# VALIDITY OF SMALL-SCALE PHYSICAL MODELS INVOLVING BREAKING WAVES

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## Introduction

The presence of air bubbles entrained by the action of wave breaking can strongly influence a number of physical processes including wave impact forces on coastal structures, sediment transport and the rate of air-sea gas transfer. Due to their complex nature, laboratory facilities are commonly used to examine the influence of breaking waves on such processes and the large majority of these experiments are made in small-scale flumes filled with freshwater.

In experiments involving non-breaking and hence non-aerating waves, scale effects are often unimportant. However very few authors have commented on the effect of scale on air entrainment by breaking waves, and the information available (Chanson *et al*., 2002; Lamarre, 1993) is contradictory. It is also noted that many researchers including Haines & Johnson (1995) and Chanson *et al*. (2002) have suggested that there are considerable differences in the total volume and size distribution of bubbles entrained in freshwater and seawater. It is clear therefore that in order to correctly interpret the results of laboratory tests involving breaking waves, the influence of scale on the entrainment and subsequent evolution of bubble plumes generated by breaking waves, as well as the effect of water type on the size, concentration and distribution of entrained bubbles must be understood.

## Comparison of air entrainment by breaking waves in fresh and seawater

In order to investigate the influence of water type on the bubble plumes entrained by breaking waves, a series of experiments were carried out in a 17m two-dimensional wave flume at the University of Southampton in which a submerged reef structure was used to generate repeatable series of breaking wave events in freshwater and artificial and natural seawater. Flow visualisation of the breakers suggested that the process of air entrainment, the distribution of entrained air and the temporal and spatial evolution of the entrained bubble plumes are very similar in all three water types. This is an interesting result because many previous studies have suggested that large differences would be expected (Chanson *et al.,* 2002; Haines & Johnson, 1995). In fact, the only observable difference between the bubble plumes in the three test cases was that a small additional population of very fine bubbles ($d$<0.3mm) was evident in the two seawater cases during the later stages of the plume evolution and that due to their small rise velocity, these bubbles had a tendency to accumulate over repeated breaking events.

In order to provide quantitative evidence to support the observations described above, detailed measurements of the time-varying void fraction field in the region of the breaking waves were made in the three different water types. The experimental method was identical to that described by Blenkinsopp & Chaplin (2005) and made use of a pair of optical fibre phase detection probes to detect the presence of air bubbles at 330 locations beneath the free surface in the vicinity of repeated breaking events, allowing ensemble averaged values of the time-varying void fraction $\alpha(x, z, t)$ to be calculated for each measurement location. These values of $\alpha$ were used to produce a series of contour plots showing the distribution of void fraction at intervals of $T/40$. A selection of these plots for the 3 water types under investigation are presented in figure 1. These plots demonstrate that the measurement technique captures the main features of the two-phase flow well and that the distribution of entrained air and the subsequent evolution of the bubble plume is very similar in all cases, in agreement with the observations.

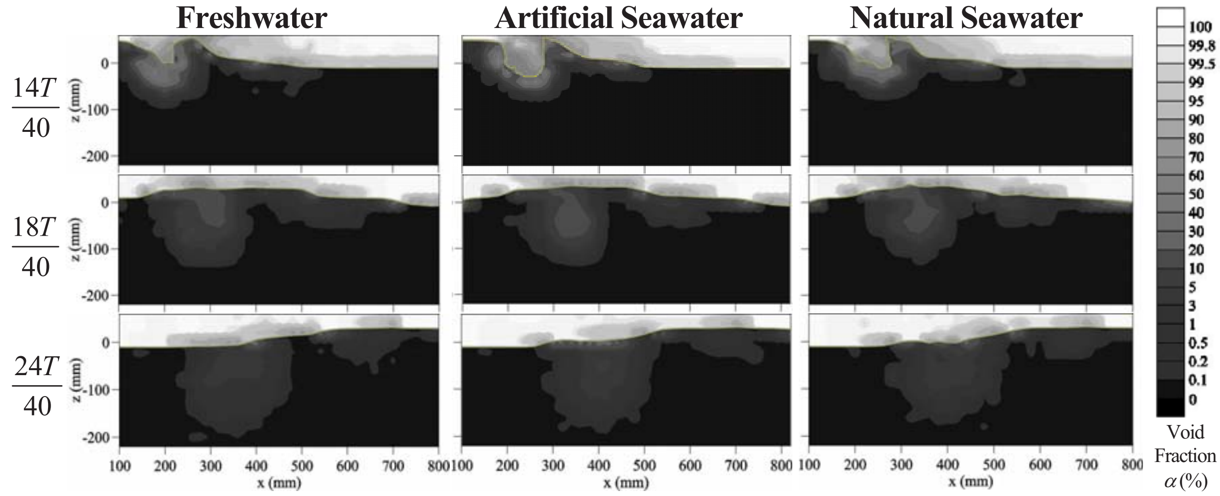


**Figure 1.** Void fraction distributions beneath plunging breaking waves in freshwater, artificial seawater and natural seawater.

To further demonstrate the similar behaviour of the entrained bubble plumes in freshwater and artificial and natural seawater, various integral properties of the void fraction field including the total volume of entrained air, the cross-sectional area of the bubble plume and the mean void fraction within the plume were calculated. The temporal variation of these values is presented in figure 2 and it is seen that they evolve in an almost identical manner for all three water types.

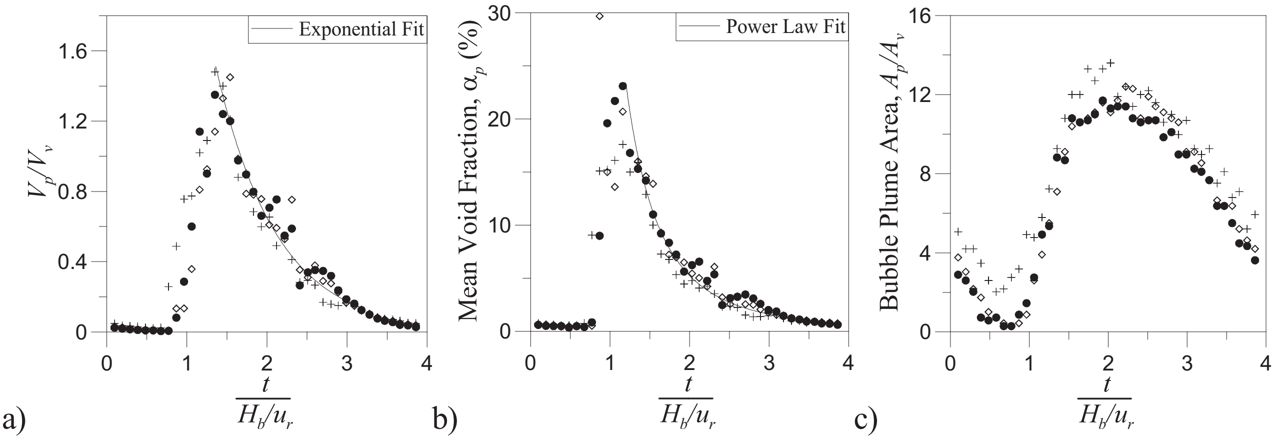


**Figure 2.** Temporal variation of **(a)** the volume of entrained air per unit width, **(b)** mean void fraction in the bubble plume and **(c)** the cross-sectional area of the bubble plume. Symbols: + Freshwater; ◊ Artificial Seawater; ● Natural Seawater.

The observed similarity between air entrainment by breaking waves in freshwater and seawater has considerable implications to the applicability of freshwater laboratory experiments for modelling oceanic processes. It is noted that the additional very fine bubble population observed in the seawater cases will reduce the compressibility of the water column and this may be significant in situations where compressibility effects are important, e.g. measurements of wave impact forces. However the results suggest that in the majority of cases, the use of freshwater in studies involving breaking waves can be considered to be valid.

**Influence of scale on air entrainment**

While the results presented above appear to confirm the validity of using freshwater in laboratory experiments involving breaking waves, very little has been published about the effect of scale on air entrainment processes and this must also be considered when interpreting the results of model tests. To address this, the issues involved in scaling the total volume of air entrained by breaking, the distribution of bubble sizes and the evolution of the entrained bubble plume are examined below.

Deane & Stokes (2002) observed two primary mechanisms responsible for air entrainment in laboratory breaking waves: Larger bubbles with a radius greater than 1mm are formed by the fragmentation of the air “vortex” trapped between the overturning jet and the wave face as the wave breaks up, while smaller bubbles are formed by the impact and subsequent splashing of the overturning jet and in the shear layer between the jet and the water in the trough in front of the breaking wave. If it is assumed that all of the air entrained by a single breaking event occurs due to these mechanisms, that for a sufficiently strong breaking event, the effects of surface tension and viscosity on the wave geometry are negligible, and that the jet impact is dominated by gravity effects, the total volume of air per unit width entrained by the breaking event would be expected to scale with the square of the breaker height.

Many studies have been completed which examine the size distribution of bubbles in both the laboratory and field, however these measurements are generally taken under very different conditions and at different points during the life of the bubble plume and consequently there has been very little comment on how the results at these two scales compare. Deane & Stokes (2002) made measurements of the distribution of bubble sizes in laboratory breakers and noted the presence of a change in the spectral slope of the distribution at a bubble radius of 1mm. The location of this slope change was found to correspond with a value of the Hinze scale deduced from observations of bubble fragmentations below which bubbles are stabilised by surface tension forces and do not fragment. Deane & Stokes (1999 & 2002) also found a similar break point in the gradient of bubble size distributions obtained in oceanic waves at $r \approx 1$ mm and put this forward as evidence that the Hinze scale is also relevant in the open ocean. This result implies that the same bubble formation mechanisms operate in both laboratory and field conditions and it is expected therefore that the distribution of bubble sizes after initial entrainment by the action of wave breaking will be similar at all scales.

The discussions above have concluded that while the total volume of entrained air is expected to scale geometrically with the wave height, the absolute sizes of bubbles present after initial entrainment has taken place will be comparable at all scales. Consequently, the rise velocities ($u_r$) of the bubbles making up the bubble plume will remain constant, independent of the scale of the breaking wave. It can be shown that the characteristic time scale of air detrainment is the bubble rise time $H_b/u_r$ and the bubble plume evolution is seen to scale well according to this time scale (figure 2). It follows that when scaling results from model to full scale, the time scale of bubble plume evolution will follow the length scale $S$, while a Froude model would imply a time scale on the wave properties of $\sqrt{S}$ . It is expected therefore that there will be large differences in the temporal evolution of bubble plumes generated at model and full scale.

In order to examine the effect of scale on the evolution of entrained bubble plumes, a Lagrangian finite-difference model which traces individual bubbles and incorporates the effects of turbulent diffusion, bubble dissolution, buoyancy and hydrostatic bubble expansion was developed. The model was designed to compute the time-varying void fraction distribution within bubble plumes after initial entrainment had taken place and was shown to compare well with the measured laboratory data described above. Figure 3 shows a series of plots of the void fraction distribution within the bubble plume at 1:20 model scale ($H_b$=0.1m) and field scale ($H_b$=2.0m) and it is seen that at model scale, the bubble plume disperses much more rapidly than in the large scale case. Indeed by the end of a single wave period, the plume appears to have almost completely dispersed in the model scale case, while at field scale significant void fractions remain. Further modelling demonstrated that for the wave case examined here, the longer characteristic rise time in the field scale case led to the accumulation of a significant ambient bubble population which never fell below 2.5% after the passage of the first three breaking events.

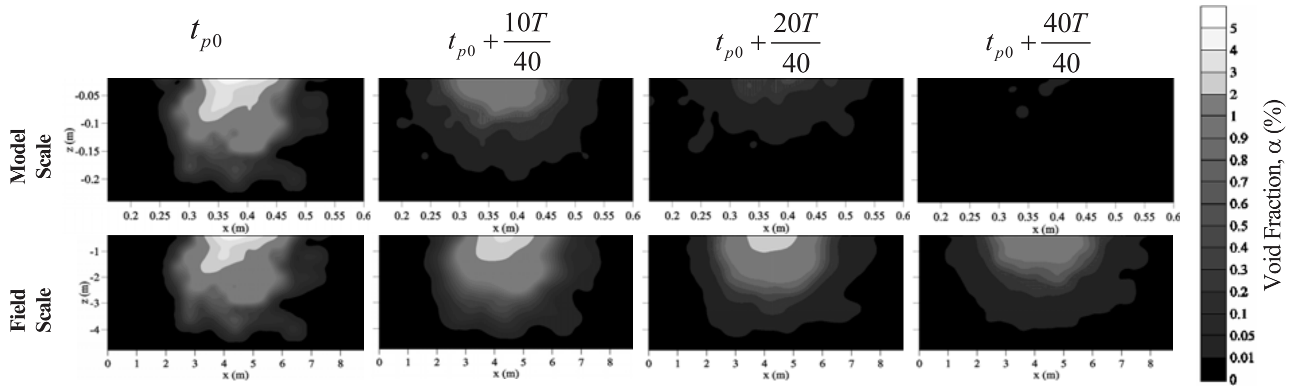


**Figure 3.** Void fraction distributions during a single wave period at model (1:20) and field scale calculated using the bubble plume evolution model.

In conclusion, this study has shown that the differences between air entrainment by breaking waves in fresh and seawater are very small and thus in most cases, physical model tests using freshwater should be reasonably applicable to field conditions. However, the effect of scale on the bubble plume evolution after entrainment and hence the average level of aeration in the region of breaking waves is seen to be far more significant than the influence of the water type and this should be taken into account by future researchers.

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