Chapter IX. Earthquake motion propagated along the major arc and the repetition of the motion propagated along the minor arc. General remarks on the propagation velocity.

W_2 MOTION, OR THE EARTHQUAKE PROPAGATED ALONG THE MAJOR ARC.

135. ***Observation at Calcutta and Bombay.*** Let us first consider the Milne horizontal pendulum observation of the W_2 wave, or the earthquake motion propagated along the major arc, at the two Indian stations of Alipore (Calcutta) and Colaba (Bombay), whose distances from the epicentre of the Kangra earthquake were only 13° 42′ and 13° 32′ respectively.

(***i***) *Alipore* (Calcutta). The preliminary tremor lasted $3^m 24^s$, the motion being largest for the first 29^m of the principal portion.

W_2 began at $3^h\ 57^m\ 30^s$, or $3^h\ 5^m\ 30^s$ after the commencement of the earthquake disturbance there, the 1st maximum group lasting for about 20^m:—$2a = 1.6$ mm (actual reading). The principal maximum group occurred 14^m later on.

(***ii***) *Colaba* (Bombay). The preliminary tremor lasted $3^m 31^s$, the motion being greatest for the first $18\frac{1}{2}^m$ of the principal portion.

W_2 began at $4^h\ 17^m$, or $3^h\ 23^m\ 52^s$ after the commencement of the earthquake disturbance there; the max. group ($2a = 0.6$ mm, actual reading) occurring at $4^h\ 24^m$. The motion lasted altogether for about 32^m, the last slight max. group in this portion possibly belonging to the W_3 motion.

Taking the average from the Alipore and Colaba observations, we obtain:—Time interval between the commencement of the principal portion and that of the W_2 motion $= 3^h\ 14^m\ 41^s$, the corresponding epicentral distance being 13° 37′. In the cases of these two stations, the W_2 recorded by the seismographs seems to be the 3rd phase of the principal portion of the major arc propagation; the time interval above obtained being nearly equal to the time required by the wave of that phase in making one complete circuit of the earth. Thus, if the velocity (v_5) of the 3rd phase of the principal portion be assumed to be 3.2 km/sec., we have:—

$$\varDelta t_5 = \frac{s-2x}{v_5} = 201.7^{\text{min.}} - 0.01008\, x^{\text{km}},$$

in which s denotes the length of the earth's circumference, x the epicentral distance of a given station, and $\varDelta t_5$ the interval between the times of arrival at the latter of the phase under consideration along the minor and the major arcs. The maximum value of $\varDelta t_5$, corresponding to $x=0$, is according to the above formula, about $3^{\text{h}}\ 21.^{\text{m}}7$.

136. ***British Stations.*** As shown later on, there are, in the W_2 motion, two predominating sets of vibrations whose periods are approximately equal to P_5 (=about 20 sec.) and P_6 (=about 25 sec.) respectively; the P_5 vibrations occurring earlier than P_6 ones. Thus it is to be readily understood that the record of the W_2 motion differs much according to the oscillation period of the "steady mass" of the seismograph. This circumstance is well illustrated by the Milne horizontal pendulum seismograms obtained at the British stations. (See §§ 67—71.)

Shide records. The maximum part of W_2 in the C-pendulum record began just at the termination of that in the B-pendulum one. As the natural oscillation period of the C-pendulum was 20 sec., while that of the B-pendulum was 25 sec., this shows that, in the W_2 motion, the vibrations of period of about 25 sec. occurred earlier than those of about 20 sec.

Edinburgh record. The W_2 motion began later than the appearance of the maximum group, marked g, in Shide records. This was probably due to the shortness of the pendulum period of the Edinburgh instrument.

Kew record. The first max. group in the W_2 motion corresponds to that marked e in the Shide C-pendulum record, which occurred at 3^h 36.4^m. The 2nd max. group, which began at 3^h 49^m, corresponds to that marked g in the Edinburgh record.

Liverpool record. The max. group corresponds to the group e in the Shide C-pendulum record.

Paisley record. The record was nearly similar to that for Liverpool. (See Pls. XVIII and XIX, the *Publications*, No. 23.)

137. *Querce.* As an illustration of the identification of the corresponding epochs in the movements propagated along the minor and major arcs, I shall here briefly consider the observation at Querce. (See § 34). The W_2 motion in the NE-SW component is much smaller than that in the NW-SE component. The latter component may be summarized as follows :—

Earthquake Commencement$=0^h$ 59^m 8^s.

(*a*) 1^h 6^m 24^s......Commencement of 2nd preliminary tremor.
(*b*) 1 20 09 ...... „ 3rd phase of princ. portion.
(*c*) 1 39 07 ......Motion active.
(*d*) 1 28 56 ......Greatest max. group of pendulum oscillation.
(*e*) 1 39 07—2^h 1^m 7^s......Motion more or less active.
(*f*) 3 10 50 ......Commencement of the W_2 motion.
(*g*) 3 28 12 ......Motion became larger, $2a=0.12$ mm.
(*h*) 3 43 19 ...... „ increased, $2a=0.14$ mm.
(*i*) 3 47 50 ...... „ most active, $2a=0.27$ mm.
(*j*) 3 57 14 ......End of motion.

Let us, for the sake of trial, suppose that (i) of the W_2

motion corresponds to (d) of the W_1 motion, or the earthquake proper; (f) and (b) being also supposed to be corresponding vibrations. On these assumptions we have:—

(i)	$3^h\ 47^m\ 50^s$	(d)	$1^h\ 28^m\ 56^s$
(f)	$3\ \ 10\ \ 50$	(b)	$1\ \ 20\ \ 09$
Difference =	$37^m\ 00^s$	Difference =	$8^m\ 47$

Therefore:
$$\frac{(i)-(f)}{(d)-(b)}=\frac{37^m\ 00^s}{8^m\ 47^s}=4.2 \ldots\ldots\ldots\ldots (1)$$

This number, being, under our supposition, the ratio of the duration of the 3rd phase of the principal portion in the W_2 motion to that in the W_1, ought to be approximately equal to the ratio of the major to the minor arc of the earth between Florence and the earthquake origin, as the duration of a given phase of the motion increases nearly in proportion to the distance. We have:—

$$\frac{\text{major arc}}{\text{minor arc}}=\frac{308°\ 06'}{51°\ 54'}=5.2 \ldots\ldots\ldots\ldots (2)$$

which ratio may be regarded as being sufficiently near to that of the durations previously obtained, in view of the very approximate nature of the discussion in question. As the ratio in (1), however, is greater than that in (2), it is perhaps better to regard (f) as corresponding to some epoch in the 2nd phase of the principal portion.

138. ***Tacubaya, Cheltenham, and Washington.*** As examples of the combination of the observations relating to the W_2 motion, at two or more neighbouring stations, let us next compare the Tacubaya, Cheltenham, and Washington records.

(*i*) *Comparison of EW Component Seismograms.*

TABLE XL. Times of Commencement of the different Phases of motion at Tacubaya and Cheltenham.

Phase of motion	Tacubaya.	Cheltenham.	Time difference:— Tacubaya— Cheltenham.
	h m s	h m s	m s
1st Prel. Tremor.	1 11 25	1 8 39	+ 2 46
2nd Prel. Tremor.	1 28 3	1 23 21	+ 4 42
1st Phase, Princ. Portion.	1 43 45	1 35 35	+ 8 10
2nd Phase, Princ. Portion.	1 50 27	1 39 28	+10 59
Do.	1 53 30	1 42 30	+11 0
3rd Phase, Princ. Portion.	2 1 49	1 49 12	+12 37
W_2: Max. Phase.	2 43 46	2 58 19	−14 33

The EW component seismograms obtained at Tacubaya and Cheltenham enable us to make a fairly accurate comparison of the times of commencement of the different phases of motion at these two places. As the arcual distances of Tacubaya and Cheltenham from the centre of the earthquake disturbance are 128° 47′ and 105° 22′ respectively, the vibrations propagated along the minor arcs of the earth ought to reach the latter place earlier than the former, the reverse being the case with those propagated along the major arcs, or the W_2 waves. Now, according to the preceding table, the time-difference of arrival at Tacubaya and Cheltenham was $2^m 46^s$ for the commencement of the 1st preliminary tremor, thence gradually increasing up to $12^m 37^s$ for the 3rd phase of the principal portion. The time difference might be greater for the later phases of the same portion, but the further identification was not possible. For the maximum phase of the W_2 motion, the corresponding difference comes out, as ought to be, negative and amounted to $14^m 33^s$.

(*ii*) *Calculation of the Transit Velocity from the seismographic records at any two places.* From the seismographic records taken at any two places at different distances from the earthquake origin, we can accurately calculate the transit velocity of the 3rd phase of the principal portion, by comparing it with the most active part in the W_2 motion, even when the clock indication at each place is slightly wrong. Thus let τ_1 denote the difference in the times of arrival at the two given stations of the 3rd phase of the principal portion of the seismic waves propagated along the minor arcs, and $(-\tau_2)$ the corresponding quantity for the waves propagated along the major arcs. If the clock indications at the two places be perfectly accurate, τ_1 ought to be equal to τ_2, supposing the identifications of the W_1 and W_2 waves to be correct. Let $\delta\tau$ be the *relative* clock correction to be applied to τ_1 and τ_2 necessary for getting the true time differences. We then have :—

$$\begin{cases} \delta\tau = -\dfrac{\tau_1 - \tau_2}{2}; \\ v_5 = \dfrac{2\delta x}{\tau_1 + \tau_2}; \end{cases}$$

where v_5 denotes the velocity of propagation of the 3rd phase of the principal portion, and δx is the difference between the arcual distances from the earthquake origin of the two given stations.

To apply the above equations to the cases of Tacubaya and Cheltenham, we have :

$$\begin{cases} \delta x = 128^\circ\ 47' - 105^\circ\ 22' = 23^\circ\ 25' \\ \tau_1 = 12^m\ 37^s \\ -\tau_2 = -14^m\ 33^s \end{cases}$$

We find therefore :—

$$\begin{cases} \delta\tau = +58 \text{ sec.} \\ v_5 = 3.17 \text{ km per sec.} \end{cases}$$

Using this time correction, we may calculate the velocities of the different phases of the earthquake motion from the time differences between Tacubaya and Cheltenham, given in the preceding table, as follows :—

$$\left\{\begin{array}{l} v_1=\dfrac{23^\circ\ 25'}{(2^{\mathrm{m}}\ 46^{\mathrm{s}})+58^{\mathrm{s}}}=11.5\ \mathrm{km/sec.} \\ v_2=\dfrac{23^\circ\ 25'}{4^{\mathrm{m}}\ 42^{\mathrm{s}}+58^{\mathrm{s}}}=7.6 \\ v_3=\dfrac{23^\circ\ 25'}{8^{\mathrm{m}}\ 10^{\mathrm{s}}+58^{\mathrm{s}}}=4.7 \\ v_4=\dfrac{23^\circ\ 25'}{10^{\mathrm{m}}\ 59^{\mathrm{s}}+58^{\mathrm{s}}}=3.6 \end{array}\right.$$

These values of the velocities agree very well with those given in a later §.

(*iii*) *Comparison of NS Component Seismograms.*

TABLE XLI. Times of Commencement of the different Phases of motion at Cheltenham, Washington, Tacubaya.

Phase of motion.	Cheltenham.	Washington.	Tacubaya.	Time Difference: Tacubaya—(Chelt. & Wash.)
	h m s	h m s	h m s	m s
1st Preliminary Tremor.	1 8 38	1 8 25	1 11 25	+ 2 53
2nd " "	1 23 23	1 23 27		
1st Ph., Princ. Portion.	1 35 39	1 35 36		
3rd Ph., Princ. Portion.	1 51 10	1 51 16		
Max. Motion, in the above phase.	1 52 15	1 52 39	2 11 18	+ 18 51
4th Ph., Princ. Portion.	2 3 2	—		
W_2 (commencement)	—	2 27 28		
W_2 (principal portion)	2 51 27	2 52 30		
W_2 (most distinct part.)	—	2 58 43	2 48 25	−10 18

The arcual distances of Cheltenham and Washington from the earthquake origin are nearly equal to one another, being respectively 105° 22′ and 105° 17′. It is, therefore, not possible to make any calculation based on the time differences for these two places. Table XLI shows, however, that the times of arrival of the different phases of the seismic motion at these two stations were practically identical. Taking means from the two seismograms, we find :—

Cheltenham, Washington.	1st preliminary tremor.	1ʰ 8ᵐ 32ˢ
	2nd „ „	1 23 25
	1st phase, principal portion.	1 35 38
Mean epicentral distance. =105° 20′	3rd „ , „	1 51 13
	Max. in the 3rd phase.	1 52 27
	Principal portion in W_2	2 51 59

Taking the average from Tables XL and XLI, we have :— Difference between the times of occurrence at Tacubaya and two American stations of the most active part of the W_2 motion= $12^m 26^s$; the corresponding propagation velocity is, using the same clock correction before found.

$$v_5 = \frac{23° 27'}{12^m 26^s + 58^s} = 3.23 \text{ km/sec.}$$

139. ***Tokyo Observation.*** To identify the corresponding vibrations in the three components, I give in the following table the time of commencement, $2a$, and T, of the successive epochs in the records furnished by the two long-period horizontal pendulums and the vertical motion instrument. (See § § 14 to 20.)

Epoch.	EW Component.			NS Component.			Vertical Component.		
	Time of occurrence.	$2a$	T	Time of occurrence.	$2a$	T	Time of occurrence.	$2a$	T
	h m s	mm	sec	h m s	mm	sec	h m s	mm	sec
A (Beginning of 2nd P. T.)	1 06 25	{2.5 {5.8	36.4 49.7	1 06 25	{2.33 {3.95	11.6 46.0	1 06 25	—	—
B	1 11 05	4.50	37.7	1 10 28	3.53	43.7	—	—	—
C (Beginning of 2nd Ph., P.P.)	1 15 44	1.08	53.0	1 16 15	3.50	42.5	1 16 45	0.07	45.2
D (Beginning of 3rd Ph., P.P.)	1 20 34	6.24	27.6	(Pointer went out)	—	—	1 20 31	0.28	29.7
E	1 22 24	2.40	16.8				1 22 00	0.13	22.3
F	1 23 31	3.67	10.3	—	—	—	1 23 07	0.29	14.7
G	—	—	—	1 27 02	1.70	10.3	—	—	—
H (Beginning of W_2)	—	—	—	2 43 37	0.10	45.0	—	—	—
I	3 15 08	0.067	30.0	—	—	—	—	—	—
J	—	—	—	3 21 17	Small	Slow.	—	—	—
K (1st Max. of W_2).	3 24 31	0.13	24.3	3 25 17	0.10	25.4	—	—	—
L (2nd Max: 3rd Ph., P.P. of W_2).	3 33 37	0.19	19.4	—	—	—	3 33 22	Small	—
M	—	—	—	3 36 30	0.12	19.5	3 37 31	,,	19.5
N	4 24 52	Small	44.0	—	—	—	—	—	—

(*H*) and (*L*) in the foregoing table seem to correspond respectively to the commencement of the 1st phase and the commencement of the 3rd phase, of the principal portion of the W_2 motion. (For the identification of (*L*), or the 2nd max. group of W_2, the reader is also referred to § 141.) According to this supposition, we obtain, by taking the means from the three components, the following value of the duration($=y_{3.4}$) of the 1st and 2nd phases of W_2:—

(*L*) .... $3^h 33^m 30^s$
(*H*) 2 43 37

Difference $= y_{3.4} = 49^m 53^s$

As the duration ($y_{3,4}$) of the 1st and 2nd phases of the principal portion of the W_1 motion or the earthquake proper was $7^m\ 21^s$ (§ 20), we have

$$\frac{y_{3,4}\ (W_2)}{y_{3,4}\ (W_1)}=\frac{49^m\ 53^s}{7^m\ 21^s}=6.8.$$

This ratio is not much different from the ratio of the major and minor arcs between Tokyo and the earthquake origin, namely,

$$\frac{308°\ 34'}{51°\ 26'}=6.0.$$

Again, the velocity (v_5) of propagation of the 3rd phase of the principal portion may be deduced from the comparison of the W_1 and W_2 vibrations, as follows :—

$$v_5=\frac{360°-(2\times 51°\ 26')}{3^h\ 33^m\ 30^s-1^h\ 20^m\ 33^s}=3.58 \text{ km per sec.}$$

140. ***Osaka Observation.*** (See § 22). The period of the principal vibrations in the most active part of the W_2 motion was 18.5 sec., while those in the preceding phase were 25.1 and 20.4 sec.; the vibrations with periods similar to one or both of these latter occurring in the 1st and 2nd preliminary tremors, and the 1st, 2nd, and 4th phases of the principal portion, of the W_1 motion, or the earthquake proper. The diagram did not indicate, in the 3rd phase of the principal portion, the vibrations with a period of exactly 18.5 sec.; but it is likely that the existence of such movements there was masked by large proper pendulum oscillations which partly confused the record.

The times of occurrence of the first feeble and the most active parts in the W_2 motion, denoted by t_4' and t_5' were respectively as follows :—

$$t_4'=3^h\ 22^m\ 30^s, \quad t_5'=3^h\ 40^m\ 56^s;$$

the time difference, $t_5'-t_4'$, being $18^m 26^s$. t_4' and t_5' may probably be taken as marking approximately the commencements respectively of the 2nd and 3rd phases of the principal portion of the W_2 motion; the corresponding times in the earthquake proper (W_1), denoted by t_4 and t_5, being respectively

$$t_4=1^h\,16^m\,51^s \text{ (approximate)}, \quad t_5=1^h\,20^m\,9^s;$$

The difference, t_5-t_4, is $3^m\,18^s$.

Now the arcual distances between Osaka and the earthquake origin are as follows:—

$$\begin{cases} x= 48°\,19' \;\ldots\ldots\; \text{Along the minor arc.} \\ x'=360°-x=311\;\;41 \;\ldots\ldots\; \text{,, ,, major arc.} \end{cases}$$

We thus obtain:—

$$\frac{360°-x}{x}=6.5; \quad \frac{t_5'-t_4'}{t_5-t_4}=5.6.$$

The approximate equality of these two ratios tends to prove that the assumed identifications of the phases in the W_2 and W_1 movements are roughly correct.

Under this supposition, the velocities, v_4 and v_5, respectively corresponding to the commencements of the 2nd and 3rd phases of the principal portion may be deduced from the observation of W_1 and W_2 movements, as follows:—

$$\begin{cases} v_4=\dfrac{x'-x}{t_4'-t_4}=\dfrac{263°\;22'}{2^h\;5^m\;39^s}=3.88 \text{ km/sec.} \\ v_5=\dfrac{x'-x}{t_5'-t_5}=\dfrac{263°\;22'}{2^h\,20^m\,47^s}=3.47 \quad \text{,,} \end{cases}$$

141. ***Time of Occurrence and Propagation Velocities of the W_2 Motion.*** The W_2 motion generally presented a series of maxima, the 1st and 2nd being specially well defined. As will be seen from Table XLII, the 2nd maximum was in most cases greater than the 1st. The following table gives, for each of a number of the stations where the earthquake was observed with large time-scale instruments, the epicentral distance (x), the times (t_1 and t_5) of commencement of the 1st preliminary tremor and the 3rd phase of the principal portion, and the times (t', t_4' and t_5') of commencement of the W_2 motion and its 1st and 2nd maxima.

TABLE XLII. Observation of W_2 Motion.
Times of Occurrence.* [Open Seismograms.]

Place.	Epicentral Distance $=x$.	W_1 (Eq. Proper.) Time of occurrence $=t_1$	W_1 (Eq. Proper.) Commencement of 3rd Ph., Princ. Portion $=t_5$	W_2 Commencement $=t'$	W_2 1st Maximum Phase $=t_4'$	W_2 2nd Maximum Phase $=t_5'$
Tokyo (EW)			h m s 1 20 34		h m s 3 24 31	h m s 3 33 37
,, (NS)	51°26′	h m s 0 59 08	——	h m s 2 43 37	3 25 17	3 36 30
,, (Vertical)			1 20 31		——	3 33 22
Osaka (EW)	48 19	0 58 51	1 19 52	——	3 22 30	3 35 09 3 39 40
Tadotsu (EW)	47 02	0 58 49	1 18 52		3 31 22	3 36 35
Potsdam (EW)	49 48	0 58 46	1 17 29	3 20 31	3 25 31	——
,, (NS)			1 17 39	——	——	3 40 16
Triest	49 52	0 58 44	——	3 13 56	3 54 26	——
Göttingen	51 45	0 58 55	1 20 18	——	3 20 —	3 45 —
Querce	51 54	0 59 08	1 20 09	3 10 50	3 28 12	3 43 19
Birmingham (EW)	58 49	1 00 35	1 25 22	3 01 27	3 18 22	——

* t_5' and t_5'' are respectively the times of commencement of the 1st and 2nd maxima in the W_2 motion.

Station.	Epicentral Distance $=x$.	W_1 (Eq. Proper). Time of occurrence $=t_1$	W_1 (Eq. Proper). Commencement of 3rd Ph., Princ. Portion $=t_5$	W_2 Commencement $=t'$	W_2 1st Maximum Phase $=t'_4$	W_2 2nd Maximum Phase $=t'_5$
Washington (NS).	105°17′	1h 08m 25s	1h 51m 16s	2h 27m 28s	2h 52m 30s	2h 58m 43s
Cheltenham (EW).	105 22	1 08 39	1 49 12	—	—	2 58 19 3 02 24 3 09 05
„ (NS).			1 51 10	—	2 51 27	2 58 32
Tacubaya (EW).	128 39	1 11 25	2 01 49	2 16 41	2 43 46	—
„ (NS).			2 09 21	—	—	2 48 25

The different places contained in the above table, with the exception of Triest, may be divided, according to the epicentral distance into two groups as follows.

TABLE XLIII. Mean Group Values of Times of Occurrence of W_2 Motion.

Group.	Epicentral Distance $=x$.	Time of Occurrence. 3rd Ph., P.P. of $W_1=t_5$	Commencement of $W_2=t'$	1st Max. of $W_2=t'_4$	2nd Max. of $W_2=t'_5$
(i) Tokyo, Osaka, Tadotsu, Querce, Potsdam, Göttingen, Birmingham.	51° 18′	1h 20m 23s	2h 43m 37s*	3h 24m 21s	3h 38m 58s
(ii) Washington, Cheltenham, Tacubaya.	113° 06′	1 54 25	2 22 05	2 49 14	2 55 09

(* Based on the Tokyo observation alone.)

Propagation Velocities, calculated by "Direct Method." Table XLIV gives the transit velocities of the W_2 motion, obtained by the formula

$$\text{Velocity} = \frac{360^\circ - x}{t_4' - t_0}, \text{ or } \frac{360^\circ - x}{t'_5 - t_0};$$

t_0 being the time of earthquake occurrence at the origin. The velocity relating to W_1 has been obtained in the usual way.

TABLE XLIV. Propagation Velocities, calculated by "Direct Method." [Comparison of W_1 and W_2 Velocities.]

Group.	v_5=Velocity of the 3rd Phase of Princ. Portion, W_1.	v'_4=Velocity of 1st Maximum of W_2.	v'_5=Velocity of 2nd Maximum of W_2.	Velocity of Commencement of W_2.
	km/sec.	km/sec.	km/sec.	km/sec.
i	v_5=3.11	$\frac{308^\circ\ 42'}{2^h\ 34^m\ 33^s}=3.70$	$\frac{308^\circ\ 42'}{2^h\ 49^m\ 10^s}=3.38$	$\frac{308^\circ\ 34'}{1^h\ 53^m\ 49^s}=5.02$
ii	" 3.25	$\frac{246^\circ\ 54'}{1^h\ 59^m\ 26^s}=3.83$	$\frac{246^\circ\ 54'}{2^h\ 05^m\ 21^s}=3.65$	$\frac{246^\circ\ 54'}{1^h\ 32^m\ 17^s}=4.96$

Thus the velocity v_5' of the 2nd, or greatest, maximum in the W_2 motion is, for Group (i), very nearly equal to the velocity v_5 of the 3rd phase of principal portion of W_1, and it seems that these two epochs are corresponding ones; the identification of the 2nd maximum in the W_2 motion of Group (ii) being probably not correct.

Propagation Velocity, calculated by "Difference Method." Calculating, for the 2nd maximum of Group (i), the velocity by the "difference method," that is to say, by taking the time and distance differences between the minor and major arc propagations, we obtain :—

$$v_5' = \frac{360^\circ - 2x}{t'_5 - t_5} = \frac{257^\circ\ 24'}{2^h\ 18^m\ 35^s} = 3.44 \text{ km/sec.}$$

This value of the velocity is not much different from that obtained by the "direct method."

142. ***W_2 Motion observed with Milne Horizontal Pendulums.*** The following table gives the results relating to the W_2 motion as registered by Milne horizontal pendulums at 11 different stations of Kew, Edinburgh, Shide, Liverpool, Paisley, San Fernando, Cape Town, Baltimore, Wellington, Alipore, and Colaba.

TABLE XLV. Observation of W_2 Motion: Times of Occurrence.
[Milne Horizontal Pendulum Seismograms.]

Station.	Epicentral Distance $=x$.	W_1 (Eq. Proper).		W_2		
		Time of occurrence $=t_1$.	Commencement of 3rd Ph., Princ. Portion $=t_5$.	Commencement $=t'$.	Principal Maximum $=t'_5$.	2nd Maximum $=t'_6$.
		h m s	h m s	h m s	h m s	h m s
Kew.	58° 05′	1 00 12	1 23 12	—	3 36 54	—
Edinburgh.	58 48	1 00 00	1 22 36	—	—	3 46 54
Shide.	58 52	1 01 00	{1 22 42 1 30 00*	3 04 36	{3 20 24 3 38 42‡	—
Liverpool.	59 18	1 00 36	{1 23 54 1 28 54*	3 28 58	3 37 48‡	—
Paisley.	59 30	1 00 00	{1 23 54 1 31 12*	—	—	3 48 24
San Fernando.	66 47	1 02 30	1 27 06	—	3 30 07	—
Cape Town.	85 46	1 02 30	1 36 12	—	3 08 18	—
Baltimore.	104 47	1 10 30	1 53 06	—	3 13 30	—
Wellington.	115 45	1 09 48	1 59 54	—	2 29 18	—
Alipore (Calcutta).	13 42	0 52 00	0 55 24†	3 57 30	4 11 36	—
Colaba (Bombay).	13 28	0 53 08	0 56 39†	—	4 17 00	—

* Time of occurrence of the absolute maximum in W_1.
‡ Time of occurrence of the absolute maximum in W_2.
† Time of the commencement of the principal portion.

The Milne horizontal pendulum observations of the W_2 motion lead to a more uniform result than was the case with those furnished by the mechanically registering instruments. I shall next consider the records obtained at the British stations.

(*i*) *British Stations.* The mean results obtained from the observations at the British stations may be summarized as follows :—

(i) *Kew, Edinburgh, Shide, Liverpool, Paisley.* 3rd phase of the principal portion of W_1, or the earthquake proper, began at $t_5 = 1^h\ 23^m\ 16^s$, the corresponding epicentral distance being 58° 55′.

(ii) *Shide, Liverpool, Paisley.* The absolute maximum trace of W_1 on the seismograms occurred at $t_{max.} = 1^h\ 30^m\ 02^s$, the corresponding distance being 59° 13′.

(iii) *Shide.* Commencement of the W_2 motion was at $t' = 3^h\ 04^m\ 36^s$; the corresponding, or major arc, epicentral distance being 360° − 58° 52′ = 301° 08′.

(iv) *Shide.* A maximum occurred at $t_4' = 3^h\ 20^m\ 24^s$. The corresponding epicentral distance = 301° 08′, as above.

(v) *Kew, Shide, Liverpool.* The principal maximum occurred at $t_5' = 3^h\ 37^m\ 48^s$, the corresponding major arc distance being 360° − 58° 45′ = 301° 15′.

(vi) *Edinburgh, Paisley.* The 2nd principal maximum occurred at $t'_6 = 3^h\ 47^m\ 39^s$, the corresponding major arc distance being 360° − 59° 09′ = 300° 51′.

Calculating the propagation velocity for the above six cases by "direct method," that is to say, by comparing the respective time of occurrence with that at the earthquake origin, or t_0 (= $0^h\ 49^m\ 48^s$), we obtain :—

TABLE XLVI. Propagation Velocity of W_1 and W_2 waves, calculated by "Direct Method."

[British Stations.]

Phase of motion.	Epicentral Distance.	Time Interval.	Velocity, calculated by "Direct Method."
(i) W_1.. {3rd Phase of Princ. Portion.	$x=$ 58°55′	$t_5-t_0=$0^h 33^m 28^s	3.26 km/sec. $=v_5$
(ii) W_1.. Absolute Max.	$x=$ 59 13	$t_{max.}-t_0=$0 40 14	2.73
(iii) W_2.. Commencement.	$360°-x=$301 08	$t'-t_0=$2 14 48	4.14
(iv) W_2.. A max.	„ =301 08	$t_4'-t_0=$2 30 36	3.71
(v) W_2... Princ. Max.	„ =301 15	$t_5'-t_0=$2 48 00	3.32 $=v_5'$
(vi) W_2... 2nd „ „	„ =300 51	$t_6'-t_0=$2 57 51	3.14

Thus it will be seen that the velocity v_5' of the principal maximum of the W_2 motion is very nearly equal to that of the 3rd phase of the principal portion of the W_1 motion, namely, v_5. Assuming, therefore, (i) and (v) to be corresponding phases in the earthquake movements propagated along the minor and the major arcs, the calculation by the "difference method" gives the following result:—

$$v_5'=\frac{360°-2x}{t_5'-t_5}=\frac{242°\ 30'}{2^h\ 14^m\ 32^s}=3.34 \text{ km/sec.};$$

this being practically identical with that deduced by the "direct method."

(*ii*) *San Fernando, Cape Town, Baltimore, Wellington, Alipore, Colaba.* The propagation velocity corresponding to the maximum in the W_2 motion at each of these stations, calculated by "direct method," is given in the following table.

TABLE XLVII. Propagation Velocity of the Maximum Phase in the W_2 Motion, calculated by "Direct Method."

[San Fernando, Cape Town, Baltimore, Wellington, Alipore, Colaba.]

Station.	Epicentral Distance.	Time Interval $=t_5'-t_0$	Velocity $v_5'=\frac{360°-x}{t_5'-t_0}$
San Fernando.	360°− 66°47′=293°13′	$2^h\ 40^m\ 19^s$	3.39 km/sec.
Cape Town.	360 − 85 46 =274 14	2 18 30	3.67
Baltimore.	360 −104 47 =255 13	2 23 42	3.29
Wellington.	360 −115 45 =244 15	1 39 30	4.55*
Alipore.	360 − 13 42 =346 18	3 21 48	3.18
Colaba.	360 − 13 28 =346 32	3 27 12	3.10
Mean........	....	....	**3.33**

* This velocity is excluded in deducing the average value.

The values of the velocity v_5' given in the above table are, with the exception of that relating to Wellington, fairly uniform, indicating that the velocity in question does not vary with the distance. The average value of v_5' is

3.33 km per sec.

Next, calculating the velocity v_5' for each of the above-mentioned stations, by "difference method," namely, by comparing the time of occurrence of the 3rd phase of the principal portion of the W_1 motion with that of the principal maximum of the W_2, we find :—

TABLE XLVIII. Propagation Velocity of the Maximum Phase in the W_2 Motion, calculated by "Difference Method."

Station.	Epicentral Distance $=x$	Time Difference $=t_5'-t_5$	Velocity $v_5' = \frac{360°-2x}{t_5'-t_5}$
San Fernando.	66° 47′	2h 03m 01s	3.42 km per sec.
Cape Town.	85 46	1 32 06	3.78
Baltimore.	104 47	1 20 24	3.47
Wellington.	115 45	0 29 24	(?)
Alipore.	13 42	3 16 12	3.14
Colaba.	13 28	3 20 21	3.09
Mean.	....	....	**3.38**

Thus the values of the v_5' calculated by the "difference method" are, place for place, nearly identical with those calculated by the "direct method." According to the above table, the average velocity is

$$v_5'=3.38 \text{ km per sec.},$$

which is practically identical with that obtained from Table XLVII.

143. ***Comparison of the Velocities of W_2 for different sets of stations.*** The results respecting the velocities of the W_2 motion stated in the two preceding §§ may be summarized as in the following table.

TABLE XLIX. Comparison of the Velocities of the W_2 Motion, calculated by "Direct Method."

(*A*) Tokyo, Osaka, Tadotsu, Querce, Potsdam, Göttingen, Birmingham. (*B*) Washington, Cheltenham, Tacubaya.		Phase of Motion.	British Stations.	San Fernando, Cape Town, Baltimore, Wellington, Alipore, Colaba.
Phase of Motion.	Velocity.		Velocity.	Velocity.
3rd Ph., P.P., W_1	$v_5=\begin{cases}3.11 \ (A)\\ 3.25 \ (B)\end{cases}$ km/sec.	3rd Ph., P.P., W_1	$v_5=3.26$ km/sec.	— km/sec.

(*A*) Tokyo, Osaka, Tadotsu, Querce, Potsdam, Göttingen, Birmingham. (*B*) Washington, Cheltenham, Tacubaya.		Phase of Motion.	British Stations.	San Fernando, Cape Town, Baltimore, Wellington, Alipore, Colaba.
Phase of Motion.	Velocity.		Velocity.	Velocity.
Commencement, W_2	km/sec. 5.02 (*A*) 4.96 (*B*)	Commencement, W_2	4.14	km/sec. ——
1st Max., W_2	3.70 (*A*) 3.83 (*B*)	1st Max., W_2	3.71	——
2nd Max., W_2	$v_5'=3.38$ (*A*)	Principal Max., W_2	$v_5'=3.32$	$v_5'=3.33$
——	——	Next Max., W_2	3.14	——

From the above table, it will be seen amongst others that the principal maximum of W_2 in the Milne photograms corresponded to the 2nd (greatest) maximum in the mechanical records. The average values of the velocities v'_5 and v_5, calculated both according to the "direct" and "difference" methods, are as follows :—

TABLE L. Average Values of the Velocities of W_1 and W_2 Waves.

Method of calculation.	v_5=Velocity of 3rd Ph, Principal Portion, W_1.	v'_5=Velocity of 2nd or Principal Max., W_2.
Direct Method.	3.21 km/sec.	3.34 km/sec.
Difference ,,	3.28 (§ 115)	3.39

The agreement between v_5 and v'_5 is very close, and we may conclude that the principal maximum in the W_2 motion approximately corresponds to the commencement of the 3rd phase of the principal portion. We have further :—

Velocity of the commencement of W_2=5.0 km/sec.
" " 1st maximum " =3.75 "

144. ***Amplitude and Period of Vibration in W_2 Motion.*** Table LI gives the elements of motion during the successive epochs of W_2 at each of the 10 stations, as follows:—

(*A*) Japanese Stations.......	Tokyo (EW). " (NS). " (Vertical). Osaka (EW). Tadotsu (EW).
(*B*) American & Mexican Stations.	Cheltenham (NS). " (EW). Tacubaya (NS). " (EW). Washington (NS).
(*C*) European Stations.......	Querce (NW-SE). Birmingham (EW). Potsdam (EW). " (NS). Göttingen.

TABLE LI. Observation

(*A*) Japanese

Phase of Motion.	Tokyo. EW Component.			Tokyo. NS Component.		
	Duration.	T	$2a$	Duration.	T	$2a$
	m s	sec.	mm	m s	sec.	mm
Commencement of W_2..	—	—	—	2 15	{ 45.0 { 11.9	0.1
	—	—	—	16 04	{ 19.1 { 12.6	—
	9 23	30.0	0.06	19 21	—	—
				4 00	—	—
1st Maximum.........	6 28	24.3	0.13	2 45	25.4	0.1
	2 38	22.1	Small	8 28	20.7	—
2nd Maximum........	7 05	19.4	0.19	4 14	19.5	0.12
				5 13	19.5	Small
				8 42	19.0	0.09
				1 58	17.4	Small
Subsequent Phases...	43 09	17.2	Small	2 57	16.9	Small
				6 56	29.5	0.05
				4 46	20.8	Small
				39 36	26.0	,,

of the W_2 Motion.
Stations.

Tokyo. Vertical Compt.			Osaka. EW Component.			Tadotsu. EW Component.		
Duration.	T	$2a$	Duration.	T	$2a$	Duration.	T	$2a$
m s	sec.	mm	m s	sec.	mm	m s	sec.	mm
—	—	—	—	—	—	—	—	—
—	—	—	1 20	—	—	—	—	—
—	—	—	5 26	25.1	Small	—	—	—
—	—	—	5 13	20.8	”	—	—	—
—	—	—	3 00	20.0	0.02	—	—	—
—	—	—	1 31	18.2	Small	—	—	—
			5 56	18.7	0.06	5 13	—	Small
{ 4 09	—	Small	5 00	—	—	12 25	19.5	0.05
{ 3 15	19.5	”						
—	—	—	—	—	—	—	—	—

(*B*) American and

Phase of Motion.	Cheltenham. NS Compt.			Cheltenham. EW Compt.		
	Duration.	T	$2a$	Duration.	T	$2a$
	m s	sec.	mm.	m s	sec.	mm.
Commencement of W_2 ······	—	—	—	—	—	—
	—	—	—	—	—	—
1st Maximum. ··············	5 19	29.0	0.06	—	—	—
	1 46	23.6	0.06	—	—	—
2nd Maximum. ··············	4 46	22.0	0.19	4 36	19.7	0.28
	10 10	18.5	0.06	{2 05 {4 20	— 17.4	Small. 0.10

(*C*) European

Phase of Motion.	Querce. NW-SE Compt.			Birm'gham. EW Compt.		
	m s	sec.	mm.	m s	sec.	mm.
Commencement of W_2. ······	—	—	—	16 55	25.2	Small.
	5 24	15.1	0.12			
	3 46	—	Small.			
1st Maximum. ········ ······	8 12	—	„	10 21	18.3	„
	6 38	18.1	0.12			
2nd Maximum. ··············	4 16	—	Small.			
	4 13	—	„	1 10	17.5	„
	4 31	18.0	0.14			
	4 36	18.0	0.27			
	4 48	—	Small.			
	6 16	—	„			

Mexican Stations.

Tacubaya. NS Compt.			Tacubaya. EW Compt.			Washington. NS Compt.		
Duration.	T	$2a$	Duration.	T	$2a$	Duration.	T	$2a$
m s	sec.	mm.	m s	s c.	mm.	m s	sec.	mm.
—	—	—	—	—	—	10 00	16.5	Small.
—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	5 30	27.0	—
—	—	—	—	—	—	—	—	—
5 00	19.4	0.48	20 35	18.0	0.10	13 00	21.9	—
15 30	16.0	0.15				5 50	13.5	—

Stations.

Potsdam. EW Compt.			Potsdam. NS Compt.			Göttingen.		
m s	sec.	mm.	m s	sec.	mm.	m s	sec.	mm.
5 00	20.0	0.13				—	25.0	—
4 44	24.4	0.18						
34 20	—	—	20 20	17.8	0.08	—	20.0	0.07

The following remarks on the amplitude and period of the W_2 motion are based on the preceding table.

Amplitude. The greatest $2a$ of 0.48 mm occurred in the NS component at Tacubaya, the dependence of the W_2 amplitude on the epicentral *major-arc* distance being as follows :—

Tacubaya........	231° 21′	$2a$=0.48^{mm}	(NS Compt.)
Cheltenham......	254 38	0.28	(EW ,,)
Querce...........	308 06	0.27	(NW-SE ,,)
Tokyo	308 34	0.19	(EW ,,)

Each of the above maximum movements had period varying between 18.0 and 19.7 sec., with the mean value of 19.1 sec. The 2nd maximum was always greater than the 1st maximum, the mean ratio being nearly that of 2 : 1.

In the NS component diagram obtained at Tacubaya, the W_2 motion was very well marked, the amplitude recorded being actually greater than that of the W_1 motion, or the earthquake proper. As Tacubaya is situated nearly in the meridian passing through the earthquake origin, the NS component motion corresponds to the *longitudinal wave*, the EW component motion corresponding to the *transverse wave*. (See also § 7.) The max. $2a$'s of the W_2 motion in these two directions were in the ratio of 4.8 : 1.

Period. At the commencement of the NS component of W_2 at Tokyo there were some slow vibrations of T=45 sec. The periods occurring in the 1st maximum group and the epoch immediately preceding it, which together form the 2nd phase of the principal portion, were as follows :—

30.0 sec.	27.0 sec.	22.1 sec.	16.5 sec.	12.6 sec.
29.0	25.4	20.8	15.1	11.9
Mean. **29.5**	25.2	20.7	*Mean*, **15.8**	*Mean*, **12.3**
(Max. $2a=0.06$ mm)	25.1	20.0	(Max. $2a=0.12$ mm)	(Max. $2a=$Small).
	25.0	20.0		
	24.4	19.5		
	24.3	19.1		
	23.6	18.3		
	Mean, **25.0**	18.2		
	(Max. $2a=0.18$ mm)	18.1		
		Mean, **19.7**		
		(Max. $2a=0.13$ mm)		

Thus in the 2nd phase of the principal portion there were 5 sorts of period, whose average values were respectively 29.5; 25.0; 19.7; 15.8; and 12.3 sec.; the $2a$ enclosed in brackets giving the absolutely maximum (single component) motion for each kind of the periods. It will be observed that the vibrations of periods 25.0 and 19.7 sec. were larger and of much more frequent occurrence than those of other periods.

The periods occurring in the 2nd maximum group and the subsequent epochs, which together formed the 3rd phase of the W_2 principal portion, were as follows :—

	22.0 sec.	18.7 sec.	13.5 sec.
29.5 sec.	21.9	18.5	(Small.)
(Max. $2a=0.05$ mm)	20.8	18.0	
	20.0	18.0	
	20.0	18.0	
	19.7	17.8	
	19.5	17.5	
	19.5	17.4	
	19.5	17.4	
	19.4	17.2	
	19.4	16.9	
	19.0	16.0	
	Mean, **18.9** sec.		
	(Max. $2a=0.48$ mm)		

Thus in the phase under consideration, the period varied, with two exceptions, between 16.0 and 22.0 sec., giving a mean value of 18.9 sec. The vibrations of this sort are evidently the same as those in the previous phase whose mean period was 19.7 sec.

Again, comparing together the three tables (*A*), (*B*), and (*C*), we see that on the whole slower vibrations occurred first, the approximate order of succession of the principal different periods being as follows:—(i) 45.0; (ii) 29.5; (iii) 25.0; (iv) 19.7—18.9 sec. This occurrence of periods in the descending order of magnitude (length) is a characteristic of the principal portion of the earthquake motion.

Average Periods. The mean values of the various periods of vibration in the W_2 motion recorded at the different stations are collected in the following table, those of more frequent occurrence being printed in thick characters.

TABLE LII. Average Values of the Periods in W_2 Motion.

	sec.	sec.	sec.	sec.	sec.	sec.	sec.
Tokyo.	**12.3**	—	**19.4**	—	**25.1**	**29.8**	45.0
Osaka.	—	—	**19.6**	—	25.1	—	—
Tadotsu.	—	—	19.5	—	—	—	—
Göttingen.	—	—	20.0	—	25.0	—	—
Potsdam.	—	17.2	20.0	—	24.4	—	—
Querce.	—	15.1	**18.0**	—	—	—	—
Birmingham.	—	17.5	**18.3**	—	25.2	—	—
Washington.	13.5	16.5	—	21.9	—	27.0	—
Cheltenham.	—	—	**18.6**	**22.8**	—	29.0	—
Tacubaya.	—	—	**18.2**	—	—	—	—
Mean.	**12.7**	16.6	**19.1**	**22.5**	**25.0**	**28.9**	45.0

Thus it will be observed that the period most frequently occurring is 19.1 sec., being almost universally indicated at the different places. The 2nd maximum group of the W_2 motion, in which the above-mentioned period predominated, may be taken as corresponding to the 3rd phase of the principal portion of the W_1 motion, or earthquake proper.

REPETITION OF THE EARTHQUAKE MOTION FIRST PROPAGATED ALONG THE MINOR ARC.

145. ***Observation of W_3 Motion.*** TABLE LIII gives the times of occurrence of the W_3 wave or the repetition of the earthquake motion first propagated along the minor arc, observed more or less clearly at the 7 stations of Tokyo, Osaka, Tadotsu, Cheltenham, Shide, Wellington, and Colaba.

TABLE LIII. Observation of W_3 Motion: Times of Occurrence.

Station.	Epicentral Distance $= x$.	W_1 Motion (Eqke. Proper) Time of occurrence $= t_1$	W_1 Motion (Eqke. Proper) Commencement of 3rd Phase, Princ. Port. $= t_5$	Commencement of $W_3 = t_5''$
		h m s	h m s	h m s
Tokyo (EW).	51° 26′	0 59 08	1 22 26	4 24 08
Osaka (EW).	48 19	0 58 51	1 19 52	4 34 59
Tadotsu (EW).	47 02	0 58 49	1 18 52	4 24 35
Cheltenham (NS).	105 22	1 08 39	1 49 12	5 22 04
Shide.	58 52	1 01 00	1 22 42	4 34 45*
Wellington.	115 45	1 09 48	1 59 54	4 36 36
Colaba.	13 28	0 53 08	0 56 39‡	4 24 00

* Meaned from the records given by the two pendulums B and C.

‡ Commencement of the principal portion.

The propagation velocity of the W_3 motion may be calculated by the "direct method" according to the formula

$$\text{Velocity} = \frac{360^\circ + x}{t''_5 - t_0},$$

where t'' denotes the time of occurrence of W_3. We obtain the following results :—

TABLE LIV. Velocity of the W_3 Motion, calculated by "Direct Method."

Station.	Epicentral Distance. $=360^\circ+x$.	Time Difference $=t''-t_0$	Velocity. "Direct Method."
Tokyo.	411° 26′	3h 33m 20s	3.57 km/sec.
Osaka.	408 19	3 45 11	3.36
Tadotsu.	407 02	3 34 47	3.61
Cheltenham.	465 22	4 32 16	3.17
Shide.	418 52	3 44 57	3.46
Wellington.	475 45	3 46 48	3.89
Colaba.	373 28	3 34 12	3.23
Mean	....	....	**3.40**

The identification of the W_3 motion was extremely difficult, and the results above obtained are to be regarded as, at the best, only gross approximations. The average value of the velocity is **3.40** km per sec.,* which is nearly equal to that of the 3rd phase of the principal portion of W_1. Assuming, there-

* As will be seen from the value of $(t''-t_5)$ given below, the identification of W_3 for Wellington is probably not quite correct. The velocity for this station has therefore been excluded in deducing the average.

fore the W_3 motion to correspond to the 3rd phase of the principal portion, we obtain, from Table LIII:—

		h	m	s
Tokyo.	$t_5''-t_5=$	3	01	42
Osaka.		3	15	07
Tadotsu.		3	05	43
Cheltenham.		3	32	52
Shide.		3	12	05
Wellington.		2	36	42*
Colaba.		3	27	21
Mean		3	15	48

The mean time difference of **$3^h\ 15^m\ 48^s$**, deduced by excluding the value for Wellington (marked with an *asterisk*), is the time interval taken by the earthquake motion in making one complete circuit round the earth and does not depend on the epicentral distance x. We have:—

$$\text{Velocity}=\frac{\text{Earth's Circumference}}{t_5''-t_5}=\frac{360^\circ}{3^h15^m48^s}=3.40\ \text{km/sec.}$$

(See also the *Publications*, No. 13).

Periods of Vibration. The periods of vibration occurring in the W_3 motion were as follows.

	sec.	sec.	sec.
Tokyo.	20.5	—	44.0
Osaka.	18.5	—	—
Tadotsu.	—	36.3	—
Cheltenham.	18.2	—	—
Mean.	**19.1**	36.3	44.0

The principal period of vibration in W_3 is the same as that occurring in the most active part of the W_2 motion.

GENERAL REMARKS ON THE PROPAGATION VELOCITIES.

146. ***Velocities calculated by "Direct Method."*** The mean values of the different velocities calculated by the "direct method" are as follows.

TABLE LV. Mean values of the Velocities.
"Direct Method."

Phase of motion.	Velocity.	Limits of Epicentral Distance.	Mean Distance.
	km/sec.		
1st Prel. Tremor.	v_1 =**10.52**	50° —121°	76°
2nd „ „	v_2 = **5.63**	40 —115 45′	61 36′
1st Phase, Princ. Port.	v_3 = **4.07**	47 —128 47	70 52
3rd „ , „	v_5 = **3.11**	39 27′—128 47	Practically independent of the distance x.
Commencement, W_2.	**5.0**		
1st Maximum, W_2.	v_5 = **3.75**		
Principal max., W_2.	v_5' = **3.34**		
W_3	v_5''= **3.40**		

The four velocities v_1, v_2, v_3, and v_5 are in the ratios of 100: 53.5 : 38.7 : 29.6. The velocity of the principal maximum of W_2 and that of W_3 are approximately equal to v_5. The 1st maximum of W_2 seems to correspond to the 2nd phase of the principal portion, and the earliest recorded commencement of the major arc propagation to some part of the 2nd preliminary tremor.

The average values of the velocities for the stations in Middle Europe and Japan are as follows:—

v_1=**10.38** km/sec. (22 stations, mean x=50° 24′)
v_2= **5.73** „ (20 „ , „ =50 12)
v_3= **3.92** „ (7 „ , „ =50 17)
v_5= **3.02** „ (8 „ , „ =50 34)

These 4 velocities are in the ratios of 100 : 55 : 38 : 29.

147. ***Velocities calculated by "Difference Method."*** The mean values of the different velocities calculated by the "difference method" are as follows.

TABLE LVI. Mean Values of the Velocities.
"Difference Method."

Phase of motion.	Velocity.	Limits of Epicentral Distance.
1st Preliminary Tremor.	v_1 = **11.36** kms/ec.	27° 57′—121° 16′
2nd ,, ,,	v_2 = **6.46**	27 42 —128 47
1st Phase, Princ. Portion.	v_3 = **4.70**	39 27 —128 47
3rd ,, , ,, ,,	v_5 = **3.28**	39 27 —128 47
Principal Maximum, W_2.	v_5' = **3.39**	
W_3	v_5'' = **3.40**	

The 4 velocities v_1, v_2, v_3, and v_5 are in the ratios of 100 : 56.9 : 41.4 : 28.9; the mutual relations being nearly the same as in the cases of the velocities calculated by the "direct method." The agreement of the velocities of W_2 (principal max.) and W_3 with that of the 3rd phase of the principal portion is here closer than in the case of the "direct method" calculation.

Comparisons of the velocities calculated by "direct" and "difference" methods. Comparing the mean values of the different velocities calculated according to the "direct method" with those calculated according to the "difference method," as given in Tables LV and LVI, we obtain :—

$$\left\{\begin{array}{l} v_1\ (\text{Difference Method})-v_1\ (\text{Direct Method})=0.84\ \text{km/sec.} \\ v_2\ (\ \ ,,\ \ )-v_2\ (\ \ ,,\ \ )=0.83 \\ v_3\ (\ \ ,,\ \ )-v_3\ (\ \ ,,\ \ )=0.63 \\ v_5\ (\ \ ,,\ \ )-v_5\ (\ \ ,,\ \ )=0.17 \\ v_5'\ (\ \ ,,\ \ )-v_5'\ (\ \ ,,\ \ )=0.05 \\ v_5''(\ \ ,,\ \ )-v_5''(\ \ ,,\ \ )=0.00 \end{array}\right.$$

Thus it will be seen that the velocities v_1, v_2, and v_3, calculated by the "difference method" were each greater 0.63 to 0.84 km per sec., than those calculated by the "direct method." The discrepancy is, however, very small or *nil* for the velocities v_5, v_5', and v_5''. This fact seems to give support to the view that the vibrations composing the 1st and 2nd preliminary tremors, as well as the earlier part of the principal portion, are propagated some considerable depth below the surface, the length of the actual path for each of these sets of waves materially differing from that of the arcual epicentral distance.

148. ***Mutual Relations of the different Velocities.*** Assuming the durations of the first 7 successive sections of the earthquake motion to be, as stated in § 8, in the ratios of 100 : 95 : 79 (1st and 2nd phases of principal portion taken together) : 91 : 95 : 95, we have the following general relations among the different velocities*:—

$$\frac{1}{v_2}=\frac{1}{v_1}+\frac{y_1}{x}; \qquad \frac{1}{v_6}=\frac{1}{v_5}+\frac{91\,y_1}{100\,x};$$

$$\frac{1}{v_3}=\frac{1}{v_2}+\frac{95\,y_1}{100\,x}; \qquad \frac{1}{v_7}=\frac{1}{v_6}+\frac{95\,y_1}{100\,x};$$

$$\frac{1}{v_5}=\frac{1}{v_3}+\frac{79\,y_1}{100\,x}; \qquad \frac{1}{v_8}=\frac{1}{v_7}+\frac{95\,y_1}{100\,x};$$

x being the epicentral distance of a given station, and y_1 the

* See the *Publications*, No. 5 and No. 13.

duration of the 1st preliminary tremor at the latter. The quotient y_1/x is to be determined from some of the equations (1) to (4) in § 121, and the equation (7) in § 123. As an example, let us apply the above relations to the velocities of the Kangra earthquake calculated by the "direct method" for the stations in Middle Europe and Japan, (§ 146); the mean value of the x being 50° 22′, and the quantity y_1/x being given by equation (1) of § 121. Assuming v_1=10.38 km/sec., we have :—

Actual Value.	*Calculated Value.*
v_1=10.38 km/sec.	10.38 km/sec.
v_2= 5.73	5.6
v_3= 3.92	3.9
v_5= 3.02	3.1

The agreement between the actual and calculated values is fairly good.

Ratio of $v_1 : v_2$. The ratios of the 4 velocities v_1, v_2, v_3, and v_5, are, according to the two preceding §§, as follows :—

(i) "Direct Method."..... 100 : 53.5 : 38.7 : 29.6
(ii) "Difference Method.".. 100 : 56.9 : 41.4 : 28.9
Mean............ **100 : 55.2 : 40.1 : 29.3**

Thus, amongst others, the mean ratio of $v_1 : v_2$ is 100 : 55.2. Now, the equation* for determining the time (t_0) of earthquake occurrence at the origin, from the duration (y_1) of the 1st preliminary tremor, is

$$t_0=t_1-\frac{y_1}{\frac{v_1}{v_2}-1} \quad \ldots\ldots\ldots\ldots(1)$$

Putting the mean ratio of $v_1 : v_2$ above obtained, the equation becomes :—

* The *Bulletin of the Imperial Earthquake Investigation Committee*, Vol. I, No. 1.

$$t_0=t_1-1.232\ y_1\ \ldots\ldots\ldots(2)$$

For the purpose of practical application, however, it seems better to adopt the ratio of $v_1:v_2$ obtained by the "direct method"; the formula then becomes

$$\boldsymbol{t_0=t_1-1.151\ y_1}\ldots\ldots\ldots(3)$$

Equation (3) does not much differ from one previously given.

149. ***Remarks on the Methods of Velocity Calculation.*** In all the velocity calculations by the "direct method" given in the preceding Chapters, the times of occurrence of the different phases of the earthquake motion at a given station have been compared with the time (t_0) at the origin of disturbance. This is equivalent to assuming that at the latter there existed no preliminary tremor; in other words, that the various sets of vibrations composing the seismic motion were generated simultaneously at the centre. I believe this supposition is generally legitimate, although there is possibility, especially in cases of large earthquakes, of slight premonitary shakings apart from the usual preliminary tremors.

Chapter X. Miscellaneous Remarks.

150. ***Notes on the Tokgo Observations.*** The following remarks on the Tokyo observations are based on the analysis of the seismograms of the Kangra earthquake given in §§ 13 to 21.

151. *Small movements of Sensible or Macro=seismic Character.* The Hitotsubashi diagram furnished by a horizontal pendulum of 8 times magnification indicated in the 1st preliminary tremor