 major drawbacks in that they employed regular waves; considered only 2-dimensional aspects; and neglected to scale the bed material to ensure similarity with prototype. Bearing in mind Dean's (Ref 24) concerns regarding the relevance of regular wave tests, Irie and Nadaoka's (Ref 18) scaling conclusions and Carter et al's (Ref 22) findings related to 3-dimensional effects, it seems unlikely that the above conclusions, as they stand, can be accepted as a rational basis for sea wall design.

At present wave-induced toe scour is virtually impossible to predict either for new or existing sea walls. Given the acknowledged seriousness and prevalence of the problem this is clearly a situation that needs to be urgently remedied. It is therefore recommended that a major research study should be set up to:

1. systematically examine the underlying causes of toe scour, and
2. develop methods for predicting both its onset and extent for various types of sea wall and sizes of bed material.

Such a study should utilise random waves and incorporate a large measure of 3-dimensional testing, though it is accepted that some 2-dimensional work will be required both to confirm scaling relationships and to provide a grounding for later work. A detailed outline of the suggested research programme is given in Appendix 1.

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Table

Table 1: Summary of previous studies

Ref	Researcher	Wave Height (mm)	Wave Period (s)	Wave Steepness	Median Sediment Size (mm)	Sediment Specific Gravity	Initial Beach Slope	Sea Wall Slope (°)	Comments
3	Hotta & Marui (1976)	108	1.1	0.057	0.15, 0.2	1.65, 2.65	1:10	90	Permeable walls
4	Ichikawa (1967)	40-135	1.71, 2.4	0.004-0.03	0.23	2.60	1:5, 1:10	90	
9	Russell & Inglis (1953)	76	2.5 - 3.6	0.038, 0.078	0.18	2.65	-	90	Tidal
10	Herbich & Ko (1968)	59-116	1.27- 2.10	0.017-0.04	0.3	2.65	Flat	15, 45	
11	Herbich, Murphy & Van Weele (1965)	56- 95	1.0 - 1.28	0.032-0.046	0.48	2.65	Flat	15, 30, 45, 67.5, 90	
14	Sato, Tanaka & Irie (1968)	87-420	1.3 - 5.1	0.006-0.051	0.21-0.69	2.65	1:10	30, 60, 90	
16	Song & Schiller (1973)	18- 74	0.8, 1.0, 1.3	0.006-0.073	0.17	2.65	1:30	90	
17	Sawaragi (1966)	80	1.3 - 1.85	0.015-0.03	-	-	1:15	20, 30, 45, 60	Permeable walls
18	Irie & Nadaoka (1984)	30- 65	1.6	0.0075-0.016	0.2, 0.27, 0.33	1.58, 2.65	Flat	90	Composite breakwaters
19	Nishimura, Watanabe & Horikawa (1978)	250, 300, 350	-	-	0.2, 0.25, 0.7	1.65, 2.65	1:5, 1:10, 1:15, 1:30	45, 60, 90	Concentrated on scour under return flows

Figures

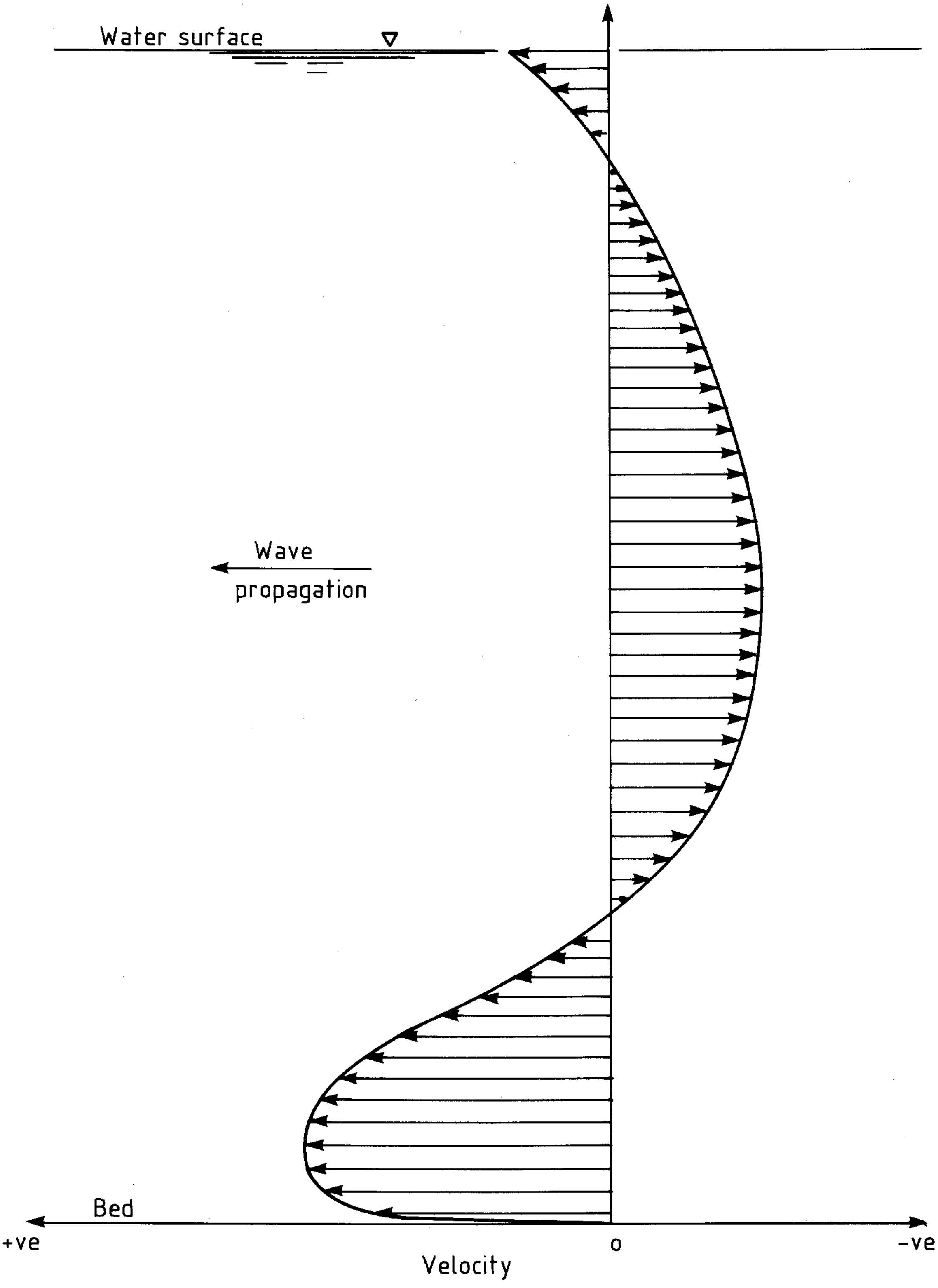

Fig 1 Typical velocity profile

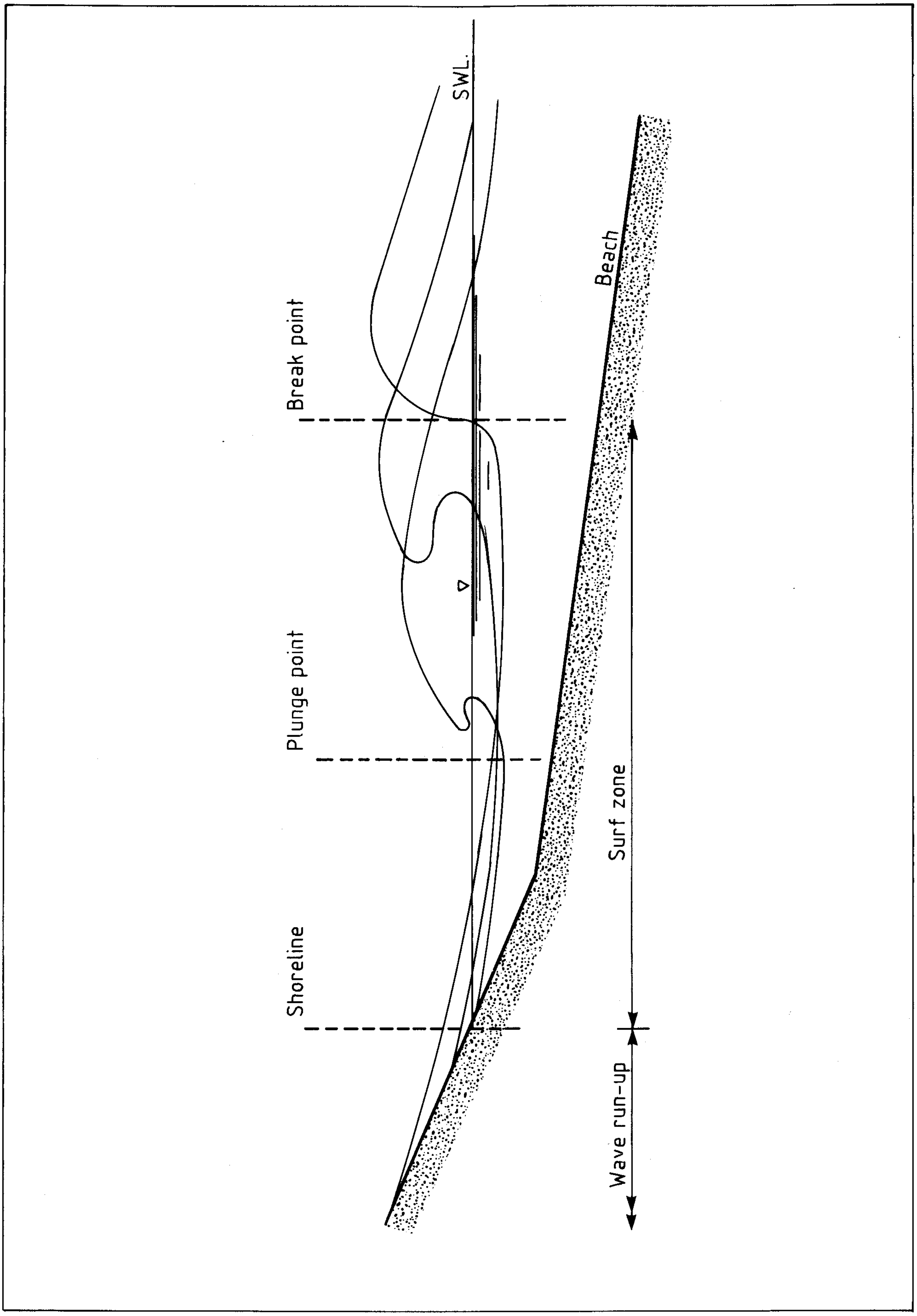

Fig 2 Surf zone definition sketch

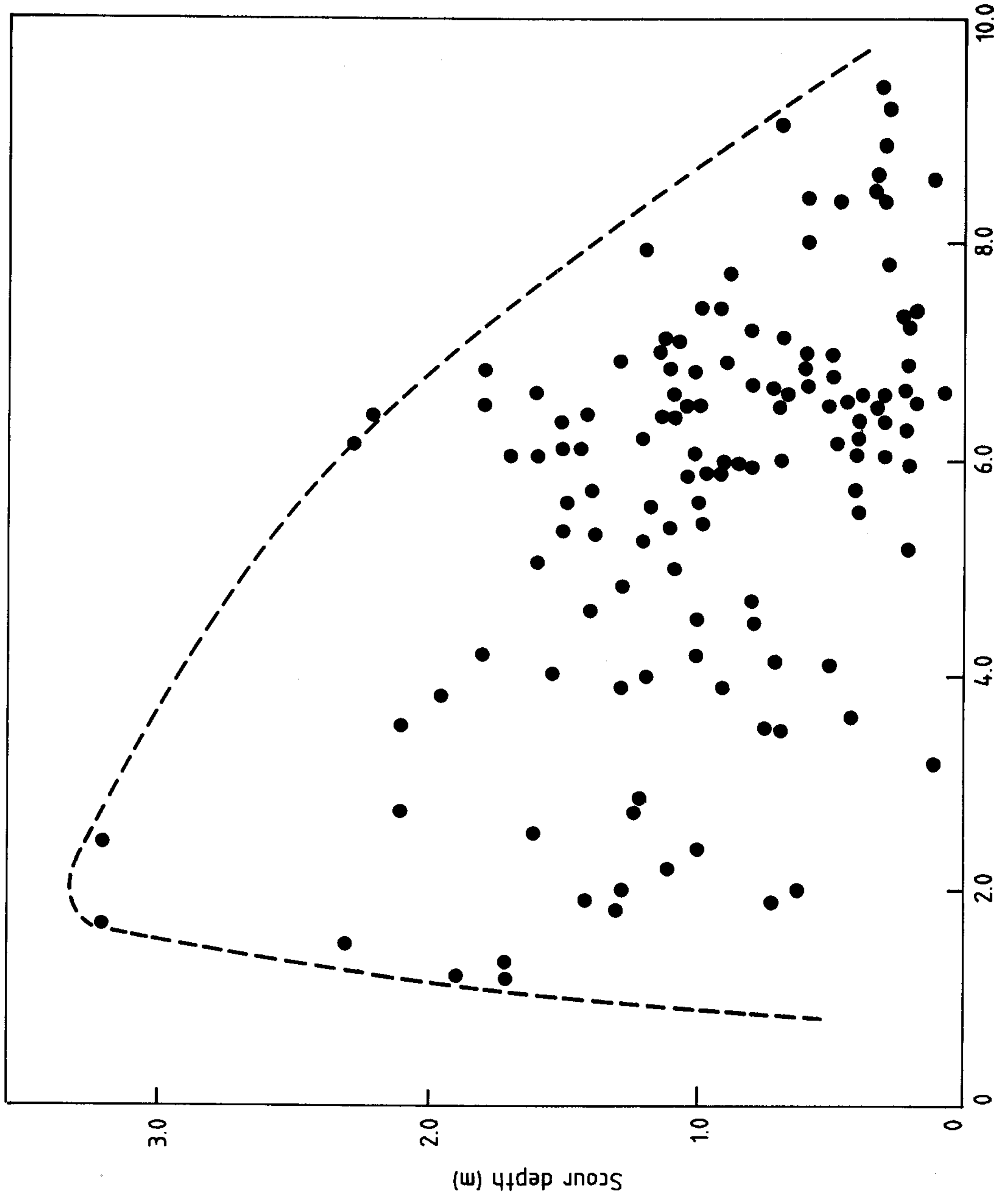

Fig 3 Relationship between scour depth and water depth obtained in Port of Kashima (Ref. 14)

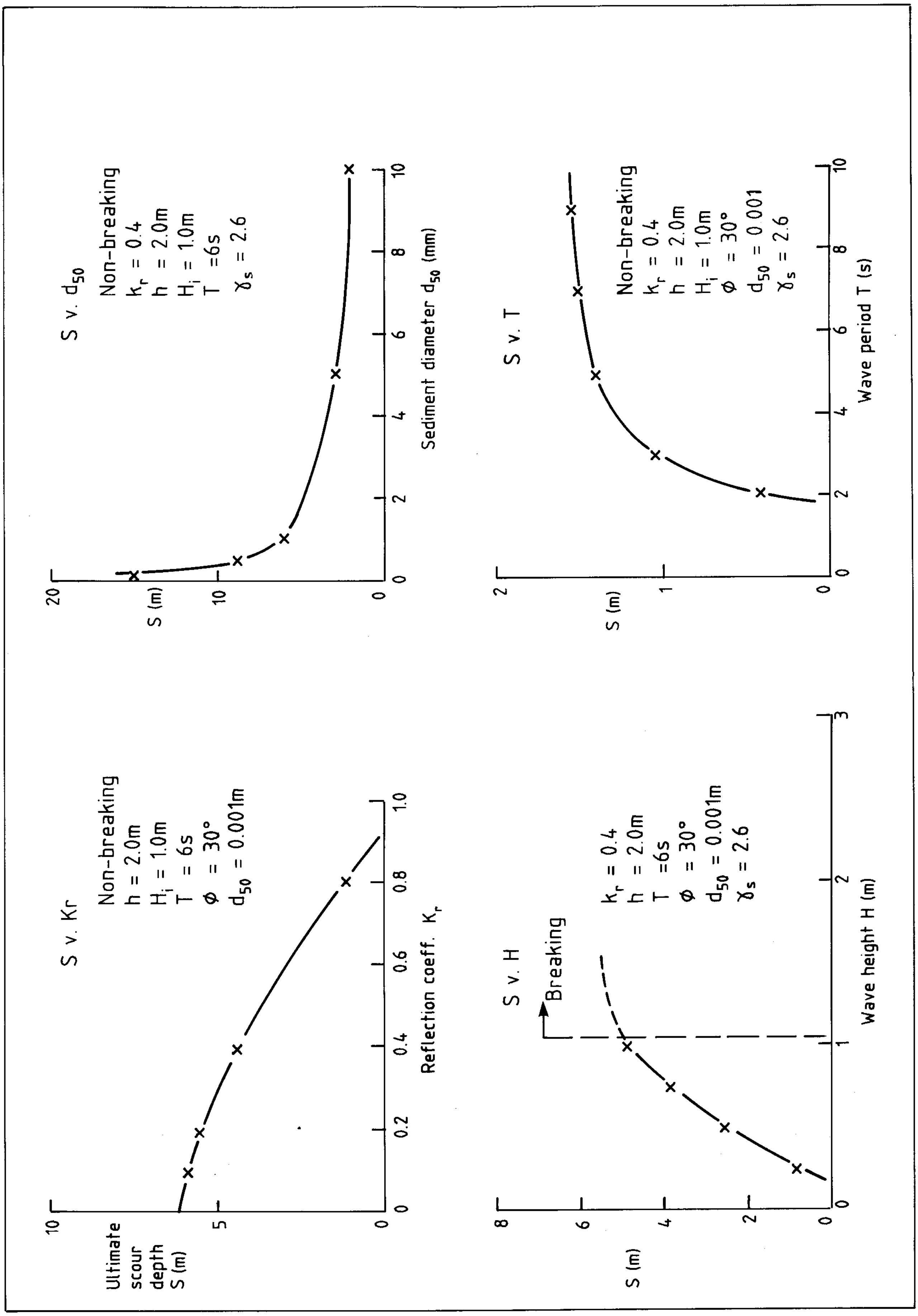

Fig 4 Parameter trends for Herbich and Ko's equation (Ref.10)

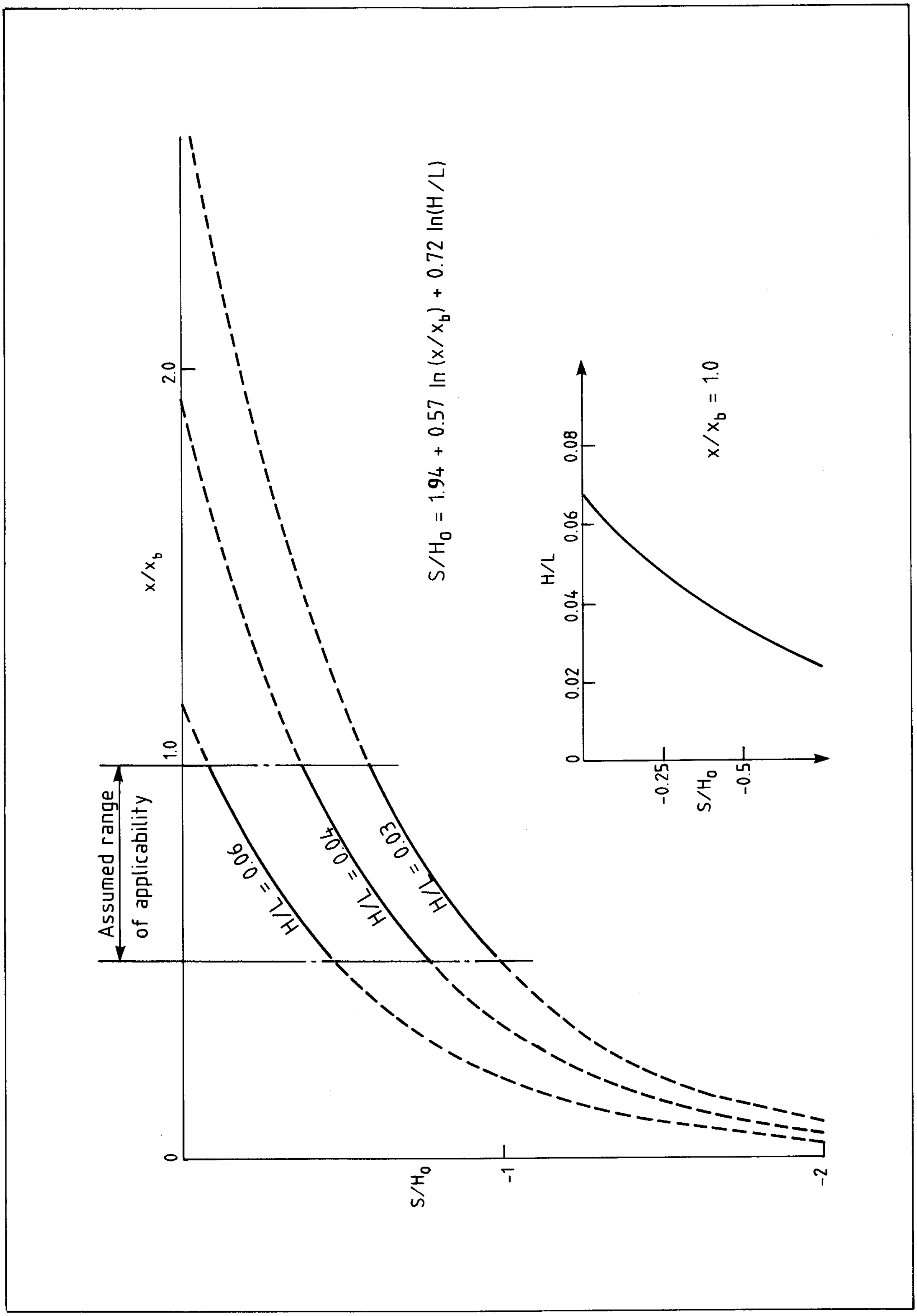

Fig 5 Parameter trends for Song and Schiller's equation (Ref.16)

Appendix

APPENDIX 1

A Proposed Research Programme

Object

It is proposed that a major research study should be set up to:

1. systematically examine the underlying causes of toe scour, and
2. develop methods for predicting both its onset and extent for various types of sea wall and sizes of bed material.

Scope

Any future study of wave-induced toe scour must be founded upon:

1. a sound scaling philosophy for the bed material
2. the use of random waves
3. three dimensional testing.

In addition to these items there will also be a need to examine both a wide range of non-cohesive bed materials and a variety of sea wall structures. Similarly there will be a requirement to vary water level and sea bed geometry.

Experimental methodology

Obviously it will be impossible to simultaneously test all the above items, therefore it is suggested that the following test methodology be adopted.

1. Two-dimensional tests, in a wave flume, using a vertical wall and three different sizes of bed material, selected to cover fine sand, coarse sand and shingle. These tests would permit verification of the scaling laws, if required, and would clarify the scouring mechanisms for each of the test materials. It is anticipated that a number of wave conditions would be tested, at

possibly 3 or 4 water levels. Data recorded would include wave reflections, water particle velocities and scour profiles. Overtopping of the walls would be prevented thus ensuring all wave energy was dissipated or reflected.

2. Following the introductory 2-dimensional testing, the main body of 3-dimensional tests, from which subsequent design guidance would be drawn, should be undertaken. Ideally these tests should be at the same scale as the 2-dimensional work and should use the same bed materials. Again, only a vertical wall will be modelled. It is anticipated that the tests will use the previously established wave conditions (and water levels) acting at varying angles of incidence including perpendicular to the wall. Measurements will be made of the bed profiles, wave reflections and wave induced currents in the vicinity of the wall. Allowance will be made to incorporate tidal currents.

3. Having established the scouring trends for vertical sea walls it is clearly important that the test programme be extended to cover inclined walls and porous rock armoured structures. In particular, emphasis should be placed on those structures where rock armouring as been laid in front of an existing vertical wall in an attempt to improve its hydrodynamic performance. The additional sea wall tests will need to be carried out in both 2 and 3 dimensions though the number of wave conditions/directions and water levels could be reduced.

4. Following testing of the sea wall variations a number of loose ends will need to be tied up.

These may include the problems of toe scouring at abrupt changes in sea wall alignment, and the question of scouring of cohesive sediments, though it is recognised that this latter topic poses considerable problems to physical modelling.

Conclusions

Clearly the research programme outlined above will be long term and may take several years to complete. The initial 2 and 3-dimensional testing should, however, unravel many of the mysteries of wave-induced toe scour and may therefore be considered as the foundation stone of the research programme. Subsequent testing will then build upon this base, following the needs and requirements of the engineering community.