CHAPTER 74

TIME AND BED AVERAGED CONCENTRATIONS UNDER WAVES

Jan J. Bosman*, research physicist, Delft Hydraulics,
Henk J. Steetzel**, MSc-student, Delft University of Technology,

Abstract:

Four types of sediment concentration under waves are discussed:
(a) instantaneous, local, (b) time-averaged, local, (c) instantaneous,
bed-averaged and (d) time and bed averaged. The first three mentioned
are either hard to interpret or difficult to obtain experimentally. The
time and bed averaged concentration is discussed in particular, both its
interpretation and its measurement. Two features are discussed: the ver-
tical concentration distribution and the bottom concentration.

1. Introduction

    Kennedy and Locher (1972) reviewed the suspension of sediment under
waves, and they concluded that the physical understanding is only poor.
They specifically paid attention to the vertical distribution of sedi-
ment concentration, and they analysed measured concentration profiles
relative to theoretical profiles based on different diffusion models.
They concluded that the analysis seems to be overwhelmed by success, but
that it is more spurious than real. It means that the theoretican can
make practically any guess about the distribution or nature of diffusi-
vities. The experimentalist, on the other hand, must achieve extreme
precision in his data before they can be used as the basis for selecting
one diffusion model over another.

    It seems that not much has changed after almost fifteen years. Here
the problem is discussed again from an experimental point of view. A
simple technique is applied to measure sediment concentrations, which
are averaged both over time and over the bed. Without pretending to ans-
wer all questions, the present results allow to reconsider the state-
ments of Kennedy and Locher quoted above.

2. The practical relevance of concentrations

2.1 The instantaneous, local concentration

    Apart from a cross-flow dependence, the instantaneous, local concen-
tration depends on the longitudinal position (parallel to the water mo-
tion), x, on the height above the bottom, z, and on the time, t:
$C(x,z,t)$. Several studies have been reported on $C(x,z,t)$ due to wave ac-
tion. The water motion being partly random (e.g. turbulence) and the bed
being a loose boundary, the question rises: 'How large is the random

*   presently: head R&D-section, Dept. of Hydro-Instrumentation,
              Tidal Waters Division-Rijkswaterstaat
**   presently: project-engineer, Delft Hydraulics

component in $C(x,z,t)$?'. Answering the question requires to measure $C(x,z,t)$ under a purely periodic water motion above a so-called 'stable' bed. The deterministic component in C is defined by the periodic part of the concentration. The non-periodic part is the random concentration component.

Wave flumes are not suitable to generate water motions which are exactly periodic. In this respect a wave tunnel is. Only two such experiments are known in which the deterministic and random components of $C(x,z,t)$ have been determined: Nakato et al. (1977) and Bosman (1982) who both performed measurements by an optical probe and in the ripple regime of bed forms under 'equilibrium conditions'. From both experiments it has been concluded that the sediment concentration under waves is largely random (30-100%). The random concentration component contains two contributions:
- from the applied instrument due to the statistical properties of light attenuation;
- from the physical process due to (small) changes in the local water motion and bed geometry.

Nakato et al. (1977) suggested that the large random component is mainly from instrumental origin. Bosman (1982) showed that, although this contribution cannot be neglected, it is almost purely due to changes in the (entrainment) process. Two reasons for this are obvious:
- Ripples are not fixed as they move (slightly) back and forth about their mean positions, viz. the longitudinal position, x, is not a constant relative to the bed geometry. As the concentration (at fixed height) varies strongly along the longitudinal position, see e.g. Nakato et al. (1977), and as the ripple motion is unlikely to be purely periodic, a random concentration component enters through x.
- Even if the ripple positions were fixed, their shapes are not: from one (wave) period to the next one a ripple may be slightly larger or smaller, steeper or smoother. So the water motion (vortices) between the ripples is not purely periodic (even apart from turbulence). Quite likely the amount of entrained sediment is not periodic either. As a result, a random concentration component enters through the time, t.

The instantaneous, local concentrations having such a large random component, its practical relevance is questionable. Under purely periodic waves, the random component can be reduced by ensemble averaging maintaining both the longitudinal and temporal resolution. But what about the relevance? Suppose the ensemble mean concentration is determined above the crest of a selected ripple. As the next ripple is certainly different, the concentration will be different too. Why is the ripple measured more decisive than is another ripple? Anyway, the ensemble mean concentration cannot be determined for natural (irregular) waves.

As the random concentration contribution enters through both t and x, there are three more ways to reduce it:
- Time-averaging of the concentration at a fixed position: $\bar{C}(x,z)$
- Bed-averaging (at fixed height along the longitudinal position) of the concentration at fixed time intervals: $\bar{C}(z,t)$,
- Time and bed averaging of the concentration at fixed height, z, above the bed: $\bar{\bar{C}}(z)$, where the double overbar indicates the averaging over the two entries, x and t.

2.2 The time-averaged, local concentration $\bar{C}(x,z)$

Such a measurement is easily performed (e.g. by suction at a fixed position). The temporal resolution is lost, but the longitudinal one is kept. As the time-averaged concentration varies with the longitudinal position, see e.g. Nakato et al. (1977), there is still a random contribution to $\bar{C}(x,z)$ due to the bed mobility. This longitudinal influence is often forgotten in the interpretation of $\bar{C}(x,z)$. This will be discussed in Section 3.2.

2.3 The instantaneous, bed-averaged concentration $\bar{C}(z,t)$

To perform such a measurement requires a 'sensitive slit' mounted horizontally at fixed height above the bed and covering several ripples. The slit should respond fast (instantaneously) to the concentration. Such measurements may be useful to study the instantaneous, vertical mixing of sediment, but for the time being there is no method to measure $\bar{C}(z,t)$. (It may be possible by measuring the attenuation/scattering of a horizontal, acoustic beam).

2.4 The time and bed averaged concentration $\bar{\bar{C}}(z)$

For convenience, the time and bed averaged concentration will be abbreviated by TABAC. It can be measured e.g. by a suction system moving horizontally at fixed height above the bed and covering several ripples. With suction at 6 to 8 different heights simultaneously, this is how the present measurements have been carried out. A few details concerning the measuring performance should be emphasized:
- The suction opening is 3 mm $\emptyset$. The suction direction is normal to the ambient water motion. The suction velocity is more than 2.5 times the main flow velocity. Under these conditions the suction calibration is defined well, see Bosman et al. (1987).
- The suction system moves slowly relative to the main flow, but fast relative to the bed form motion: approx. 5 mm/s. The suction system moves back and forth at constant velocity to obtain a fair average over the longitudinal positions.
- Reproduction tests, see Steetzel (1984), showed that (in order to reduce the relative random concentration error under 10%):
  * the averaging time interval should cover at least 100 waves,
  * the averaging bed length should cover at least 3 ripples.

3. Vertical mixing of sediment under waves

3.1 Theoretical approach

The vertical mixing of sediment is usually described by the steady state diffusion equation for the time-averaged concentration, $\bar{C}$:

$$\varepsilon(z) \frac{d\bar{C}}{dz} + w.\bar{C} = 0, \tag{1}$$

where
$\varepsilon(z)$ = the sediment diffusion coefficient (under waves) depending on the height above the bed, z, in general,
w   = sediment fall velocity, in general (unsorted sediment), depending on z as well.

The equation simply states that sediment goes vertically upwards by turbulent diffusion, the first term in Eq. (1), which is compensated by the downward flux due to gravity, the second term. Under definite assumptions for ε (constant, linear, parabolic) and usually with w not depending on z, Eq. (1) can be solved resulting to the concentration profile, $\bar{C}(z)$.

The diffusion equation can be understood quite simply. Let the steady state concentration at level z be denoted by $\bar{C}$, and that at level z+dz by $\bar{C}$-dC (the minus sign indicates that the concentration decreases with increasing height). For small values of dz it may be assumed that the concentration decay (-dC) is proportional to:
- $\bar{C}$ itself (the larger the concentration, the larger the difference in concentrations is between the levels z and z+dz),
- dz (the larger the distance between the two levels, the larger the difference in concentrations is).

This can be expressed as $dC = -\gamma \cdot \bar{C} \cdot dz$, where γ is a positive proportionality factor. Considering an other level, the same expression still holds, although γ may be different, viz. γ depends on the height: $\gamma(z)$. Letting dz diminish, Eq. (1) is obtained with $\gamma(z) = w(z)/\varepsilon(z)$. So Eq. (1) can be established without making any assumption on the suspension mechanism (either turbulent diffusion, or convection by vortices or orbital motion; or both).

The 'classical' theoretical approach has been reconsidered by Kennedy and Locher (1972) under a few assumptions, ending up with a modified diffusion equation. They compared concentration profiles measured to those calculated through their diffusion equation for various 'diffusion models'. They found good agreement between the profiles measured and the ones predicted, no matter on which diffusion model the prediction is based (see Introduction).

Considering this problem, two questions are raised here:
* What is the concentration meant in the diffusion equation? (Section 3.2).
* How is a diffusion model tested in comparing concentration profiles predicted to the ones measured? (Section 3.3).

3.2   The concentration in the diffusion equation

In general, the concentration $\bar{C}$ in a diffusion equation is defined simply by a time-averaged concentration as a steady state is assumed. Recalling Chapter 2, it means that $\bar{C}$ denotes either the time-averaged, local concentration, $\bar{C}(x,z)$, or the time and bed averaged one, the TABAC $\bar{C}(z)$. When testing a diffusion concept, the concentration measured is usually a time-averaged one obtained at a fixed longitudinal position, viz. $\bar{C}(x,z)$ which depends definitely on x, see e.g. Nakato et al. (1977). The question should be raised whether this is the concentration meant in the diffusion equation. In the equation, it is not accounted for any longitudinal influence, viz. it is assumed that $\varepsilon(z)$ is identical 'everywhere' along the bed. Stated alternatively: the diffusion equation relates the concentrations at different heights, no matter where the sediment comes from. This concept is often illustrated by the (turbulent) exchange of a water parcel (level z) with some sediment content and an upper parcel (level z+Δz) with smaller sediment content, see Fig. 1a (the magnitude of the sediment concentration in a parcel is indicated by the cross section of a bold circle).
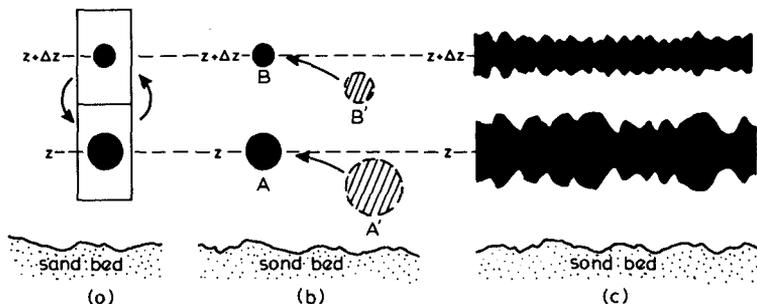
Fig. 1 Sediment exchange due to diffusion (a), motion of sediment con-
        centration under waves (b), and time-averaged local concentra-
        tions at levels z and z+Δz (c).

To demonstrate that $\overline{C}(x,z)$ conflicts with this concept, consider Fig. 1b
showing the concentrations at positions A and B (levels z and z+Δz) at
some instant t. The concentration C_A at time t originates from the con-
centration $C_{A'}$ (partly dispersed) at time t−Δt. Similarly C_B originates
from $C_{B'}$. Near the bed the upward motion of sediment is mainly due to
vortices between the ripples. Far from the bed the upward sediment mo-
tion is due to the wave orbital velocity (and due to turbulence, if
any). Considering the concentrations C_A and C_B (measured at the same
longitudinal position), the relationship is determined by $C_{A'}$ and $C_{B'}$
(A' and B' not necessarily at the same longitudinal position), viz. the
relationship depends on vertical and longitudinal concentration gradi-
ents. (At other moments C_A and C_B may originate from quite different po-
sitions A' and B').

    To eliminate the longitudinal influence, the concentration must be
averaged over all longitudinal positions (at fixed level). These concen-
trations are the TABAC-s as defined before. So Eq. (1) describes the re-
lationship between TABAC-s at different levels. The time-averaged local
concentrations are illustrated in Fig. 1c, where the magnitude of the
time-averaged concentration at level z is presented by a vertical bar
for all longitudinal positions. The result is a 'cloud' at level z. By
averaging over the longitudinal positions it is eliminated from the se-
diment transfer between two levels, no matter where and when the sedi-
ment comes from. So after bed-averaging Fig. 1c is essentially identical
to Fig. 1a.

    It should be noted that the situation close to the bed under unidi-
rectional flow is not essentially different. But measuring time-averaged
concentrations, a bed-averaging is more or less carried out simultane-
ously (without the experimentalist being aware of it) since 'other
longitudinal positions' are passing along the measuring position both
due to the nett flow and due to the moving bed.

3.3 Testing concentration profiles

    When concentration profiles are compared to an analytical model, the
conclusion is usually drawn in terms of 'good or bad fit', whatever it
means. Here a general criterion is defined to establish whether a model

is 'realistic' or not. The test on descriptions of concentration profiles can be formulated, in general, by

$$C(z) = f(z) + \Delta C(z), \tag{2}$$

where
$C(z)$ = measured TABAC at level z (dropping the double overbar),
$f(z)$ = some analytical concentration profile,
$\Delta C(z)$ = random measurement error of $C(z)$.

The error ΔC is often forgotten in such tests. However, it represents the realistic scatter of $C(z)$-values measured around the profile $f(z)$ (measured if the analytical profile were exact and the measurements were infinitely precise). This scatter must be reflected properly when comparing $C(z)$ (measured) and $f(z)$ (predicted). Only then the model $f(z)$ is realistic. A realistic model is not necessarily the 'best fit' model. This is easily illustrated by considering an 8-points profile. The best fit is a seventh order polynomial in z, as it passes exactly through all data-points, leaving no scatter. As a result, ΔC is zero which is not realistic.
This acceptance demand for a model requires ΔC to be known in advance.

Concentrations under waves vary over a wide range and the concentration measurement accuracy varies over a wide range too. It is reasonable to assume that large concentrations carry a large random measurement error and that small concentrations have a small one (when there is not much sediment, the absolute error cannot be large). Hence it will be assumed that the relative concentration error, $\Delta C/C$, is of the same magnitude for both small and large concentrations. With this assumption, it is sensible to replace Eq. (2) by a test-equation of the form
$\ln C(z) = g(z) + \Delta(\ln C)$, where $g(z) = \ln f(z)$ and $\Delta(\ln C) =$ random error in $\ln C = \Delta C/C$, since $d(\ln C)/dC = 1/C$.

To simplify the notations, the data $\ln C_i$ obtained at level z_i will be denoted by y_i. Also, the test-equation will be linearized by replacing $g(z)$ by a linear function $\beta_0 + \beta_1 x$. If the model tested, $g(z)$, is linear in z, it is obvious to define $x = z$. If the model tested is nonlinear, x must be defined by a proper transformation. For example, for the Rouse-distribution (see section 4.3) $x = \ln (h/z-1)$ is a proper transformation, where h is the local water depth. With these definitions the test-equation becomes

$$y(x) = \beta_0 + \beta_1 x + \Delta y, \tag{3}$$

As $\Delta y = \Delta C/C$ is assumed to be approximately constant, all measurement results y are equally weighted when testing a model in the form of Eq. (3), which simplifies the testing procedure. Usually concentration profiles are fitted in the form of Eq. (3) without weighing for practical reasons. Thus without being aware of it, the common procedure assumes implicity that $\Delta C/C$ is constant.
The standard procedure to fit the model to the data is the least squares method, viz. to minimize the sum of squared deviations of the data-points y_i form the prediction $\hat{y}_i$, that is $S_E = \sum(y_i - \hat{y}_i)^2$, where the summation is over all data $i(i=1, \ldots, N)$. The prediction $\hat{y}(x)$ is defined by choosing β_0 and β_1 in the model such that S_E is minimum, viz. $\hat{y}$

is the fitted line. Quantitative tests on the goodness of fit can be
carried out by regression analysis. A discussion of regression analysis
is beyond the scope of the present work, so the reader is referred to
one of the handbooks on that topic, e.g. Draper and Smith (1966). Two
important quantitative measures are the percentage of explained variati-
on, R^2 (R is the correlation coefficient) and the F-parameter.
The parameter R^2 should be near to 100% for a close fit. However, it is
a relative measure, since there is no reason to select a model yielding
R^2 = 96% over a model yielding R^2 = 94%.
The F-parameter measures the significance of a regression obtained (with
a chosen probability). Thus F-tests can detect a false model, but they
do not verify a true model. So in a sense, such tests are relative too.

   Under the assumptions that:
- the distribution of y_i is normal for each level z_i,
- the values of Δy_i at different levels are uncorrelated,
- and the variance of y_i does not depend on the level z_i (remember that
  $\Delta y = \Delta C/C$ does not depend on C, viz. it does not depend on z),
it can be shown that the sum of squares about regression, S_E, is a fair
(unbiased) estimator for $(N-2)(\Delta C/C)^2$, see Draper and Smith (1966). Thus
$\Delta C/C$ can be estimated from a concentration profile measured, and it can
be compared to the value expected. This provides a mean to classify a
model to be realistic or not. When testing a two-layer model (see sec-
tion 4.3) the total sum of squares about regression is an unbiased esti-
mator for $(N-4)(\Delta C/C)^2$.

4.   TABAC-results from a wave flume

4.1 Experimental conditions

   Time and bed averaged concentrations have been measured in a labora-
tory wave flume (length x width x depth = 50m x 1m x 1m) for a single
bed material (unsorted sand, D_{50} = 0.1 mm) with different bottom slopes
(horizontal, 1:80, 1:25) and with local water depths between 0.1 m and
0.6 m. The irregular waves (two different spectra) in the experiments
were either non-breaking or breaking (plunging or spilling) at or near
the measuring location. Wave heights (significant) were typically in the
range 0.1 m – 0.4 m and the averaged zero-crossing wave period was near
2 sec. The experiments have been performed for waves without nett cur-
rent, for nett current without waves and for waves combined with a nett
current. In the wave/current combinations the nett flow velocities were
near $\pm$ 0.2 m/s and $\pm$ 0.4 m/s, the plus-minus signs indicating that wave
direction and nett flow were both parallel and antiparallel.

   The averaging time interval in each measurement was 6 min. and the
averaging bed length was 0.3 m. Except for locations in or near breaking
waves, the bed was covered with ripples with lengths in the range 0.08 m
– 0.12 m. The averaging time interval (approx. 180 wave periods) and the
averaging bed length (3 to 4 ripple lengths) are slightly too short to
reduce the relative random concentration error under 10%. Nevertheless,
the accuracy obtained is sufficient for the present purposes.

   The concentration profiles have been obtained by continuous suction
at eight levels (see Section 2.4). The distances (in mm) between the
suction openings are from bottom to top: 20, 20, 25, 30, 30, 30 and 40.

The lowest measuring height is either 10 or 20 mm above the mean bed
level. The total number of concentration profiles measured amounts 134.

4.2 Estimation of concentration accuracy

The acceptance of a 'theoretical' concentration model requires (see
Section 3.3) that it yields a realistic value for the relative random
concentration error, $\Delta C/C$. As it cannot be measured directly, it must be
estimated in advance. For this purpose, four concentration profiles have
been chosen arbitrarily out of 134, see Fig. 2. (To separate the profi-
les the horizontal axis is logarithmic without absolute values.) As the
concentrations over the height are related somehow, 'smooth curves' (of
arbitrary shape) have been sketched through the data-points. For the mo-
ment, these curves are believed to represent the 'true concentration
profiles'. Thus the averaged scatter of the data-points around the cur-
ves represents the relative random concentration error, $\Delta C/C$ (as the ho-
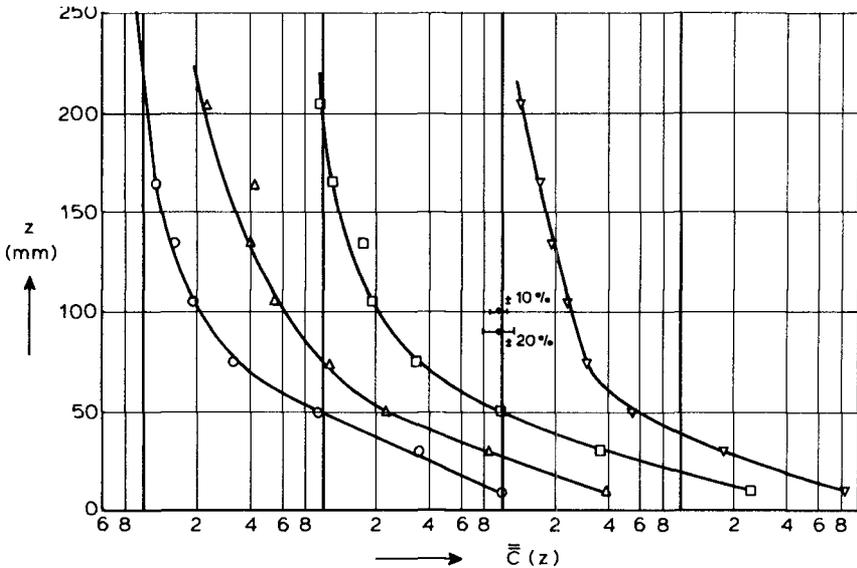rizontal scale is logarithmic).

Fig. 2   Four TABAC-profiles 'fitted' by smooth curves

To give some impression, it is indicated in the figure how much scat-
ter on the average corresponds with $\Delta C/C = 10\%$ and 20 %. Considering the
figure, it is estimated that $\Delta C/C$ is certainly less than 20%, and that
it is close to (or probably even less than) 10%. This is the estimate
made for $\Delta C/C$ in advance.

4.3 Models tested

Two curved concentration distributions are known from literature:
- The well-known Rouse-distribution:

$$C(z) = C(a) \left[\frac{h-z}{z} \frac{a}{h-a}\right]^{w/\varepsilon_m},\tag{4}$$

where w = sediment fall velocity, h = local water depth, ε_m = maximum diffusion coefficient (at half the water depth) and a = reference level.
- The Bhattacharya-distribution, see Kennedy and Locher (1972):

$$C(z) = C(a) \left(\frac{a}{z}\right)^{w/\varepsilon_m},\tag{5}$$

where ε_m = maximum diffusion coefficient (at the surface).

In addition a simple two-layer model is considered, which is mainly a guess and which is based only partly on common sense (Section 4.5):

$$C(z) = C(0) \exp (-z/r_1) \text{ for } z < A$$
$$\tag{6}$$
$$C(z) = C(A) \exp (-z/r_u) \text{ for } z > A$$

where A   = transition level of the two layers which is defined by the continuity of C(z) for z = A,
     r_1, r_u = concentration decay length for the lower and upper layer, respectively. In terms of a diffusion concept, r_i (i = 1 or u) can be interpreted as $r_i = \varepsilon_i/w_i$ with ε_i being constant and w_i denoting the fall velocity in the specific layer.
These three models have been tested on the TABAC-profiles.

4.4 Results of model tests

From visual comparison of the data-points to the least squares fits, it is concluded that all models fit quite well, except for 2 profiles measured (out of 134). As these profiles may be due to some experimental failure they will be omitted furtheron.
Considering the explained variations, R^2, it is found:
- for the Rouse-distribution: (92 ± 8)%,
- for the Bhattacharya-distribution: (96 ± 5)%,
- for the two-layer distribution: (97 ± 4)%.
Considering, the F-tests it is found that all models provide significant regression except for one to three profiles.
Thus far no model can be selected over another, as stated before by Kennedy and Locher (1972).

The test on the prediction of $\Delta C/C$ yields quite remarkable differences as illustrated in Fig. 3. It shows for each profile measured (measurement number) what $\Delta C/C$ should be if the specific model were true.

Obviously, $\Delta C/C$ (and its scatter) is largest for the Rouse-distribution, and smallest for the two-layer distribution. Averaging over 132 measurements yields for $\Delta C/C$ from:
- the Rouse-distribution: (31 ± 15)%,
- the Bhattacharya-distribution: (23 ± 11)%,
- the two-layer-distribution: (13 ± 6)%.
Recalling that $\Delta C/C$ has been estimated in advance to be near 10%, it is concluded that the two-layer model describes the concentration profiles in the most realistic way.
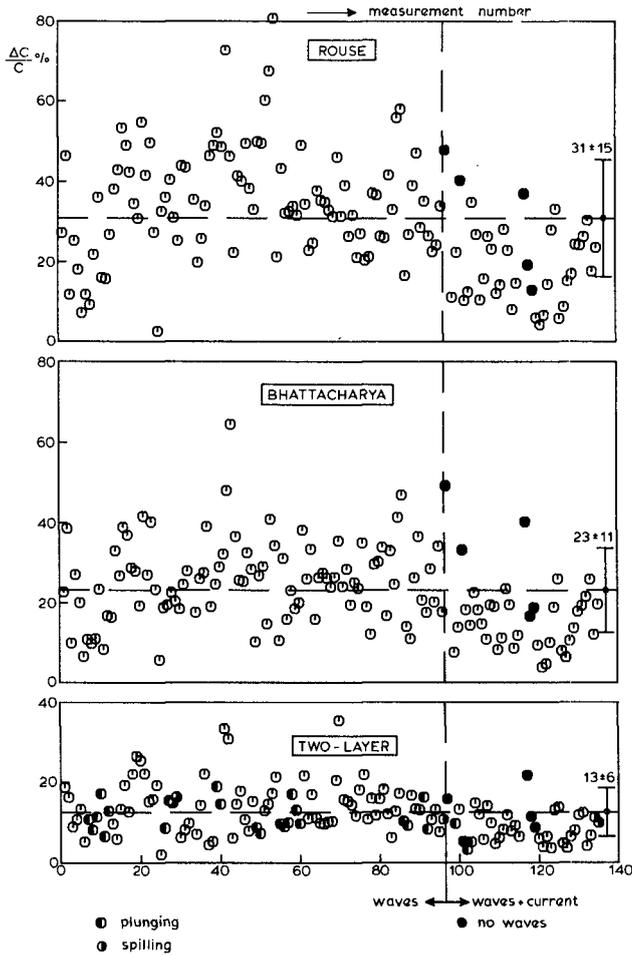
Fig. 3 Results for ΔC/C for the various models

In the two-layer approach the averaged values for ΔC/C for the lower and upper layer yield (7 ± 5)% and (9 ± 5)%, respectively. Since the concentrations in the two layers often differ by two orders of magnitude, the result seems to confirm the assumption that ΔC/C does not depend on C itself.

4.5 The realistic concentration profile

In the former section it has been concluded that the two-layer model provides a 'realistic' description of the concentration profile under widely varying conditions. It means that it fits to the data in a 'natu-

ral way', generating the random concentration error as it should be ap-
proximately. It is not the 'best fit', see Section 3.3.
Neither is it the 'true profile', since it yields a concentration gra-
dient which is not continuous, and such gradients occur rarely in natu-
re.
The results show that the two-layer model approaches the truth closely.
Therefore it is called 'realistic', viz. it provides a simple mathemati-
cal description which is close to the more complicated truth.

The two-layer concentration model states that two layers must be dis-
tinguished in the suspension mechanism. This corresponds to the state-
ments by Kennedy and Locher (1972) that two different mechanisms deter-
mine the sediment suspension by waves, viz. the turbulence production at
the bed and the wave induced orbital velocities, and that the relative
importance of the two mechanisms varies with depth. In view of the pre-
sent results these statements are slightly adjusted: sediment suspension
under waves is determined by vortices (and turbulence) near the bed, and
by the orbital velocities (and some turbulence) at higher levels. The
transition level A indicates a rather abrupt change in the relative im-
portance of the two mechanisms.

5. TABAC-results from a wave tunnel

5.1 Experimental conditions

In order to study near-bottom concentrations in more detail, TABAC-
profiles have been measured in a wave tunnel, see Hulsbergen and Bosman
(1980). The test results have been described extensively by Steetzel
(1984). Here only a few important characteristics will be given. For si-
nusoidal water motions the periods have been varied over the range 1-7 s
and the (maximum) horizontal orbital velocities over the range 0.2-0.6
m/s. The bed (unsorted sand; D_{50} = 0.21 mm) was covered with ripples up
to velocities of 0.5 m/s. At larger velocities the ripples changed into
bumps: irregular with large heights and lengths. For each condition the
experiment started with a flat bed and the height of the suction device
was adjusted relative to the flat bed level. The lowest measuring height
was chosen such that the lowest suction line did not touch the ripple
crests after the suction system had started to move once the bed had
reached the equilibrium stage. Only then the actual measurement was
started. The averaging time interval in the concentration measurements
was 6.5 min. and the averaging bed length was 0.6 m. More than 275
TABAC-profiles have been measured.

5.2 Concentration profiles

In a wave tunnel only the near-bed water motion under waves is simu-
lated. Hence the attention is focussed to this region. Some examples of
near-bed TABAC-profiles are shown in Fig. 4. The profiles were found to
be exponential (over the height) explaining typically over 99.5% (=R^2)
of the variation. The relative random concentration errors found were
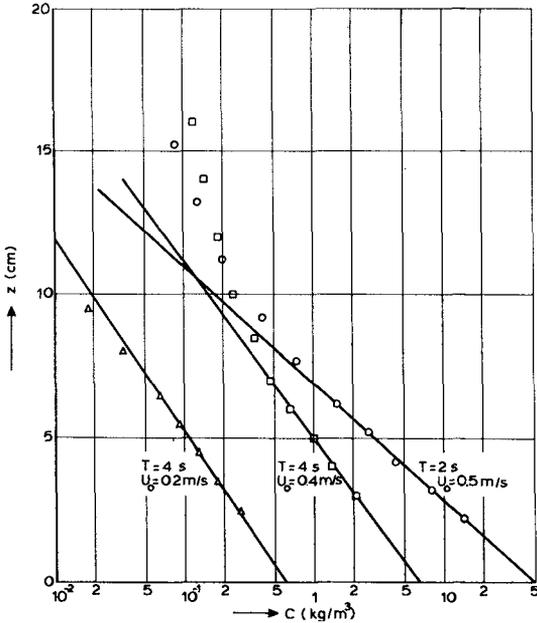typically less than 5%.

Fig. 4   Some examples of TABAC-profiles near the bed (T = wave period;
         u_o = peak orbital velocity)

5.3   Bottom concentrations

Analytical descriptions for the concentration profile are only rela-
tive, viz. they describe the height dependence of the profile and the
magnitude of the concentration is determined by the concentration at
some reference level, see for example Section 4.3. Usually the reference
concentration is hard to obtain experimentally, also because the choice
of the reference level is rather arbitrary (a few grain diameters, or
the ripple crest level). The exponential decay of TABAC-s near the bed
(if generally valid) permits a good definition of the reference concen-
tration. The measuring heights in TABAC-s are defined relative to the
mean bed level (z=0) which can be measured rather easily. Exponential
extrapolation (to z=0) of the near-bed TABAC-profile as measured yields
a well defined 'bottom-concentration', C(0). This definition of bottom-
concentration is a mathematical one rather than a physical one, viz. it
determines the magnitude of the concentration, and it is not important
whether or not it represents the true TABAC at the mean bed level (defi-
ned partly by sediment in suspension and partly by settled sediment).
With this unique definition C(0) is expected to be consistently related
to the physical process i.e. to the hydraulic conditions. Hence, it has
been investigated how C(0) depends on the peak orbital velocity and on
the wave period for the conditions described in Section 5.1. It has been
found that (over almost 4 orders of magnitude) C(0) can be described
well by:

$$C(0) = G \cdot u_o^3 \cdot {}^5/T^2, \tag{7}$$

where u_o is the peak orbital velocity for purely sinusoidal water moti-
on, and T is the wave period. To be complete, the velocity exponent was
found to be 3.5 ± 0.1 and that for the wave period 2.0 ± 0.1. The pro-
portionality factor G, depends on the sediment grain size. For the
single sediment type in the measurements (see Section 5.1) it was found
that 97% of the variation in C(0) is explained by choosing

$$G = (3000 \pm 8) \text{ kg} \cdot \text{m}^{-6\frac{1}{2}} \cdot \text{s}^{5\frac{1}{2}} \tag{8}$$

In Fig. 5 the values of C(0) as measured for given u_o and T are related
to the values of C(0) as calculated through Eqs. (7–8). The drawn line
represents the measured and calculated values being identical. Some of
the data in the figure are placed between brackets to indicate that the
measured values are somehow suspected since one of more other parameters
(e.g. concentration gradient, ripple height or length) showed a discon-
tinuity occurring at larger velocities (u. $\gtrsim$ 0.5 m/s). Without going
into further detail, this is thought to be due to the limited height
(0.4 m) of the wave tunnel which may be troublesome when the ripples
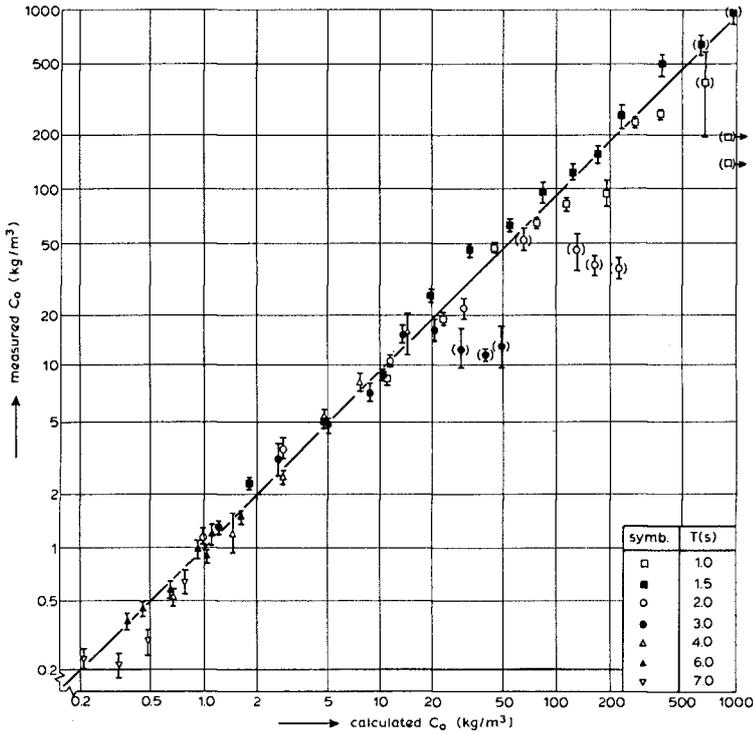grow.

Fig. 5 C(0) measured vs. C(0) calculated

It is hoped for that Eq. (7) is more generally valid, viz. that the influence of the water motion on C(0) can be described fully by $U_0^3 \cdot {}^5/T^2$ and that the grain size dependence can be fully accounted for through G. So the tests have been continued for other grain sizes. The results are still to be reported.

6. Conclusions/Recommendations

From the present work it is concluded that
- care should be taken in measuring the proper parameter (concentration here) when comparison is made to theory,
- tests on the goodness of fit should be defined well to enable qualification of the goodness of test.

It is concluded more tentatively (because only a few conditions have been examined yet) that
- time and bed averaged concentration profiles under waves/currents look like two-layer distributions with a height-independent <u>relative</u> concentration gradient,
- near the bed, time and bed averaged concentrations under waves/currents depend very consistently on the water motion.

The experiments reported here (wave flume, Chapter 4, and wave tunnel, Chapter 5) are rather limited as they apply to only two (unsorted) sediment types (D_{50} = 0.1 mm and 0.21 mm, resp.) and to mainly rippled beds due to the only moderate orbital velocities. Furthermore, the wave tunnel tests deal with sinusoidal water motions only. Many more tests are required to obtain more evidence. Hence it is recommended to perform similar experiments for
- other grain sizes (sorted/unsorted),
- both regular and irregular water motions,
- higher velocities (with other bed forms).

In principle, the experiments can be carried out easily without requiring sophisticated instruments.

Acknowledgements

References

Bosman, J.J., 1982
'Concentration measurements under oscillatory water motion',
Report on model investigation, M1695–Part II, Delft Hydrualics Labora-
tory,

Bosman, J.J., Van der Velden, E.T.J.M. and Hulsbergen, C.H., 1987
'Sediment concentration measurement by transverse suction',
Submitted to Coastal Engineering (Elsevier).
Draper, N. and Smith, H., 1966
'Applied regression analysis', ed. J. Wiley & Sons, New York.

Hulsbergen, C.H. and Bosman, J.J., 1980
'A closely responding, versatile wave tunnel',
Proc. 17th Coast. Eng. Conf., Sydney, pp. 310–317.

Kennedy, J.F. and Locher, F.A., 1972
'Sediment suspension under waves', in "Waves on Beaches",
pp. 249–295, ed. R.E. Meyer, Academic Press, New York.

Nakato, T., Locher, F.A., Glover, J.R. and Kennedy, J.F., 1977
'Wave entrainment of sediment from rippled beds', Proc. ASCE,
J. Waterw., Port, Coast. and Oc. Div., Vol. 103, WW1, pp. 83–89.

Steetzel, H.J., 1984
'Near bottom sediment suspension under oscillatory water motion',
MSc Thesis, Techn. Univ. Delft, Civ. Eng. Dept., Coast. Div. (Dutch
text).