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Dispersed Shots at Optimum Depth - An Efficient Seismic Source for Lithospheric Studies

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Abstract. The case for dispersing charges fired at sea into a number of packages fired simultaneously at optimum depth is outlined and an experiment, carried out to check that linear addition of the signals from separate sources does occur, is described. The advantages of this system for lithospheric studies are demonstrated.

Key words: Dispersed Underwater Explosions — Seismic Source — Seismic Long Range Profiles.

Introduction

It has been known for some time that there are considerable advantages to be gained from firing underwater explosions at "optimum depth" (O'Brien, 1967a; Jacob, 1970, Jacob and Willmore, 1972). In the third paper it was reported that this method, of firing at the depth where the bubble pulse and the surface reflection are in phase, had been used to produce teleseismic signals from an explosion of only 10 tons TNT. Other 10 ton shots have since been fired in 1972 and in 1973. In all cases teleseismic signals were observed.

These 10 ton explosions have also been used to provide observations at shorter range (Hirn *et al.*, 1974, Bonjer *et al.*, 1974) and further work has been carried out using optimum depth explosions of up to 5 or 10 tonnes to investigate the lithosphere in Europe.

An alternative system which could be used for this type of work, i.e. up to ranges of the order of 1000 km, is considered here. It generates rather higher frequencies but the lithosphere is a region of relatively high Q and losses due to absorption are not serious up to the frequencies considered here (about 4 Hz).

If the explosion is to be fired in one package, the optimum depth system is the most efficient way to generate seismic waves for investigating the Earth's structure, but there are a number of limiting factors:

1. It has been theoretically calculated that the particle velocity generated in the far-field increases only as $W^{0.47}$ (Wielandt, 1972) where Q is infinite and W is the weight of the charge. The effect of finite Q is considered

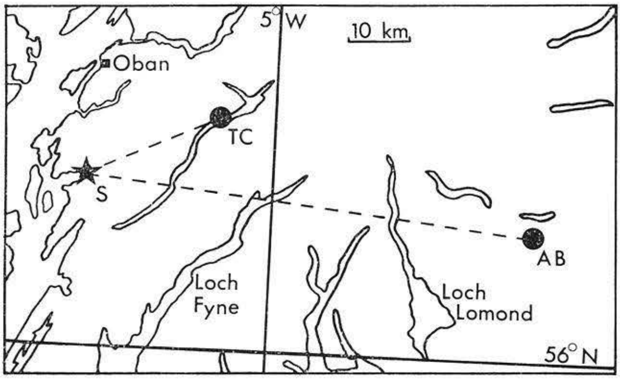

Fig. 1. The positions of the shot-point (S) and the two recording stations. TC is Taycreggan and AB is Aberfoyle

later but in practice a square root law may be a good approximation in the 2 to 4 Hz range when 1 Hz seismometers are used.

2. As the charge size is increased the water depth required increases. If the shot is to be kept clear of the bottom then depths of about 90 metres are required for a 0.1 tonne shot, 140 metres for a 1 tonne and 220 metres for a 10 tonne one. This considerably reduces the number of available shot sites near to land.

3. Large single charges are difficult to handle at sea, calm conditions are necessary and to wait for these is expensive.

4. When charge size is increased both amplitudes and predominant frequencies are changed.

A logical step is thus to split the explosive into a number of smaller packages. If there is linear addition of the signals generated by N packages, then the summed signal should be N times that generated by one package. The water depth required should only be that necessary to accomodate an individual package and, as these would be smaller, they should be easier to handle though the shot pattern as a whole may present difficulties of a different kind. Finally, the source waveform should be unchanged as the number of packages is increased. The dispersal of charges when firing in boreholes on land is quite common practice if the shot totals more than a few hundred pounds (O'Brien, 1967b), but seems not to have been used for optimum depth firing in water.

Experimental Test of Linear Addition

We have recently carried out an experiment to check that linear addition does occur. If $A = kN^X$ for a given shot/station pair where A is the trace amplitude observed, k is a constant, N is the number of packages, and the

Table 1

(a)

No. of packages N	No. of shots	Average V at TC (μms^{-1})	Average V at AB (μms^{-1})
1	1	0.57	0.073
2	1	1.43	0.142
3	4	2.26	0.183
4	4	3.42	0.274
5	2	3.72	0.312

(b) N = 3 for all shots

Shot	Separation (m)	V at TC (μms^{-1})	V at AB (μms^{-1})
1	24	2.42	0.205
2	18	2.36	0.167
3	12	2.19	0.182
4	6	2.08	0.178

index X is to be measured, then factors that might cause X to be less than 1 include interference between the individual bubbles, and inhomogenietites in the structure under the shot pattern, which would reduce coherence.

The experiment was carried out in Loch Melfort in the West of Scotland (Fig. 1, point S). The Loch has an area of very sheltered water deep enough (about 40 metres) to allow optimum depth shooting with 1.36 Kg (3 lb) packages of TNT. There is a possible fault in the Precambrian basement running NE/SW through the Loch, but the shots were all fired on the SE side of its likely position. They were fired in North/South strings of up to 5 packages and the shot area extended about 250 metres from North to South. Most of the shots were fired with a separation of 24 metres between charges (this is equivalent to separating 0.2 tonne charges by about 90 metres) though three were fired at separations of 18 metres, 12 metres, and 6 metres to test for any loss of signal when the bubbles are closer together. The maximum bubble radius for these charges at optimum depth is about 1.1 metres.

The packages were suspended by the firing cable below small buoys and they were fired electrically using two N79 detonators in each package. The N79 detonators normally explode between 1 and 5 msec. after the onset of the firing current, giving a scatter of sources within only $\pm 2\%$ of the dominant period of the waveform (about 100 msec.).

Results are shown in Table 1 (a) for two recording stations at Taycreggan (TC) and Aberfoyle (AB), at distances of 23.6 and 72.9 km respectively (Fig. 1). The figures in columns 3 and 4 of Table 1 (a) give an average ground

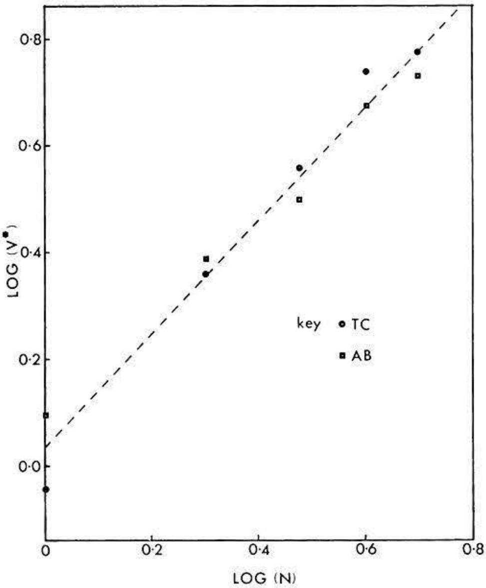

Fig. 2. Plot of Log (V*) against Log (N) demonstrating the linearity of the relationship between them

velocity V (proportional to the trace amplitude) within a window of 0.25 second around the maximum observed in the first phase. This was calculated by taking the average of 5 swings on the seismogram centred around the largest swing. The velocity response of the system at that frequency then gives an average ground velocity for that window.

Table 1(b) shows the results obtained from 4 shots fired with $N = 3$ but various shot separations. Shot 1 was at a slightly different position from shots 2, 3, and 4, but there is no clear loss of amplitude due to the compression of the pattern. Fig. 2 shows a plot of log (N) against log (V*) for both stations. V* is the ground velocity V normalized so that the average value of V for each set (TC and AB) becomes 3. The slope of 1.06 (standard error 0.06) demonstrated experimentally that the relationship is linear.

The radiation will be noticeably directional for linear shot patterns whose length is comparable to the wavelength λ of the seismic signal. The trace amplitude of the dominant frequency component in the far-field at an angle ϕ to the perpendicular to the array is given by:

$$A = A_0 \frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)} \quad \text{where} \quad \psi = \frac{2\pi d \sin\phi}{\lambda}$$

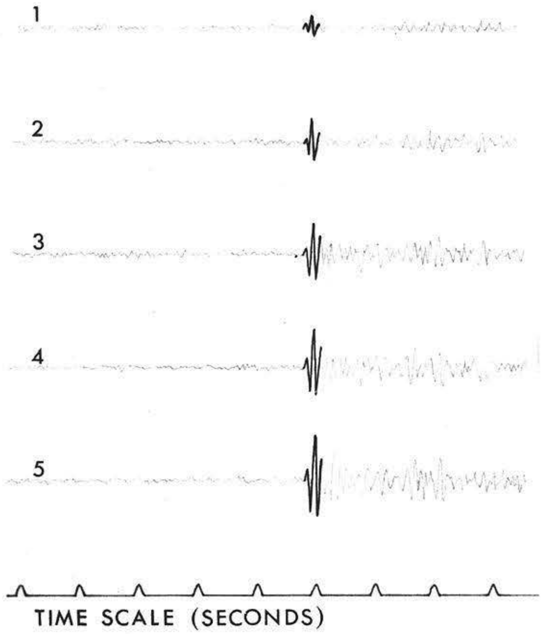

Fig. 3. Records from AB band-pass filtered 2—32 Hz. The coherence of the addition is very clear

A_0 is the trace amplitude from one charge and d is the spacing between charges.

The Effect of Absorption

We have not so far considered losses in the transmission path due to absorption, scattering, etc. For a station at distance r from the source we may write (see, for instance, Berg *et al.*, 1971).

$$A(f,r) = V(f)\, I(f)\, F(r) \exp\left(-\pi f t/Q\right) \tag{1}$$

Where A is the amplitude spectrum of the seismogram, $V(f)$ is the source velocity spectrum, $I(f)$ is the velocity response of the recording system, $F(r)$ is the geometrical spreading factor. The factor F can be considered to be frequency-independent for the narrow band of frequencies considered here. t is the travel time and Q is an average value over the path. There may be losses due to scattering by heterogeneities in the structure along the ray path. However, it is precisely this structure that is under investigation when seismic profiling is carried out, amplitude variations are part of the information gained from an experiment and they should be used in its interpretation. As these factors are unpredictable before the structure is known and as there may even be preferential transmission of some higher frequencies in certain structures, these factors may be ignored for the purposes of source comparison. Treating the sources as nearly monochromatic, we can deduce from Eq. (1) that the ratio R of the trace amplitudes generated for a given shot/station path is

$$R = \frac{A_1}{A_2} = \frac{V_1(f_1)}{V_2(f_2)} \exp\left[\frac{\pi t}{Q}\left(f_2 - f_1\right)\right]$$

Where A_1 and A_2 are the trace amplitudes generated in a particular phase by two sources of weight W_1 and W_2 which produce at optimum depth a dominant frequency of f_1 and f_2. The recording system velocity response is assumed constant in the frequency band including f_1 and f_2. Given that the peak value of the source velocity spectrum varies as $W^{0.47}$ we can write

$$R = \left(\frac{W_1}{W_2}\right)^{0.47} \exp\left(\frac{\pi t}{Q}\left(f_2 - f_1\right)\right] \quad (2)$$

f can be deduced from the charge weight W (in kilograms) using the relation (derived from Willis, 1941)

$$W = \left[\frac{d(d+10)^{\frac{5}{6}}}{803}\right]^3 \quad (3)$$

which gives d, the optimum depth in metres, and f is then given by $f = 380/\mathrm{d}$ where the assumed velocity of sound in water is 1520 metres/sec. Eq. (3) applies to TNT and if a different explosive is used, the equivalent weight in TNT should be calculated.

Use of the Dispersed Shot System in Practice

We can now consider a particular case. In the summer of 1974, an experiment to investigate the structure of the lithosphere in Britain (LISPB) was carried out. The maximum shot to station distance planned for this experiment was about 1000 km. The explosives available were in the form of Minol depth charges and these are equivalent to 0.2 tonne TNT. Depth charges are a convenient size to use in a dispersed charge pattern. They can be manhandled while larger charges demand power assistance with a consequent slowing down in the process of setting up the pattern

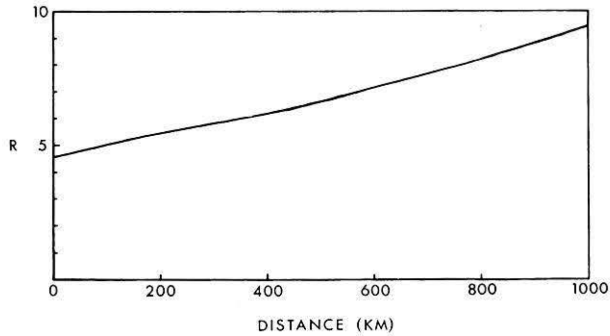

Fig. 4. Dominant period trace amplitude ratios between 5 tonne and 0.2 tonne TNT explosions (Q = 1000). Use of this diagram is explained in the text

and a more critical need for calm sea conditions. To produce useful seismograms out to a range of 1000 km one would normally use a charge of about 5 tonnes. We can use the equation (2) to calculate the relative seismogram amplitudes which would be generated by a 5 tonne and a 0.2 tonne charge if we calculate $f_1 = 2.16$ Hz and $f_2 = 3.97$ Hz and substitute values for Q and a travel time t appropriate to the distance at which we are making the comparison. At a distance of 1000 km, t is about 130 seconds for the first arrival and if we assume Q to be 1000, then R is found to be 9.5. This means that a dispersed shot with 10×0.2 tonne charges ($N = 10$) could be used to produce a signal 5% greater in amplitude than that produced by a 5 tonne shot. At a shorter range, Q has less effect, R is smaller, and the number of packages needed is correspondingly less. Fig. 4 shows how R and therefore, the required N will vary if we want to equal a 5 tonne shot at ranges between 0 and 1000 km. The LISPB experiment has only just finished but the indications are that the dispersed shots have produced signals out to the required range of about 1000 km.

While the dispersed charge system should be very effective in regions of reasonably high Q, there is no substitute for large single charges generating low frequency waves if the seismic work is to be carried out in, for instance, a low-Q volcanic area. In the case of LISPB it enabled us to bring the northern shot point well onto the shelf and nearer the Scottish mainland and in the south it enabled us to generate large seismic signals in an area where there is not enough depth of water to allow optimum depth firing of large charges.

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