CHAPTER III

VELOCITY DISTRIBUTION

3.1 Methods

The classical method of construction of velocity distribution is the Herglotz-Wiechert-Bateman (H.W.B) integral method of inversion of $P(\triangle)$ function. As mentioned earlier, a monotonically decreasing continuous function of $p(\triangle)$ yields a velocity distribution in a straightforward manner. An alternative method due to Bullen (1960) is based on $T-\triangle$ curve. According to this method if the travel time curve can be represented by a polynomial of the form

$$T = a \triangle - b \triangle^3$$

(6)

the seismic velocity inside the mantle can be represented by

$$v = AT^c$$

(7)

where, $a$, $b$, $c$ are constants.

In particular when $\alpha$ and $\varphi$ are constants the velocity is given by

$$v = v_0 \left( \frac{r}{r_0} \right)^{\varphi_0}$$

(8)
where the quantities defined as

\[ \xi = \frac{d\log v}{d\log r} ; \quad \lambda = \frac{2}{1 - \xi} ; \quad \eta = \frac{r}{v} \]

\( v_0 \) denotes velocity corresponding to \( r_0 \), the radius of the earth. With constant \( \alpha \) and \( \xi \)

\[ p = \frac{dT}{d\Delta} = \eta_0 \cos \left( \frac{\Delta}{\alpha_0} \right) \]

\[ T = \eta_0 \alpha_0 \sin \left( \frac{\Delta}{\alpha_0} \right) \]  

\( \eta_0 \) and \( \alpha_0 \) can be determined as first approximation from the experimental data. The relation (6) however, is only an approximate one the departure being representable by a correction term of the form \( \text{e}^{-4} \). Bullen developed the methods by adding corrections to \( \alpha_0, \, (r/r_0) \) etc. and construct velocity-depth profile subsequently. This method is, therefore, applicable for regions where \( T \) obeys relation (6). However, it fails for \( \xi > 1 \).

Gradier determined velocities inside the mantle by considering it to be consisting of eight concentric layers of constant velocity increasing in steps. Boundary of these layers are indicated by the breaks in travel time curves obtained from nuclear explosion in the pacific region. His method essentially consists of calculating \( T \) and \( \Delta \) values by assigning values of velocities and radius of the layers at their top in succession, starting from the surface of the earth, using basic principles of ray-theory. These are matched with the observed values,
Dowling and Nuttli (1964) studied the possibility of low velocity channel evidenced by Shadow zone by calculating T and \( \Delta \) values and matching them with observed ones by iterative process. For that they summed the series

\[
\Delta = 2 \sum \frac{p \left( r_i - r_{i+1} \right)}{r_i \sqrt{\left( \frac{r_i}{v_i} \right)^2 - p^2}} \\
T = 2 \sum \frac{r_i \left( r_i - r_{i+1} \right)}{v_i^2 \sqrt{\left( \frac{r_i}{v_i} \right)^2 - p^2}}.
\]

which replaced the corresponding integrals. \( r_i, v_i \) denote the radius and velocities of the ith layer respectively, p and r are the ray-parameter and radius corresponding to the depth of penetration of the ray emerging at epicentral distance \( \Delta \).

Taking comparatively larger number of layers, and assigning values of velocity from a simple velocity model and adjusting them particularly for suspected anomalous regions, their presence could be explored by trial and error method.

Julian et al. (1973) and Sengupta et al. (1978) have used perturbation methods coupled with least square fitting to obtain good match between observed and calculated travel times for different earth models.

Despite these special techniques for determination of velocity, Herglotz-Wiechert-Bateman integral method remains the basic and versatile one.
This method is applicable if the velocity gradients $dv/dr$ in the medium satisfy the following conditions (Macelwane, 1932)

(i) $dv/dr$ is negative (velocity increases with depth)
(ii) $dv/dr$ is positive (velocity decreases with depth), but numerically less than $v/r$.

If in any zone occurs, in which this criterion is not met, which are often called anomalous zones, special considerations are needed to elicit the necessary informations in such cases. One of them is that, if the anomalous zones are not very wide they can be assumed as discontinuities for all practical purposes. H.W.B method then can be applied in the regions above and below these discontinuities provided the above conditions are satisfied in those regions.

3.2 Herglotz-Wiechert-Batemann Integral

The Herglotz-Wiechert-Batemann integral gives

$$
\ln \frac{r_o}{r_j} = \frac{1}{\pi} \int_0^{\Delta} \cosh^{-1} \left( \frac{b}{r_j} \right) d\Delta
$$

$$
= \frac{1}{\pi} I_j \quad (\text{say})
$$

where $r_j =$ radius of the earth corresponding to the lowest depth attained by a ray emerging at epicentral distance $\Delta$ , $r_o =$ radius of the earth.
\[ p = \frac{dT}{d\Delta} \]  
ray parameter

\[ \eta_j = \frac{T_j}{v_j} \]

\( \varphi (\Delta) \) is a function of \( \Delta \) and \( \eta_j \) is its value at \( \Delta_j \).

The velocity at the level corresponding to \( r_j \) is then given by

\[ v_j = (\frac{v_o}{r_0}) r_j \quad (12) \]

\( v_o \) = apparent velocity at \( r = r_0 \), i.e., the surface of the earth.

The integrand function of (11) is replaced by

\[ \cosh^{-1}\left( \frac{p}{\eta_j} \right) = \ln\left\{ \frac{p}{\eta_j} + \sqrt{\left(\frac{p}{\eta_j}\right)^2 - 1} \right\} \quad (13) \]

and it is a direct consequence from above that for the method to be valid \( p/\eta_j \) should be greater than unity, otherwise the quantity under the radical sign becomes imaginary. Hence for the applicability of this method \( p(\Delta) \) should be a monotonically decreasing function. The other condition is that \( dv/dr \) may be positive but should be less than \( v/r \) numerically.

In the present analysis the \((p-\Delta)\) profiles are represented by straight line segments with negative gradient and the width of the breaks are reduced to a line. Therefore, H.W.B. integral method is applicable on both sides of the probable zones of anomalous velocity, appearing as discontinuities. Thus, calculating the integral \( I_j \) for some suitably chosen \( \Delta \) values upto the ray touching the next discontinuity (bottom of the upper layer), corresponding to the last value of \( p \) of
each segment in the \((p-\Delta)\) profile. The velocity \(v_j\) can be calculated. The earth may then be stripped of the layer, and the process carried on successively.

3.3 Stripping of the Earth and Reduced Values of \(\Delta\)

In fig. 5(a) ACDA\(_\perp\) represents a seismic ray passing through two layers, emerging at epicentral distance \(\Delta\). The ray meets the boundary of the lower layer at an angle \(\theta\) from below and is refracted to the top layer with angle \(\phi\).

From Snell's law, we have

\[
\frac{\sin \phi}{\sin \theta} = \frac{\overline{v}}{\overline{v}_r} \tag{14}
\]

where \(\overline{v}\) = average velocity in the upper layer
\(\overline{v}_r\) = average velocity in the lower layer

Also from 5(b), by Bendorff's law (Machelwane, 1932),

\[
\sin \theta = \frac{\overline{v}_r}{v_a} \tag{15}
\]

\(v_a\) = apparent velocity on the layer as observed from the slope of \((T-\Delta)\) curve

\[
= \frac{d\Delta}{dT} \text{ in degree/sec}
\]

\[
= \left(\frac{180 \pi}{\overline{v}_a}\right) \frac{1}{\overline{v}_a} \text{ in km/sec} \tag{16}
\]
\[ p_2 = \text{ray parameter of the ray emerging at epicentral distance} \]

\[ r_0 = \text{radius of the earth}. \]

Combining (14), (15) and (16)

\[ \sin \phi = \left( \frac{180}{\pi r_0} \right) \cdot \vec{v} \cdot p_2 \]  

(17)

Now stripping the earth of the upper layer would mean to consider the rays to originate and emerge on the top of the second layer, assigning the different parameters with respect to this surface. In this case, the new epicentral distance \( \Delta r \) is the relevant parameter to be used in the integral (11).

In fig. 5(a) \( CD \) is the segment cut off by the ray on the surface of the stripped earth. This would give an epicentral distance with respect to the stripped earth radius. However, since the p-values are observed on the earth's surface, this is to be referred to the earth's surface.

The projection of \( CD \) from the interior centre to the surface of the earth, \( BB_1 \) divided by the radius \( r_0 \) is, therefore, taken as the reduced epicentral distance.

Now,

\[ \partial \chi = B_1 A_1 = d \tan \phi \]  

(18)

approximately being exact for flat earth

where \( d = \text{thickness of the layer} \).

Reduction in the value of epicentral distance = \[ \frac{\partial \chi}{r_0} \]
Assuming the rays to be symmetrical about the central radius passing through the lowest point touched by the ray this is to be doubled. Hence the total reduction in epicentral distance is given by

$$\Delta = \frac{360}{\pi r^2} d \tan \theta \text{ (in degree)}$$

(19)

The difference \( \Delta_r = \Delta - \Delta \), is then the reduced epicentral distance. The values of \( \theta \) for the different rays characterised by the \( p \)-values are given by (14) and a new set of \( \Delta_r \) values are obtained, which are utilized in evaluating the integral (11). The average velocity of the upper most layer \( v \) is calculated in accordance with the derivation given in Appendix I. For subsequent layers the process is repeated.

Since the velocity distribution in this study is restricted to the part of the mantle below the maximum depth of penetration of a ray emerging around 30° epicentral distance, a velocity distribution model is to be assumed for the layer from the surface of the earth to the depth corresponding to the first epicentral distance considered for each profile. Here Herrin's (Herrin, 1968) model of velocity distribution with depth is taken for this layer for each profile.

In this study, quite a few number of discontinuities (anomalous zones) had to be assumed and therefore, stripping had to be carried out successively. In that case all the upper layers together are taken as one layer and average velocity is calculated each time. The thickness of each layer is obtained
from the integral equation (11) corresponding to the end point of each \((p-\Delta)\) segment.

The various steps involved in the computation of reduced epicentral distance, \(\Delta_r\), for the first layer of Eastern Kazakh profile, after stripping off, of the 760 km thick layer above it, is given in Table 3 as an example of the procedure adopted here.

3.4 Velocity Depth Distribution

To find the maximum depth of penetration, the integral (11) is replaced by a sum to facilitate numerical integration as given below

\[
I_j = \sum_{j=1}^{j-1} q_j \, d(\Delta_j) + \frac{1}{2} \sum_{j=1}^{j} (q_j - q_{j-1}) \, d(\Delta_j)
\]  

(20)

where,

\[
q_j = \cosh^{-1} \left( \frac{p_j}{p_{j-1}} \right) = \ln \left( \frac{p_{j-1} + \sqrt{(p_{j-1})^2 + 4 \Delta_j^2}}{2 \Delta_j} \right)
\]

and the interval

\[
\Delta_j = \Delta_j - \Delta_{j-1}
\]

In view of the reduced \(\Delta_r\) values, the original constant interval (0.5 degree) will also be changed and vary from point to point.
Table 3

Reduced epicentral distance $\Delta r$ for first stripping, for the $(p-\Delta)$ profile of Eastern Kazakh.

Here $d = 760$ km, taken from Herrin's seismological table corresponding to $29.5^\circ$ epicentral distance.

$\bar{v} = 9.89$ km/sec, calculated using Appendix I.

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Finally taking $r_0 = 6371$ km in equation (12), the velocity $v_j$ becomes

$$v_j = 0.01745 \frac{r_j}{p_j}$$

(21)

The velocities have been calculated at interval of 0.5 degrees and finally interpolated at 25 km depth interval. Figs. 6(a), (b) and (c) represent the velocity depth profiles obtained for the sources at the three regions - Eastern Kazakh, Nevada and Novaya Zemlya. For comparison Herrin's profile is also reproduced along with each profile. The velocity depth distributions for each source region are enlisted in Table 4.
FIG. 6 Velocity distribution with depth in the mantle below 700 km for sources in (a) Eastern Kazakh, (b) Novaya Zemlya and (c) Nevada. The dashed line represents velocity distribution with depth due to Herrin. (d) Average velocities.
Table 4

Velocity-depth distribution in the mantle below 700 km
for sources at different sites

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<th>Depth (km)</th>
<th>Eastern Kazakh (km/sec)</th>
<th>Novaya Zemlya (km/sec)</th>
<th>Nevada (km/sec)</th>
<th>Average (km/sec)</th>
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(Table 4 continued)

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*The velocities below the depth of 2350 km represents average of the velocities for sources at Eastern Kazakh and Novaya Zemlya only.