RESEARCH COMMUNICATIONS

The yields of the Indian nuclear tests of 1998 and their relevance to Test Ban verification

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Indian scientists estimate the yield of the 11 May 1998 nuclear test at Pokhran as around 60 kt. Some of the assumptions made in making this estimate appear unjustified; for example, the assumption that interference between P waves from the two largest explosions in the test reduces the observed body-wave magnitude and that the NEIS estimate of surface wave magnitude is reliable. We show from a comparison of P amplitude observations at twelve common stations for the 11 May 1998 and 18 May 1974 tests that the maximum yield of the 1998 test is around 40 kt with the assumption that the yield of the 1974 test is 13 kt. However, one Indian estimate of the yield of the 1974 test is 8 kt, implying that the 1998 test has a maximum yield of around 25 kt. Our estimate of yield from surface waves is 15–20 kt. The evidence is then that the yield of the 1998 test is closer to 20 kt than the 60 kt obtained by Indian scientists. Even assuming however that the Indian yield estimate is correct the capacity of the International Monitoring System being set up to verify the Comprehensive Test Ban, should be sufficient for the System to act as a strong deterrent to any nation on the Indian Sub-continent and adjacent areas attempting to carry out a clandestine test.

Following its nuclear tests of 11 and 13 May 1998 (referred to here as 980511 and 980513 respectively) at the Pokhran test site, India announced that 980511 and 980513 respectively attempted to carry out a clandestine test. In a series of papers, Indian scientists derive from the body-wave magnitude, \( m_b \), and the failure of 980513 to be detected.

Seismological estimates of yield are most commonly derived from the body-wave magnitude, \( m_b \) (see footnote to Table 1). The relationship between \( m_b \) and yield \( (Y \text{ kt}) \) is assumed to be of the form:

\[
m_b = a + b \log_{10} Y,
\]

where \( a \) and \( b \) are constants. For most hard rock sites such as eastern Kazakhstan and Pokhran, \( b \) is usually assumed to be \( -0.75 \). (Wallace\(^6\) uses this value, Sikka et al.\(^1\) use 0.77.) The principal difference in the yield estimate of Sikka et al.\(^1\) and others is in the value of \( a \). Sikka et al.\(^1\) use 4.04 on the assumption that the yield of the first Indian test (18 May 1974 referred to below as 740518) was 13 kt. Wallace\(^6\) uses 4.45 on the assumption that \( a \) for Pokhran is the same as that of eastern Kazakhstan. Barker et al.\(^5\) use a different method which relies on matching of observed and theoretical spectra of the \( P \) waves.

Both Wallace\(^6\) and Sikka et al.\(^1\) take \( m_b \) for 980511 to be 5.2, the value published by the National Earthquake Information Service (NEIS). This gives 10 kt on the Wallace\(^6\) formula and 32 kt on that of Sikka et al.\(^1\). Sikka et al.\(^1\) however, argue that for 980511 the NEIS \( m_b \) is an underestimate because of interference between the \( P \) waves from the 43 kt and 12 kt explosions and that the unbiased estimate of \( m_b \) is 5.4, giving their yield of 58 kt.

According to Sikka et al.\(^1\), the 43 kt and 12 kt explosions were fired simultaneously in separate boreholes 1 km apart; the line joining the holes being oriented roughly E–W. For stations to the north (or south) of the test site the observed and theoretical spectra of the \( P \) waves.

Table I. Log \( A/T \) for the 18 May 1974 and 11 May 1998 Indian tests

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (°)</th>
<th>Azimuth (°)</th>
<th>Log ( A/T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYB</td>
<td>11.4</td>
<td>145</td>
<td>1.7</td>
</tr>
<tr>
<td>NUR</td>
<td>46.2</td>
<td>330</td>
<td>1.1</td>
</tr>
<tr>
<td>KEV</td>
<td>49.9</td>
<td>341</td>
<td>1.4</td>
</tr>
<tr>
<td>GRF</td>
<td>51.1</td>
<td>313</td>
<td>1.1</td>
</tr>
<tr>
<td>HFS</td>
<td>51.2</td>
<td>327</td>
<td>1.3</td>
</tr>
<tr>
<td>NBO/NB2</td>
<td>52.8</td>
<td>328</td>
<td>1.0</td>
</tr>
<tr>
<td>BNG/BGCA</td>
<td>55.5</td>
<td>256</td>
<td>1.6</td>
</tr>
<tr>
<td>LOR</td>
<td>56.0</td>
<td>310</td>
<td>0.9</td>
</tr>
<tr>
<td>EKA</td>
<td>59.7</td>
<td>372</td>
<td>0.7*</td>
</tr>
<tr>
<td>COL/OLA</td>
<td>83.4</td>
<td>16</td>
<td>1.1</td>
</tr>
<tr>
<td>PMR</td>
<td>85.8</td>
<td>18</td>
<td>1.0</td>
</tr>
<tr>
<td>YKA</td>
<td>90.7</td>
<td>3</td>
<td>0.8*</td>
</tr>
</tbody>
</table>

Average 1.14 1.51
Difference 0.37

\( m_b = \log_{10} A/T + B(\Delta, h) \), where \( B(\Delta, h) \) is a correction for distance \( \Delta \), of the station and depth \( h \) of the source. \( A \) is half the maximum peak-to-trench ground displacement in the first few seconds of the short-period (\( \sim 1 \text{ Hz} \)) P seismogram, and \( T \) is the corresponding period.

Log \( A/T \) measured as part of this study. The remaining observations for the 1974 explosion are from the ISC Bulletin and those for the 1998 explosion are from the NEIS. MOX reports log \( A/T \) from the 1974 and 1998 explosions as 0.0 and 1.4 respectively. This large difference suggests that one of these observations is incorrect so the observations from the station have been omitted from the calculation of the average differences in magnitude.

The log \( A/T \) reported to the NEIS for YKA is 1.2, whereas the value measured in this study is 1.5. Note that for the 1974 explosion the log \( A/T \) reported for YKC, which is very close to YKA, is 1.3.

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the $P$ signals from the two explosions arrive simultane-
ously and sum constructively, whereas on E–W azimuths
the signals are separated by some short-time interval and
thus sum destructively. This, they argue, biases the average
$m_b$ low by 0.2 magnitude units. However, at long range,
the maximum time-separation of the two signals is less
than 0.1s, so the frequency for optimum destructive inter-
ference is $> 5$ Hz, well above the dominant frequency
($1–2$ Hz) of the $P$ waves at most stations. Thus any effects
of destructive interference in the frequency band where $m_b$
is measured are negligible.

Nevertheless it could be argued that $m_b$ for explosions
at Pokhran is biased low relative to those of explosions of
the same yield at test sites of the Former Soviet Union
(FSU) because of differences in path effects. For example,
there is evidence that $P$ waves from earthquakes and
explosions in the south of the FSU, that follow paths that
pass under the mountain ranges and adjacent sedimentary
basins that lie to the north of India, are more strongly
attenuated than on average paths (see for example ref. 7).
Presumably then, $P$ waves travelling from Pokhran to
stations that lie on azimuths ranging from northwest
to north to northeast will be similarly attenuated and
so $m_b$ might be biased low. However, assuming that sta-
tions that lie on other azimuths, that is in those in southern
Africa and Australia, are not biased gives an estimate for
$m_b$ for 980511 of 5.2, the same as the NEIS estimate.

The yield estimate obtained by Sikka et al.\textsuperscript{1} is made on
the assumption that the estimate of $m_b$ for 740518 pub-
lished in the *Bulletin of the International Seismological
Centre*, and the NEIS estimate for 980511 have the same
baseline, even though they are determined using widely
different networks of stations. These differences in the
networks can be minimized by considering only observa-
tions from stations that recorded both explosions as is
done in Sikka et al.\textsuperscript{2}. Using eight stations that recorded
740518 and 980511, Sikka et al.\textsuperscript{2} obtain a difference in
$m_b$ of 0.45 m.u. (implying a yield for the 1998 test of
about 48 kt) or 0.5 m.u. (implying a yield for the 1998
test of 53 kt) when allowance is made for the assumed
interference effects. We have repeated the exercise using
magnitudes from twelve stations (and assuming no inter-
ference effects) and obtain a magnitude difference (Table 1)
of 0.37 m.u. implying a yield for 980511 of $\approx 40$ kt.

These results illustrate how sensitive the yield estimate
of 980511 is to assumptions on interference effects and
on the stations used. Further, yield estimates made from
comparisons of the 1974 and 1998 explosions depend
crucially on 13 kt for 740518 being the true yield. How-
ever, 13 kt is itself a seismological estimate based on
the surface wave magnitude, $M_s$, from one station, so the
uncertainty is large. ($M_s$ is calculated from the Rayleigh
surface waves from a seismic disturbance.) Nevertheless,
the estimate is supported by Marshall et al.\textsuperscript{2} who obtain
an estimate of 12 kt from $M_s$ from three stations. Further,
Chidambaram and Ramanna\textsuperscript{3} by combining seismological
and close-in observations of ground motion also estimate
the yield at 12 kt. However, P. K. Iyengar, BARC gives
the yield of 740518 as 8 kt ‘exactly as predicted’ (lecture
at Henry L. Stimson Center, Washington reported in ref.
10). This implies that 980511 has an yield of only $\approx 25$ kt,
much closer to the estimates of Barker et al.\textsuperscript{3} and Wallace\textsuperscript{4}.

Another point to be considered is the depth of the
explosions. The 1974 explosion was fired at shallow
depths (107 m) above the water table in dry sandstone and
shale\textsuperscript{5}. As the largest of the 1998 explosions was
apparently expected to have a yield of 43 kt, it was pre-
sumably fired much deeper than that of 1974 to ensure
that the radioactivity is contained. Thus, the 1998 explo-
sion was probably fired in water-saturated rocks. If this is
so, then for a given yield, explosions in water-saturated
rocks have higher magnitudes than those fired in dry
porous rocks, the larger magnitude of 980511 compared
to 740518 may be due at least in part to the differences in
water content of the rocks in which the nuclear devices
were emplaced. The estimate of $\approx 25$ kt derived above
may then still be too high.

Sikka et al.\textsuperscript{2} find that as with $m_b$, the yield from $M_s$
(3.62) is 58 kt; $M_s$ being determined from observations at
three stations in India in the distance range 2–17°, and
two outside India (reported by the NEIS) in the range
50–59°. If $M_s$ was 3.62 then it would certainly imply that
the 980511 yield is much larger than the 12 kt of Barker
et al.\textsuperscript{2} and Wallace\textsuperscript{4}. However, our estimate of $M_s$
from observations at Nilore, Pakistan (NIL) and Xi’an, China
(XAN) is 3.2, implying an yield of 15–20 kt, consistent
with the non-Indian estimates from $m_b$. One possible
explanation of the high estimate of Sikka et al.\textsuperscript{2} is that
$M_s$ for stations in India are biased high because their
distances are less than 20° and the conventional magni-
tude scale does not correctly account for the effects
of propagation at such distances\textsuperscript{11}. Further, it seems
unlikely the NEIS estimates of $M_s$ are for the 980511 test.
Had $M_s$ been so large, surface waves would have been
detected more widely than they were. The observations
reported to the NEIS are surface waves from earthquakes
and just fortuitously arrived at the recording stations at
about the expected time of those from the Indian explo-
sion. Analysis of the surface waves from Kevo, Finland
associated in the NEIS report with 980511 shows that the
waves are arriving at the station from the north, and are in
fact from an earthquake north of Svalbard. Had the waves
been from 980511 they should have arrived at Kevo from
the south east.

Our conclusion is that there is no significant evidence
from body and surface wave magnitudes that the yield of
980511 was nearly 60 kt. A case can be made from $m_b$
for the yield being about 40 kt but only if the true yield
of 740518 was close to 13 kt and the coupling between
explosion and surrounding rock is the same for both the
1974 and 1998 tests. Roy et al.\textsuperscript{5} and Sikka et al.\textsuperscript{1} also
make estimates of yield from Lg using seismograms recorded at stations within India. We intend to carry out a similar study once we have been able to obtain digital files of the seismograms from these in-country stations.

Sikka et al.\(^2\) argue that many of the assumptions made by others in estimating the yield of 980511 are incorrect and that without the availability of ‘close-in ground motion measurements, radiochemical methods, calibration events and hydrodynamic shock measurements’ together with ‘knowledge of the surroundings of the device’ any estimates other than those by scientists involved in the test ‘will be not just highly subjective but erroneous’. If Sikka et al.\(^1,2\) have so little confidence in such methods – and we agree that yields estimated by seismological methods are subject to large uncertainties – it is not clear why they have gone to such lengths to obtain so precise a seismological estimate of yield. The only close-in information that Sikka et al.\(^1,2\) seem to have used in estimating the yield seismologically is the relative positions of the three explosions in the 980511 test and we suggest above that the spatial separation of the explosions has a negligible effect on seismic magnitude. The close-in information that might enable non-Indian scientists to improve their yield estimates is: the depth of firing of the explosions; the firing medium; and the water content of the medium, but none of this information seems to have been released.

The failure of Barker et al.\(^5\) and Wallace\(^6\) to obtain a yield estimate close to that of Sikka et al.\(^1,2\) for 980511, or of any stations outside India to detect 980513 leads Sikka et al.\(^7\) to express doubts as to whether the Comprehensive Test Ban (CTB) can be verified effectively. However, even accepting that the yield of 980511 was around 60 kt it still implies that a 1 kt explosion at Pokhran will have a magnitude around \(m_{\text{b}} 4\) and it is expected that the International Monitoring System (IMS) being set up to verify the CTB will, when completed, have a threshold at long range below this magnitude, so that sub-kiloton tests at the site should be detected and recognized as possible explosions. Extrapolating from the amplitudes observed from 980511 supports the view that signals 20 times smaller (equivalent to a yield ratio of 60) would be detected in Canada. (Of course if the true yield of 980511 was close to the non-Indian estimates of ~ 12 kt, very low yield explosions at Pokhran should be detectable at long range.)

The failure of existing stations – particularly the seismological station at Nilore, Pakistan – to detect 980513 which India claims had a total yield of 0.8 kt is then a puzzle. The only possible explanations seem to be that either the yield was much lower than expected or that the explosions were fired in dry, porous material or both. It would be useful to have some seismograms of signals from the explosion from within India to make an estimate of the range of possible yields assuming best- and worst-case coupling. The failure of the Nilore station to detect the signal leads Barker et al.\(^5\) to assume low coupling, to put an upper bound on yield of 300 tons.

If the reason the seismic signals from 980513 are weak is that the explosions were fired in dry, porous material then the relevance of this test to CTB verification is marginal. Anyone trying to carry out a clandestine test in violation of the treaty has to bury the device much deeper than for simple containment to ensure it produces no surface effects that would be visible from a satellite and that there is no escape of radioactive particulates or noble gases which could be detected by radionuclide sensors. This will usually mean that any such explosion will be in water-saturated, consolidated rock which leads to good coupling between the explosion and the surrounding material, and the efficient generation of seismic waves.

Currently the IMS is incomplete; eventually the System will comprise four networks of sensors (seismic, acoustic, hydroacoustic and radionuclide) a total of 321 stations, and were India to sign the Treaty presumably there would be at least a station of the seismological network within that country. It is also to be hoped that recordings from the seismological stations within India would be made available to organizations verifying compliance with the Treaty. All this should act as a strong deterrent to any nation on the Indian Sub-continent and in adjacent areas, attempting to carry out a clandestine test.


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