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Development of an air bubble curtain to reduce underwater noise of percussive piling

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Abstract

Underwater bubbles can inhibit sound transmission through water due to density mismatch and concomitant reflection and absorption of sound waves. For the present study, a perforated rubber hose was used to produce a bubble curtain, or screen, around pile-driving activity in 6–8-m depth waters of western Hong Kong. The percussive hammer blow sounds of the pile driver were measured on 2 days at distances of 250, 500, and 1000 m; broadband pulse levels were reduced by 3–5 dB by the bubble curtain. Sound intensities were measured from 100 Hz to 25.6 kHz, and greatest sound reduction by the bubble curtain was evident from 400 to 6400 Hz. Indo-Pacific hump-backed dolphins (*Sousa chinensis*) occurred in the immediate area of the industrial activity before and during pile driving, but with a lower abundance immediately after it. While hump-backed dolphins generally showed no overt behavioral changes with and without pile driving, their speeds of travel increased during pile driving, indicating that bubble screening did not eliminate all behavioral responses to the loud noise. Because the bubble curtain effectively lowered sound levels within 1 km of the activity, the experiment and its application during construction represented a success, and this measure should be considered for other appropriate areas with high industrial noises and resident or migrating sound-sensitive animals. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Sounds; Attenuation; Bubble curtain; Bubble screening; Dolphins, *Sousa chinensis*; Environment; Mitigation; Noise; Pile driving

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1. Introduction

The underwater world is a much noisier place because of human industrial activities than it was for the great majority of time during which marine animals evolved (Wenz, 1962). We now know that noise pollution can adversely affect marine mammals, many of which rely on sound as a primary means of exploration and communication (Au, 1993; details of sound types, intensities, and species are summarized in Richardson, Greene, Malme & Thomson, 1995). Among the cetaceans, baleen whales tend to be most sensitive to frequencies below 10 kHz, and several are highly sensitive even below 100 Hz (Richardson, 1995). Dolphins and porpoises of the odontocete suborder of cetaceans, on the other hand, have acute hearing above 500 Hz, and echolocate and communicate well into human ultrasound, above 20 kHz (Ridgway, 1983). Because of propagation characteristics of sound, those frequencies below 10 kHz tend to travel longer distances before attenuating than those reaching into ultrasound, and we expect these lower frequencies to be especially disruptive to cetaceans that are sensitive to them because of their own channels of hearing (Ketten, 1991, 1994).

Most underwater noises of stationary industrial activities, such as dredges, oil drill ships or platforms, and construction pile driving, have their highest energy at lower frequencies, from about 20 Hz to 1 kHz (Greene, 1987; Greene & Moore, 1995). While smaller-toothed whales of sizes around 3–4 m in length are not known to be highly sensitive to sounds below 1 kHz, they nevertheless can hear in much of this range; and any loud sounds occurring in their vicinity could cause behavioral reactions, interference with communication, and physiologic and morphologic damage (Ketten, 1994; Ridgway, 1983). Since an important communication channel exists for these smaller whales, dolphins, and porpoises in the somewhat higher range of 1–10 kHz, where pile driving still has much energy (see below), the suite of frequencies in this range is also of potential concern.

Humans can at least partially mitigate noise effects on marine mammals by one or more prophylactic actions. These include equipment design and decoupling of equipment from water to reduce noise, changes in seasonal and hourly timing of noise production, and changes in position or routing of noisy activities to place them further away from marine mammal concentrations. They also include operational procedures that could involve regulation of vessel speeds, minimizing source levels and duty cycles to the absolute minimum to get the job done when sounds are purposefully emitted for ocean or substrate measurements, creating lower-level warning sounds to clear the area of marine mammals, ramping up sounds for the same reason, etc. (Richardson & Würsig, 1995).

It is with this background in mind that the Hong Kong Airport Authority (AA) commissioned a study to ascertain how to mitigate against industrial sounds potentially affecting Indo-Pacific hump-backed dolphins (*Sousa chinensis*). The study was conducted during construction of an aviation fuel receiving facility (AFRF) near the island of Sha Chau, north of the newly constructed Hong Kong International Airport at Chek Lap Kok (Fig. 1). Dolphins sometimes occur within only meters of the area that was slated for industrial development (Jefferson, 1998;

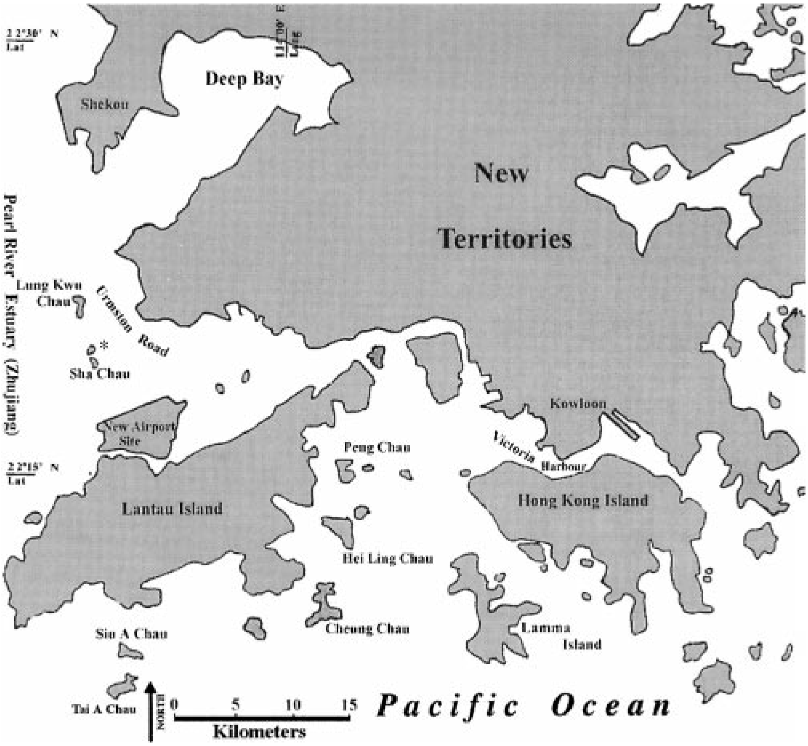

Fig. 1. Map of central and western Hong Kong. The asterisk in the mid-left of this map represents the pile driving/bubble curtain area discussed in the text. Average water depths in that part of Hong Kong are 4–8 m, with considerably deeper water in Urmston Road (a shipping channel) to the north of Sha Chau, and several shipping lanes in the estuary of the Pearl River immediately to the west. The aviation fuel-receiving facility for which pile-drive construction took place is presently supplying aviation fuel by underwater pipeline to the Chek Lap Kok airport south of Sha Chau.

Jefferson & Leatherwood, 1997). It was feared that prolonged disruption of prime habitat could drive them out of an area that might be essential to their survival and reproduction. Percussive pile driving to construct the pile footings of the AFRF instead of drilling (bored piling) into hard substrate was used, largely because of reduced time. In this study, we discuss the test of a bubble curtain to lower the noise level of pile driving outside of the immediate area of construction. In earlier work, bubble curtains contained or reflected underwater noises, essentially by creating an impedance mismatch in the medium (Graves, 1968; Jacobsen, 1954). In each earlier case highly intensive shock waves and sounds of explosions were absorbed in order to minimize damage to structures. This paper describes bubble screening as a mitigation measure to protect wildlife. It presents the development and general set-up of the bubble curtain structure, testing of its efficacy, and data on potential effect on dolphins.

2. Materials and methods

As part of the design of the bubble curtain, Electronic and Geophysical Services, Ltd. (EGS) of Hong Kong carried out noise attenuation tests in a large swimming pool at Ocean Park, Hong Kong, using compressed air forced into perforated galvanized steel pipes laid across the bottom of the pool. Impulsive sounds were played by underwater transducer at one end of the pool, the bubble curtain was strung along the middle, and a calibrated recording system picked up sounds on the other end of the pool. The experiment was imperfect for extrapolation to the open ocean because there was much sound path interference and transmission by and through the concrete of the pool. However, enough data on attenuation (especially on appropriate pipe diameter, hole size, and hole spacing) were gathered to make feasible the full-scale construction effort off Sha Chau (EGS, 1996). This paper is limited to the more realistic open ocean experiment and mitigation procedures.

2.1. General procedure

For construction of the AFRF, a pile-driving barge was transported to just off the eastern edge of Sha Chau, in the northwestern sector of Hong Kong (Fig. 1). The single pile driver consisted of a 6 metric tonne diesel hammer, that fell by gravity about 1.0–1.5 m during each stroke, detonating a fuel–air mixture to drive down the piling. Blow heights and detonation explosions varied with substrate hardness (and other mechanical features), and maximum blows corresponded to approximately 90 kJ of energy. Rate of blows varied between 0.95 and 1.35 blows/s. Pile driving transmits most of its considerable noise energy into air and water during a 40 ms period per blow (EGS, 1996).

The bubble curtain arrangement consisted of an approximately 160-m circumference circle of rubber hose anchored to the sea bottom. The inside diameter of the hose was 50 mm, with 3-mm diameter holes for air extrusion spaced every 0.3–0.4 m. Each end of the perforated hose was connected to a non-perforated supply hose that terminated in an air compressor on the piling barge (Hokuetsu Industries, Model PDS750S). Each compressor, capable of delivering 750 ft^3/min of air, operated at a pressure of about 0.4 Mpa. In this manner, much of the pile-driving operation was potentially shrouded by the bubble curtain. The piling barge disrupted the bubble curtain near the surface by extending outside of it (Fig. 2). The system was tested as described below, and then kept operational for all but short mechanical 'down times' throughout the period of pile driving, which lasted about 7 months.

Three boats were used to record sound levels outside of the bubble curtain. During testing, sources of noise from the boats were minimized by switching off the engine, pumps, echosounders, and miscellaneous gear. The only source of noise was a quiet 600-W generator used to run the recording equipment. This generator was placed on soft rubber mounts so that its noise would minimally propagate to the water. Each boat was equipped with a precise electronic positioning system and with voice communication capability to coordinate pile driving and bubble curtain on/off

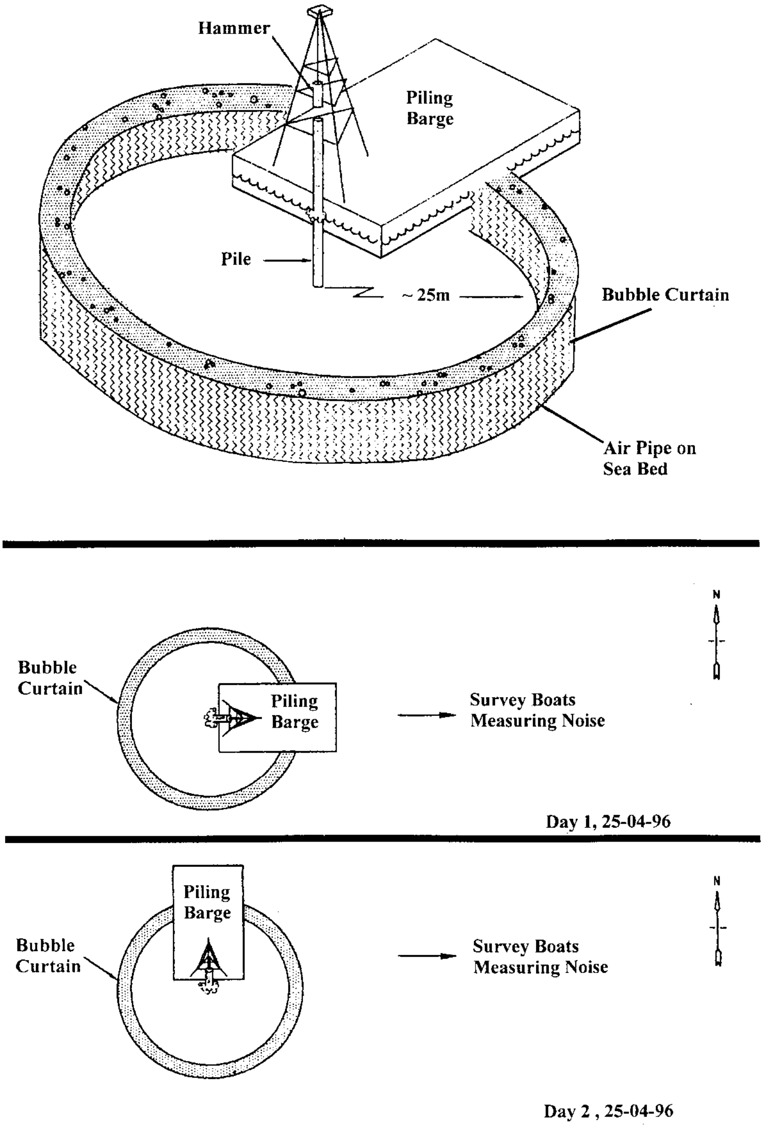

Fig. 2. A schematic of the pile-driving activity, bubble curtain, and orientation of the piling barge relative to recording boats to the east on the two days, 25 and 26 April, of the main experiment described in the text. This figure is by courtesy of Dick Hale, Electronic and Geophysical Services, Ltd.

efforts. Calibrated hydrophones, amplifiers, analog to digital converters, and a computer-based high speed data-logging system (with frequency response approximately flat from 100 Hz to 50 kHz) were used to gather sound recordings from each vessel. The three boats were originally anchored next to each other 162 m from the pile driver, to simultaneously record with all three systems. In this manner, it was confirmed that the systems were sufficiently inter-calibrated to show no operationally significant difference in received sound intensity levels at any tested frequency. The three boats were then moved to their testing positions, at 250, 500, and 1000 m east of the pile-driving barge. Testing was conducted on two days, 25 and 26 April 1996. On day 1, the barge was aligned so that it extended out over the bubble curtain towards the boats to the east. On day 2, the barge had been repositioned so that there was a continuous uninterrupted bubble curtain between the pile driver and the sound-recording boats, and the barge extended over the bubble curtain only towards the north.

2.2. Sound sampling and data processing procedures

From each boat, the calibrated hydrophone was dropped to a depth of 6 m in a water depth of 8 m. The main recording parameters were a sampling rate of 100 kHz, record length of 2.5 s, and amplifier gain and voltage range variable, depending on sound levels. When piling started, all three boats measured noise levels simultaneously. Ten piling records were obtained, and then the operators were asked to stop piling. The 10 records were examined for possible clipping and amplifier re-adjustment to make sure that the full dynamic range of noises was received. After this initial inspection and re-adjustment, the operators were asked to continue pile driving, and further records were obtained. A total of 20 piling records were obtained per pile.

Raw voltage figures were converted to sound amplitudes by standard formulae from calibration data (EGS, 1996), and recalculated from narrowband analysis to one-octave band frequency widths from 100 Hz to 25.6 kHz. Display is in the underwater standard of decibels relative to one micropascal, or dB re. 1 μPa. A summary of sound analysis and interpretation procedures is provided by Richardson and Greene (1995). Potential differences in sound amplitudes between bubbles off and on at different frequencies were tested by the Mann–Whitney U statistic (Zar, 1984), from 20 piling records per pile. This non-parametric test was used because sound intensity data do not have a normal distribution. The statistic U is given in the Results section, with sample sizes of 20 per piling record, and 40 when two records per bubbles off or on were compared (see data figures).

2.3. Dolphin theodolite tracking and abundance surveys

Observations of dolphins were conducted from a shore-based station on Sha Chau, at an elevation of 56.5 m above mean water. Two observers searched for dolphins with a pair of Fujinon 15×80 tripod-mounted binoculars, and tracked movements with a Leica Wild TC500 surveyor's theodolite (Würsig, Cipriano & Würsig, 1991). Theodolite data were converted into grid references with the PC-based program TTRACK to obtain information on positions, orientations, speeds, and distances from human activities.

To determine if there was evidence of a decline in dolphin use of the area during construction of the AFRF, line-transect vessel surveys were conducted to estimate abundance (for a description of survey and analysis methods see Jefferson, 1998, and Jefferson & Leatherwood, 1997). Methods, vessels, and personnel were held as constant as possible during the study period to minimize the potential for other sources of variability to affect results. Survey data were allocated to four time periods, based on phases of construction of the AFRF, as defined below:

1. pre-construction phase (15 November 1995–10 February 1996)—period prior to the commencement of construction work for the AFRF, in which baseline data were collected on dolphin distribution and abundance patterns in the area;
2. piling phase (11 February–2 September 1996)—period during which active piling for the AFRF was occurring; this is the phase in which noise was produced that was considered potentially damaging to dolphins, the bubble curtain was used, and testing was carried out;
3. on-jetty construction phase (3 September 1996–10 June 1997)—period after completion of piling work, in which structures were being built upon the jetty legs. This phase involved some noisy activities, but not nearly so much as during phase 2; and
4. near-completion phase (11 June–31 August 1997)—period in which small-scale work on the AFRF was occurring, generally not involving any significant noise (except for vessel traffic) to enter the marine environment from Sha Chau.

3. Results

3.1. Sound testing of the bubble curtain

The data obtained from days 1 and 2 were roughly comparable by oceanographic parameters: water temperatures, salinities, and surface wave action were similar (EGS, 1996). However, barge orientation was different on the two days, as described in the Materials and methods section and Fig. 2, and this difference may explain variability in results between days.

3.1.1. Broadband pulse levels

Fig. 3 presents broadband root mean square (RMS) pulse sound levels received at each distance for the two days. On 25 April (Fig. 3A), levels at 250 m distance were similar for bubbles on and off. At distance 500 m, sound level with bubbles on was 16 dB higher than with bubbles off ($U = 290$, $p < 0.02$), the opposite of a desired effect of less sound with bubbles on. At 1000 m, the levels were again essentially the same for bubbles on and off. At all three distances, the broadband RMS noise level measured between hammer pulses was 8–16 dB below the RMS hammer pulse levels. On 26 April (Fig. 3B), broadband RMS pulse levels were lower with bubbles on than off at all three distances; the bubble curtain was attenuating the pulse sounds by 3–5 dB on a broadband basis ($U = 274$, 285, and 280, for distances 250, 500, and 1000 m, respectively; all $p < 0.05$).

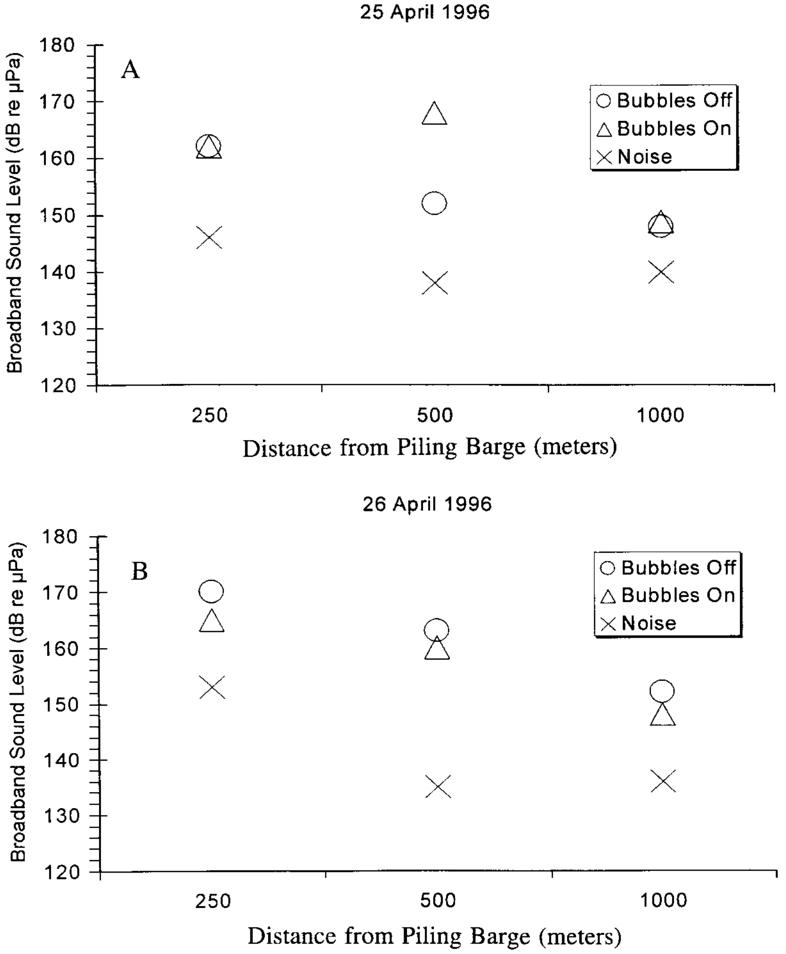

Fig. 3. Broadband sound levels on two experimental days, at ranges of 250, 500, and 1000 m, with the bubble curtain on and off. Measurements include the frequency range of 100 Hz–25.6 kHz.

3.1.2. *Effects of frequency*

Fig. 4 presents the received sound levels in one-octave bands for the two days at the three distances. On 25 April, distance 250 m, pulse levels were highest for the frequency band 200–800 Hz. At frequencies 3.2–6.4 kHz, pulse levels were higher for bubbles off than on ($U = 274-285$, $p < 0.05$), the expected result if attenuation occurred. At other frequencies (100–1600 Hz and 12.8–15.6 kHz), levels were similar for bubbles off and on. At 500 m distance, however, anomalous results occurred; and at 1000 m distance, received levels were too low to document a difference for the two conditions. Noise spectrum level measurements were not made on the day of the pile-driving measurements, but it is likely that background noise was a significant fraction of sound at the 1000-m receiver.

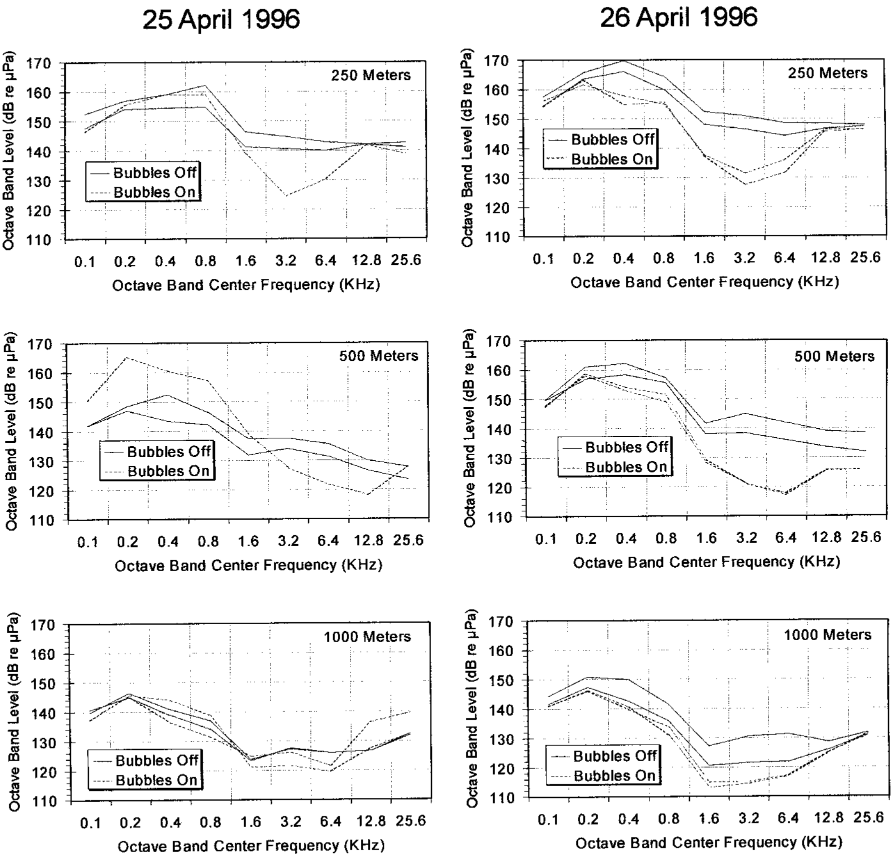

Fig. 4. One-octave band sound levels for the full frequency range of measured sounds, with separate lines for bubble curtain on and off, for the two experimental days.

On 26 April, the day the barge was oriented north and not in the path between the bubbles and the receiver, bubbles clearly reduced hammer blow sounds in the direction of the receivers, at all three distances. Pulse energy was strongest at frequencies 200–800 Hz. At distance 250 m, the results for 100–200 Hz and 12.8–25.6 kHz were about the same for bubbles on and off. At frequencies 400–6400 Hz, distance 250 m, sound levels were higher with bubbles off than on, by 10–20 dB depending on frequency; the strongest difference was for the 3.2-kHz band ($U = 610$, $p < 0.001$). At distances 500 and 1000m, the differences were smaller, but were also lower for bubbles on (at 3.2 kHz, $U = 600$, $p < 0.002$ at 500 m; $U = 580$, $p < 0.005$ at 1000 m).

Fig. 5 presents the differences in one-octave band levels for the two bubble conditions versus frequency for the two days. For the broadband pulses, the effectiveness of bubbles was not clear on 25 April, although with bubbles off at a distance of 250 m, higher levels of sound were recorded for frequencies of 800–6400 Hz. On 26 April, however, lower received levels were recorded in all frequency ranges with

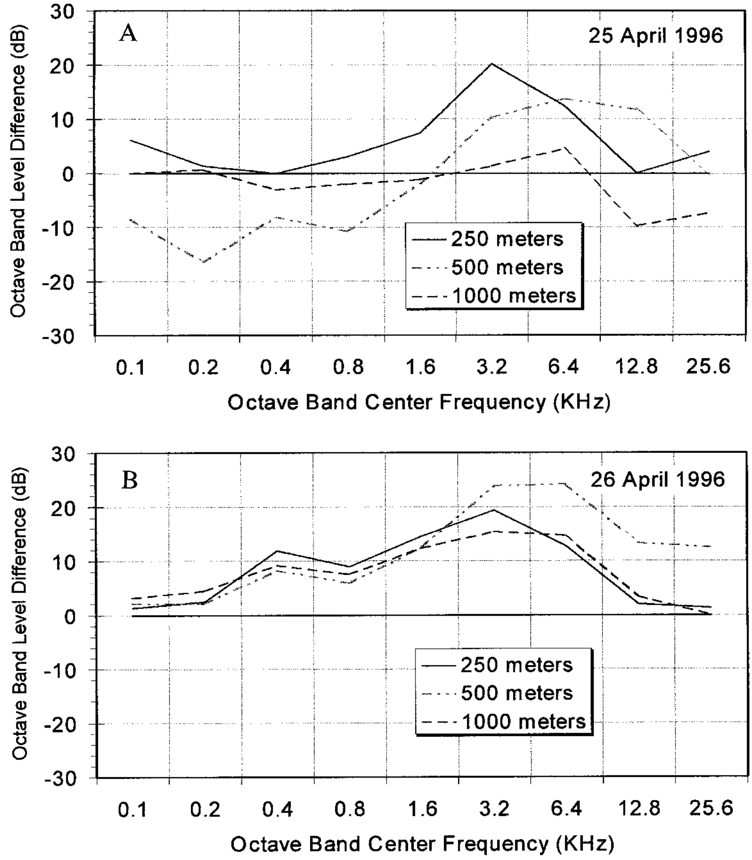

Fig. 5. The one-octave band level difference between bubble curtain on (curvilinear lines) and off (straight line at ordinate of "0"). This figure shows the unequivocal attenuation of bubbles on at all frequencies and distances for 26 April 1996, when the barge was not situated over the bubble curtain in direct line with the recording vessels.

bubbles on (Fig. 5B). The improvement was minimal at 100–200 Hz and at 12.8–25.6 kHz. The improvement was near or exceeded 10 dB at all three distances at frequencies of 400 Hz and 1.6–6.4 kHz. Furthermore, it climbed to 20 dB at 3.2 kHz at 250 m and beyond 20 dB at 3.2–6.4 kHz at 500 m (see previous paragraph for statistical significance).

3.2. Potential reactions of dolphins

Indo-Pacific hump-backed dolphins were sighted within 300–500 m of the industrially active Sha Chau area before, during, and after pile driving. Line-transect estimates of abundance indicate potential evidence of a decline in dolphins in the area during the piling and on-jetty construction phases (Fig. 6). However, point estimates for all four periods fall within the 95% confidence interval of the 'baseline'

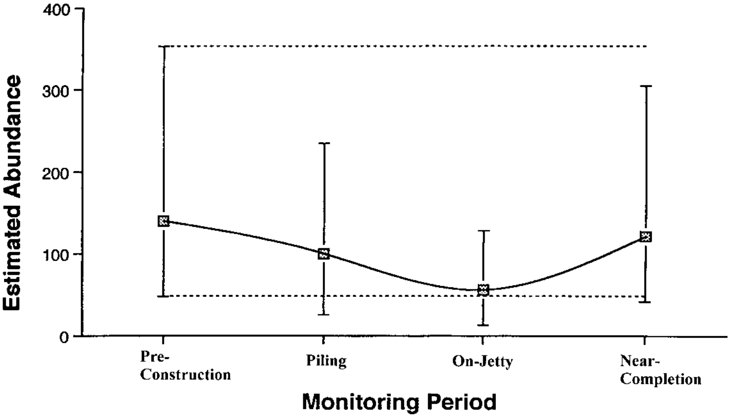

Fig. 6. Estimated abundance of dolphins in the North Lantau study area, around the aviation fuel-receiving facility during four phases of construction (see Materials and methods section for details). Bars represent 95% confidence intervals for each phase.

(pre-construction phase) estimate; and this suggests that the differences may not be biologically meaningful (to be discussed below).

There was no significant difference in the average degree of direction change (or re-orientations) between surfacings, for dolphins theodolite-tracked during piling operations (92.4 ± SD 63.21°, $n = 253$ theodolite readings on 16 different days) versus those tracked at times when piling was not occurring (93.0 ± SD 62.12°, $n = 73$ theodolite readings on 16 different days, t-test, $p > 0.05$). However, the average speed of dolphin groups tracked by theodolite during the period of active piling for the AFRF (2.3 ± SD 1.78 m/s, $n = 253$) was over twice as high as for other periods (1.1 ± SD 0.67 m/s, $n = 73$), a highly significant difference (t-test, $p < 0.001$; for more details, see Jefferson, 1998).

4. Discussion

When the barge was not in the sound propagation path, the bubble curtain clearly provided a reduction of 3–5 dB in the overall broadband sound level. In one-octave frequency bands, the bubbles reduced sound levels by 8–10 dB in the 400–800-Hz bands and by 15–20 dB in the 1.6–6.4-kHz bands. Sound conduction probably occurred through the substrate under the bubble curtain for at least the lowest frequencies of 100–200 Hz (Malme, 1995; Richardson & Greene, 1995). Furthermore, background noises from adjacent shipping channels (Urmston Road and others in the Pearl River Estuary) and industrial centers (Shekou, Chek Lap Kok) probably also confounded the measurements.

When the barge was in the sound propagation path measured by the receiver systems, bubble screening was much less effective. This was probably because the barge itself vibrated with every percussive hammer blow, and effectively transmitted the piling noise over the bubble curtain towards the east. It is unknown whether a complete bubble curtain surrounding the barge would have further attenuated the strongly reduced sounds recorded when the barge pointed to the north. To test this, bubble screening in the future should entirely enclose any sound emission structure in need of noise reduction to the environment.

Underwater noise is known to alter cetacean behavior at least in the short term (Reeves, 1992; Richardson & Würsig, 1996). Reactions to sounds vary dramatically depending on sound type, general behavior pattern of the cetaceans subjected to the sound, and other variables which are presently only incompletely understood. Behavioral modifications may include attraction when dolphins approach to ride bow and stern waves of vessels; or flight when the sound is related to perceived danger, such as from a whaling vessel or at the approach of a tuna fishing boat that can entrap and kill (Au & Perryman, 1982). Response thresholds are often quite low for gradually increasing sounds, such as those of an approaching vessel. Steady sounds, such as those made by offshore drilling, cause responses at intermediate thresholds. The highest thresholds are observed for pulsed sounds, such as those created by industrial seismic surveys or by percussive hammering of pile driving, as in the present case (summarized by Richardson & Würsig, 1996). It is likely that habituation plays an important role when sounds slowly increase or are steady; but continued disturbance with tolerance may also be manifest, as well as sensitization (and possible heightened ‘irritability’) when a sound is perceived as particularly noxious.

The present bubble curtain experiment was successful. It demonstrated sound attenuation especially well in those single digit kHz frequency ranges in which at least bottlenose dolphins (*Tursiops truncatus*) are particularly sensitive, and where they conduct much of their low frequency whistling (Herman & Arbeit, 1972). No precise audiogram data exist for Indo-Pacific hump-backed dolphins, but similar size and internal ear morphology predict that they too are sensitive in this general range (Ketten, 1991).

At least some dolphins stayed within the vicinity of Sha Chau during percussive pile driving, but many appear to have partially and temporarily abandoned the area immediately after it. Because of the scarcity of longitudinal time data from other years and environmental situations, it is not possible to ascertain whether a shift in dolphin distribution occurred due to the industrial activities or other factors. It cannot be ruled out that at least some prey distribution changed on a seasonal or other time-related basis due to human fishing activities or natural causes. It is also possible that at least some prey distribution changed due to the activities related to pile driving, as many fishes are known to be very sensitive to sounds (Tavolga, 1964) and to bubbles (Sharpe & Dill, 1997).

The estimate of dolphin numbers for the final period rose considerably, back to near the original mean abundance. If indicative of a real trend, this may indicate a rebound in dolphin numbers after the period of most intensive disturbance. It is also suggestive that any decline was not caused solely by mortality, but instead by temporary shifts of animals to outside of the immediate area.

Dolphins did not change patterns of general orientation between pile driving and no pile driving conditions. However, they traveled at speeds over twice as rapidly with than without pile driving. Thus, their behavior may have been altered by the activity in a significant manner, even with bubble screening. It is possible, but unproved, that the dolphins were more stressed or 'nervous' as a result of the activity. It is not known how much more or less dolphins would have been affected had bubble screening not been in effect, and had hammering noises therefore been even louder. Killer whales (*Orcinus orca*) have shown a similar speed increase in the presence of human-made noises (Kruse, 1991), as have bowhead whales (*Balaena mysticetus*) (Richardson et al., 1995). Noise produced by the bubble screening itself may have altered behavior to some degree, but we have no information on this point.

The fact that the bubble curtain strongly reduced sounds in the 400–800-Hz bands makes it likely that bubble screening would work to reduce sounds for baleen whales known to communicate in these frequencies, such as hump-back whales (*Megaptera novaeangliae*), gray whales (*Eschrichtius robustus*), right whales (*Eubalaena glacialis* and *Eubalaena australis*), bowhead whales, and sperm whales (*Physeter macrocephalus*). These whales also tend to spend considerable time near shores and potentially in contact with loud human activities, during both mating/calving and feeding stages of their yearly cycles (Leatherwood, Reeves & Foster, 1983).

Although bubble screening appears to show promise for reducing anthropogenic sounds underwater, it is only one of several potential mitigation tools (Richardson et al., 1995). In the present case, three other measures were implemented during AFRF construction. These were: (1) development of a dolphin exclusion zone, where an area within a radius of 250 m around the piling barge was thoroughly checked for dolphins before initiation of each piling episode, by land-based observers on Sha Chau and by vessel; when dolphins were found in the exclusion zone, piling was delayed until they had moved out of the area; (2) production of warning sounds just before piling operations commenced, consisting of loud but non-hazardous noises to emit warnings to dolphins potentially in the area; these sounds were made by banging with a hammer on an iron pipe held into the water; and (3) finally, acoustic decoupling was practiced by placing air compressors on rubber tires that effectively reduced transmission of motor noises into the water.

Bubble screening may be logistically possible and biologically effective in cases where loud human-made noises, as during construction or explosive structure removals (Anonymous, 1996), occur in discrete areas with important (and perhaps spatially restricted) habitat availability to marine or riverine animals. This experimental, mitigative approach requires further investigation in highly industrially active areas such as Hong Kong (Leatherwood & Jefferson, 1997; Liu & Hills, 1997), where marine mammals and other acoustically sensitive animals are exposed to potentially harmful noise.

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References

Anonymous. (1996). *An assessment of techniques for removing offshore structures*. Washington, DC: National Academy Press.

Au, D., & Perryman, W. (1982). Movement and speed of dolphin schools responding to an approaching ship. *Fish. Bull., 80*, 371–379.

Au, W. W. L. (1993). *The sonar of dolphins*. New York: Springer Verlag.

EGS. (1996). *Sha Chau aviation fuel receiving facility construction of jetty using percussion piling—attenuation of piling noise by use of air bubble curtain noise measurements during percussive piling* (Final Report to the Hong Kong Airport Authority, Job No. HK105696). Hong Kong: EGS.

Graves, M. (1968). Air-bubble curtain in sub-aqueous blasting at Muddy Run. *Civil Engineering, June*, 59–61.

Greene, C. R., Jr. (1987). Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea. *J. Acoust. Soc. Am., 82*, 1315–1324.

Greene, C. R., Jr., & Moore, S. E. (1995). Man-made noise. In W. J. Richardson, C. R. Greene, Jr., C. I. Malme, & D. H. Thomson, *Marine mammals and noise* (pp. 101–158). San Diego, CA: Academic Press.

Herman, L. M., & Arbeit, W. R. (1972). Frequency difference limens in the bottlenose dolphin: 1–70 cs/s. *J. Aud. Res., 12*, 109–120.

Jacobsen, R. C. (1972). Air-bubble curtain to cushion blasting. *Ontario Hydro Research News, 1*, 17–23.

Jefferson, T. A. (1998). *Population biology of the Indo-Pacific hump-backed dolphin* (Sousa chinensis *Osbeck, 1765) in Hong Kong waters* (Report submitted to AFD, Hong Kong). Aberdeen, Hong Kong: Ocean Park Conservation Foundation.

Jefferson, T. A., & Leatherwood, S. (1997). Distribution and abundance of Indo-Pacific hump-backed dolphins (*Sousa chinensis* Osbeck, 1765) in Hong Kong waters. *Asian Marine Biology, 14*, 93–110.

Ketten, D. R. (1991). The marine mammal ear: specializations for aquatic audition and echolocation. In D. Webster, R. Fay, & A. Popper, *The biology of hearing* (pp. 717–750). Berlin: Springer Verlag.

Ketten, D. R. (1994). Functional analyses of whale ears: adaptations for underwater hearing. *IEEE Proc. Underwat. Acoustics, 1*, 264–270.

Kruse, S. (1991). The interactions between killer whales and boats in Johnstone Strait, B.C. In K. Pryor, & K. S. Norris, *Dolphin societies—discoveries and puzzles* (pp. 148–159). Berkeley, CA: University of California Press.

Leatherwood, S., & Jefferson, T. A. (1997). Dolphins and development in Hong Kong: a case study in conflict. *IBI Reports, 7*, 57–69.

Leatherwood, S., Reeves, R. R., & Foster, L. (1983). *The sierra club handbook of whales and dolphins*. San Francisco, CA: Sierra Club Books.

Liu, J. H., & Hills, P. (1997). Environmental planning, biodiversity, and the development process: the case of Hong Kong's Chinese white dolphins. *J. of Env. Management, 50*, 351–367.

Malme, C. I. (1995). Sound propagation. In W. J. Richardson, C. R. Greene, Jr., C. I. Malme, & D. H. Thomson, *Marine mammals and noise* (pp. 59–86). San Diego, CA: Academic Press.

Reeves, R. R. (1992). Whale responses to anthropogenic noise: a literature review. *Science and Research Series, 47*, 1–47.

Richardson, W. J. (1995). Marine mammal hearing. In W. J. Richardson, C. R. Greene, Jr., C. I. Malme, & D. H. Thomson, *Marine mammals and noise* (pp. 205–240). San Diego, CA: Academic Press.

Richardson, W. J., & Greene, C. R., Jr. (1995). Measurement procedures. In W. J. Richardson, C. R. Greene, Jr., C. I. Malme, & D. H. Thomson, *Marine mammals and noise* (pp. 35–58). San Diego, CA: Academic Press.

Richardson, W. J., Greene, C. R., Jr., Malme, C. I., & Thomson, D. H. (1995). *Marine mammals and noise*. San Diego, CA: Academic Press.

Richardson, W. J., & Würsig, B. (1995). Significance of responses and noise impacts. In W. J. Richardson, C. R. Greene, Jr., C. I. Malme, & D. H. Thomson, *Marine mammals and noise* (pp. 387–424). San Diego, CA: Academic Press.

Richardson, W. J., & Würsig, B. (1996). Influences of man-made noise and other human actions on cetacean behaviour. *Mar. Fresh. Behav. Physiol., 29*, 183–209.

Ridgway, S. H. (1983). Dolphin hearing and sound production in health and illness. In R. R. Fay, & G. Gourevitch, *Hearing and other senses: presentations in honor of E.G. Wever* (pp. 247–296). Groton, CT: Amphora Press.

Sharpe, F. A., & Dill, L. M. (1997). The behavior of Pacific herring schools in response to artificial humpback whale bubbles. *Can. J. Zool., 75*, 725–730.

Tavolga, W. N. (1964). *Marine bio-acoustics*. New York: Pergamon Press.

Wenz, G. M. (1962). Acoustic ambient noise in the ocean: spectra and sources. *J. Acoust. Soc. Amer., 34*, 1936–1956.

Würsig, B., Cipriano, F., & Würsig, M. (1991). Dolphin movement patterns: information from radio and theodolite tracking studies. In K. Pryor, & K. S. Norris, *Dolphin societies—discoveries and puzzles* (pp. 79–111). Berkeley, CA: University of California Press.

Zar, J. H. (1984). *Biostatistical analysis* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.