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Lisbon Earthquake of 1 November 1755

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ABSTRACT. Available data on the Lisbon earthquake have been reviewed. Some new aspects of the earthquake have been brought out and a few others reinterpreted in the light of data of the recent Assam earthquake. The fresh calculations made show that this Lisbon earthquake may be considered as the strongest of all shocks for which scientific data are available. The magnitude of the earthquake has been approximately determined as 8·7 and energy between 10^{27} ergs and 7×10^{27} ergs or double the energy of the Assam earthquake of 1950 with depth of focus 18 km.

Seiches appear to be associated with shallow earthquakes of magnitude exceeding 8·5. True seiches are generally observed over the region just outside the felt area. The shock may be felt and hanging objects may oscillate at isolated places over the same region. The maximum epicentral distances of these phenomena are proportional to the energies of the shocks. Isolated seiches may occur at very large distances, say, even 4000 or 5000 miles, from the epicentre.

1. Introduction

The Lisbon earthquake of 1 November 1755, its severity, the damage and loss of life due to it, the distance to which it was felt, the great sea waves it gave rise to, the agitation of waters of lakes and ponds at very great distances (from the epicentre), all combined make it probably the most notable earthquake in history. It is also to be remembered that the power of an earthquake to agitate lakes and ponds at very great distances was first noticed in the case of the Lisbon earthquake and that it incited the first scientific attempt to explain the cause of the sea waves that follow some submarine earthquakes (Reid 1914), and also the cause of oscillations of distant masses of inland water that followed this earthquake.

The unique feature of the earthquake appears to lie in the great strength which it exhibited in initiating oscillations of large masses of water in rivers, lakes, ponds etc near about and far away from the outermost limit of the felt area in such distant regions as north of Scotland, North Europe, Central Sweden, Finland and the East Danube basin. Rhythmic oscillations of water of rivers, bays, lakes etc by meteorological or seismic causes, are denoted by 'seiches'. In no earthquake have seiches been so generally and widely observed as in the Lisbon earthquake of 1755. If this phenomenon is considered as an index to the strength of an earthquake, it may be said that the Lisbon earthquake was the strongest of all shocks on which scientific information is available. An attempt is made in this note to estimate the approximate value of the magnitude of this shock which has become remarkable in history on account of manifestation of varied phenomena with available data and comparing it with certain features of the Assam earthquake of 1950.

Remarkable seiches were also observed after the Assam earthquake of 1950. These started within the felt area near the outermost limit but extended far outside this area. The phenomenon was prominent mainly in the Gangetic alluvium. Some observations were also reported from central Burma. It has been reported that standing waves were observed in fiords and lakes in Europe approximately at the time of arrival of the maximum waves from the Assam earthquake. It was widely reported that 'the water of the Lake Ontario rose with great violence five and a half feet, three times within half an hour' and the phenomenon was connected with the Lisbon earthquake. Reid could not accept the report for want of local evidence but occurrence of seiches in the Lake Ontario due to the Lisbon earthquake cannot be discredited on the ground of distance. In respect of remarkability of the phenomenon of seiches, the Assam earthquake appears to stand second only to the Lisbon earthquake.

It is clear from the study of the Lisbon and Assam earthquakes that true seiches start within the 'felt area' but near its outermost limit and extend over a belt outside the 'felt area'. Earthquakes are perceptible and hanging objects may swing at isolated places over the same belt. The epicentral distances of the phenomena are related to the energies of the shocks. Isolated seiches may occur at large distances, even 4000 to 5000 miles, beyond the belt where they are generally observed. It appears that conspicuous seiches are generated by earthquakes when their magnitudes exceed 8·5 and whose focal depths are sufficiently small. Alluvial lands such as river deltas, sea coasts and islands appear to be more favourable for generation of seiches.

Gutenberg and Richter (1949) have assigned a value between $8\frac{3}{4}$ and 9 to the magnitude of the Lisbon earthquake. They have not indicated any basis for their determination but have merely stated that the surface waves of the earthquake were very large and the area shaken was enormous.

2. Energy and amplitude of an earthquake

The energy of an earthquake is proportional to the square of the amplitude coming up to the surface.

$$E = \text{constant} \times A^2 \qquad (1)$$

where E = the energy and A = the amplitude.

The constant term in equation (1) can be obtained as follows (Gutenberg and Richter 1942)—

Let us assume that at the epicentre of an earthquake, the radiated energy arrives principally in a series of n equal sinusoidal waves of length λ, amplitude A_0 and period T_0. The kinetic energy per unit volume is

$$\frac{\rho}{4} = \left(\frac{2\pi A_0}{T_0}\right)^2$$

If the wave velocity v is constant, this will be the mean energy in a spherical shell of volume $4\pi h^2 . n\lambda$

Putting $nT_0 = t_0$

$\lambda = v\,T_0$

and $n\lambda = v\,t_0$

$$\text{we get, } E = \frac{4\pi^3 h^2 v t_0 \rho}{T_0^2} \times A_0^2 \qquad (2)$$

where h = focal depth of the shock (km),

t_0 = duration of the sinusoidal wave group at the epicentre (sec),

ρ = density (gm/cc),

T_0 = period of the wave group at the epicentre,

and A_0 = the maximum ground amplitude at the epicentre.

If we substitute E_1, t_1, h_1, T_1 and A_0' and E_2, t_2, h_2, T_2 and A_0'' for E, t_0, h, T_0 and A_0 in equation (2), for the Assam and Lisbon earthquakes, we get

$$\frac{E_2}{E_1} = \frac{t_2 h_2^2 T_1^2}{t_1 h_1^2 T_2^2} \times \left(\frac{A_0''}{A_0'}\right)^2 \qquad (3)$$

The energy of the Assam earthquake is known. The energy of the Lisbon earthquake can be obtained by substituting the values of the first expression on the right-hand side from observational data if the amplitudes can be replaced by other known quantities.

Let us assume that $A_1, A_2, A_3 \ldots\ldots\ldots$ and $A_1', A_2', A_3' \ldots\ldots$ are the maximum amplitudes of the surface waves at distances $\triangle_1, \triangle_2, \triangle_3, \ldots\ldots$, due to the Assam and the Lisbon earthquakes,

$$\text{Then } A_1 = \frac{K_1}{\sqrt{\triangle_1}},\ A_2 = \frac{K_1}{\sqrt{\triangle_2}},\ \ldots \qquad (4)$$

$$\text{and } A_1' = \frac{K_2}{\sqrt{\triangle_1}},\ A_2' = \frac{K_2}{\sqrt{\triangle_2}},\ \ldots \qquad (5)$$

where K_1 and K_2 are constants.

From equations (4) and (5)

$$\frac{A_1}{A_1'} = \frac{K_1}{K_2}$$

$$\text{Also } \frac{A_1}{A_1'} = \frac{A_2}{A_2'} = \frac{A_0'}{A_0''} = \frac{K_1}{K_2} \qquad (6)$$

Let $\triangle_1$ and $\triangle_2$ stand for the maximum distances where seiches due to the Assam and the Lisbon earthquakes were observed. We may assume that the amplitudes and periods of the waves due to the Assam earthquake at $\triangle_1$ were equal to those due to the Lisbon earthquake at $\triangle_2$. From equations (4) and (5), we have

$$\frac{A_1}{A_2'} = \frac{K_1}{K_2} \times \frac{\sqrt{\triangle_2}}{\sqrt{\triangle_1}} \qquad (7)$$

Since $A_1 = A_2'$

$$\frac{K_1}{K_2} = \frac{\sqrt{\triangle_1}}{\sqrt{\triangle_2}} \qquad (8)$$

From relations (6) and (8)

$$\frac{A_0'}{A_0''} = \frac{\sqrt{\triangle_1}}{\sqrt{\triangle_2}} \qquad (9)$$

Substituting the value of $\frac{A_0'}{A_0''}$ from equation (9) in equation (3), we get

$$\frac{E_2}{E_1} = \frac{t_2 h_2^2 T_1^2}{t_1 h_1^2 T_2^2} \times \frac{\triangle_2}{\triangle_1} \qquad (10)$$

3. The depth of focus—h

In equation (10), the values of t_1 and t_2 are available from observation and for all practical purposes, $T_1 = T_2$. h_1 is known from microseismic data. There is however no means of estimating the focal depth of the Lisbon earthquake (h_2) except making an attempt from microseismic data. If the radius of the outermost limit of the felt area can be found out, either of the following empirical relations can be used to estimate h_2. It is difficult to assess the relative merits of these relations. We will therefore use the mean value from all the three equations.

$$J - j = -s \log_{10} \cos\theta \qquad \text{(Blake 1941)}$$

where $\theta = \tan^{-1}\left(\frac{R_j}{h}\right)$,

J = maximum intensity of the shock,

j = intensity corresponding to a particular isoseismal,

R_j = radius of the area enclosed by the isoseismal of intensity j,

h = the depth of focus (km),

s = a parameter which stands for absorption and is 5·35.

The above relation is equivalent to (Gutenberg and Richter 1942)

$$I_0 - I = s \log \frac{D}{h} \qquad (11)$$

where $I_0 = J$ in modified Mercalli scale,

$I = j$ in modified Mercalli scale,

D = hypocentral distance (km) $= \sqrt{h^2 + \triangle^2}$

$\triangle$ = epicentral distance (km) at the limit of perceptibility,

and $s = 6$

Other relations are

$$\frac{r}{h} = \sqrt{10^{I_0/3 - 1/2} - 1} \qquad (12)$$

where

$r = \triangle$ the value of the epicentral distance at the limit of perceptibility,

and
$$\frac{r}{h} = \frac{I_0^3 - 3\cdot 4}{2H} \qquad (13)$$

where $H = 18 \pm$ km

we have $I_0 = 12$ for both the shocks.

4. The extent of the felt area and the radius of perceptibility—r

Many attempts have been made by several investigators to estimate the extent of the felt area. The estimated values range from one to fifteen million square miles. The complexity of the Lisbon earthquake is thus evident. Enormous strength of the earthquake shock, the remarkable seismic seiches and the sea waves and, probably the occurrence of a separate and strong shock in northwest Africa with epicentre near Mequinez at about the time of the Lisbon shock (Davison 1936) were in no small measure responsible for the diversity in the estimated values.

A summary of the observations reporting times of some of the observed phenomena is given in Table 1. The observations without times cannot be utilised with as much

TABLE 1

Observations on the Lisbon earthquake of 1 November 1755

Serial No.	Place of observation	△ (miles)	(T—O) (min)	Remarks
1	Lisbon, Portugal	—	— 3	Felt
2	Securial, Spain	185	+ 4	Felt
3	Cadiz, Spain	230	+ 5	Felt
4	Seville, Spain	250	+25	Felt
5	Gibraltar, Spain	300	+12	Felt
6	Saffe, Oran	490	— 8	Felt
7	Madeira Islands, Atlantic	605	+26	Felt
8	Bordeaux, France	610	—18	Felt and water of river disturbed
9	Portsmouth, Great Britain	850	+18	Water of dock disturbed
10	Dartmouth, Great Britain	850	— 6	River disturbed
11	Poole, Great Britain	895	+18	Dock water disturbed
12	Cork, Great Britain	905	+ 6	Felt
13	Havre, France	930	+40	Dock and canal water disturbed
14	Bushbridge, Great Britain	955	+12	Canal water disturbed
15	Earley Court, Great Britain	965	—15	Ponds disturbed
16	Shirburn Castle, Great Britain	970	—16	Canals disturbed
17	Geneva Lake, Switzerland	970	—48	Lakes disturbed
18	Eaton Bridge, Great Britain	975	+ 8	Ponds disturbed
19	Cran Brook, Great Britain	975	+10	Ponds disburbed
20	Brieg, Switzerland	985	—46	Felt
21	Peerless Pool, Great Britain	985	+12	Ponds disturbed
22	Rotherhithe, Great Britain	985	+70	Rivers disturbed
23	Eyam Edge, Great Britain	995	+45	Felt
24	Luton, Great Britain	1005	+10	Ponds disturbed
25	Rochford, Great Britain	1010	—17	Ponds disturbed
26	Thaxted, Great Britain	1020	+68	Ponds disturbed
27	Lake Brieg, Switzerland	1025	—52	Lakes disturbed
28	Milan, Italy	1045	+33	Lakes and canals disturbed
29	Milan, Italy	1045	+ 3	Hanging object swang
30	Wickhamhale, Great Britain	1048	+85	Ponds disturbed
31	Near Barlborough, Great Britain	1070	+76	Ponds disturbed
32	Yarmouth Haven and Hull, Great Britain	1090	+70	Docks disturbed
33	Conistan Lake, Great Britain	1105	— 8	Lakes disturbed
34	Esthwaite Water, Great Britain	1105	— 7	Lakes disturbed
35	Windermere, Great Brtiain	1115	— 8	Lakes disturbed
36	Leyden, Holland	1140	+12	Felt and canals disturbed
37	Hague, Holland	1140	+19	Canals disturbed
38	Near Durham, Great Britain	1165	+15	Ponds disturbed
39	Queen's Ferry, Firth of Forth, Great Britain	1220	— 4	Ponds disturbed
40	Loch Lomond, Great Britain	1220	—34	Lakes disturbed
41	Loch Long, Great Britain	1220	—11	Lakes disturbed
42	Lock Katrine, Great Britain	1230	—34	Lakes disturbed
43	Loch Ness, Great Britain	1305	— 2	Lakes disturbed
44	River Oich, Great Britain	1305	+18	Rivers disturbed
45	River Tariff, Great Britain	1305	+58	Rivers disturbed
46	Hamburg, Germany	1360	+100	Water disturbed and felt
47	Itzeho-river Stoher, in the province of Holstein at Brandstadt, Elmshorn, Gluckstadt, Kellinghausen, and Steinburg Fort	1360	+32	Water disturbed
48	Meldorf	1360	+27	Water disturbed
49	River Trave, Lubeck	1400	+27	River disturbed
50	River Aurosaki at Abo, Finland	2174	+10	River disturbed

confidence as those with times. The former have not, therefore, been incorporated in this table.

The epicentre of the Lisbon earthquake is not known with certainty. According to David Milne (1841), it was near 39° N and 10°W and Choffat placed it near 38°N and 10° W. From the directions of the sea waves, Perreira de Sousa concluded that the epicentre lay in an area between the southwest of the Iberian peninsula and the African continent and to the west of the Straits of Gibralter. According to Davison, the focus of the Lisbon earthquake was of great size and a very active part of it must have been not many miles to the southwest of Lisbon. On account of the uncertainty of the position of the epicentre, the distances of the observing stations in Table 1 have been measured from Lisbon.

The time of occurrence of the shock has been adopted as 1040 GMT on 1 November 1755. The differences between the observed times (T) and the time of occurrence of the shock (O) in column 4 in Table 1 suggest that the latter time should be increased by some 4 or 6 minutes. 1045 GMT would perhaps be nearer the correct time of origin of the shock. In case of more than one observed times, the mean of all has been taken. Where a range of time indicating a period of observation has been reported, the middle of such a period has been used.

The areas supposed to have been shaken by the earthquake, according to different investigators, have been exhibited in Fig. 1 and the estimated values given in Table 2. The map in Fig. 1 has been copied from Reid. The dotted line curve (B) refers to Reid, and the continuous line curves (C and D) refer to the author. The system of broken line curves (including curve A) refers to Woerle. The inner curves enclose areas of greater intensity. Curve D roughly corresponds to Rossi-Forel scale VII.

Woerle's main curve A including Lisbon near about the centre, is completely isolated from the rest of his system of curves. Struck by this apparant discontinuity of the areas over which the earthquake was felt and the anomalous high intensities manifested by some of them, Woerle offered the explanation on some earlier suggestions that the subsidiary system of curves were due to relay earthquakes initiated by the shock at the Lisbon focus. In fact, the area enclosed by the curve A represents approximately the 'felt area proper' (principally the effects of P and S) and the areas beyond this region exhibit mainly the effects of the surface waves, in the form of 'seiches', 'oscillations of hanging objects' and in a few favourable cases, even physical perceptibility of the waves. On this basis there is agreement between the values of the felt area of the Lisbon earthquake, as estimated by Woerle, Davison and the author. Even in spite of wide diversity in the estimated values, we may adopt $1\frac{1}{4}$ to $1\frac{1}{2}$ million square miles as the nearest approach to the correct value of the felt area of the Lisbon earthquake. Giving equal weights to the estimates by the three investigators, the mean value is about 1·4 million square miles. This suggests that the depths of focii of the Assam and the Lisbon earthquakes were not very different from each other.

TABLE 2

Earthquake and author	Felt area (*million sq. miles*)	Radius of perceptibility	
		(*miles*)	(*km*)
Lisbon earthquake 1755			
Woerle	13.7		
Woerle (curve A)	1.6	715	1130
Tarr and Martine (1912)	2.2	845	1360
Oldham (1899)	1.0	570	920
Davison	$1\frac{1}{4}$ to $1\frac{1}{2}$	610 to 690	980 to 1110
Mukherjee (curve C)	1.3	650	1040
Assam earthquake 1950			
Mukherjee (adopted value)	1.3	640	1030
Mukherjee (alternative possible value felt not exceeding)	1.7	740	1190

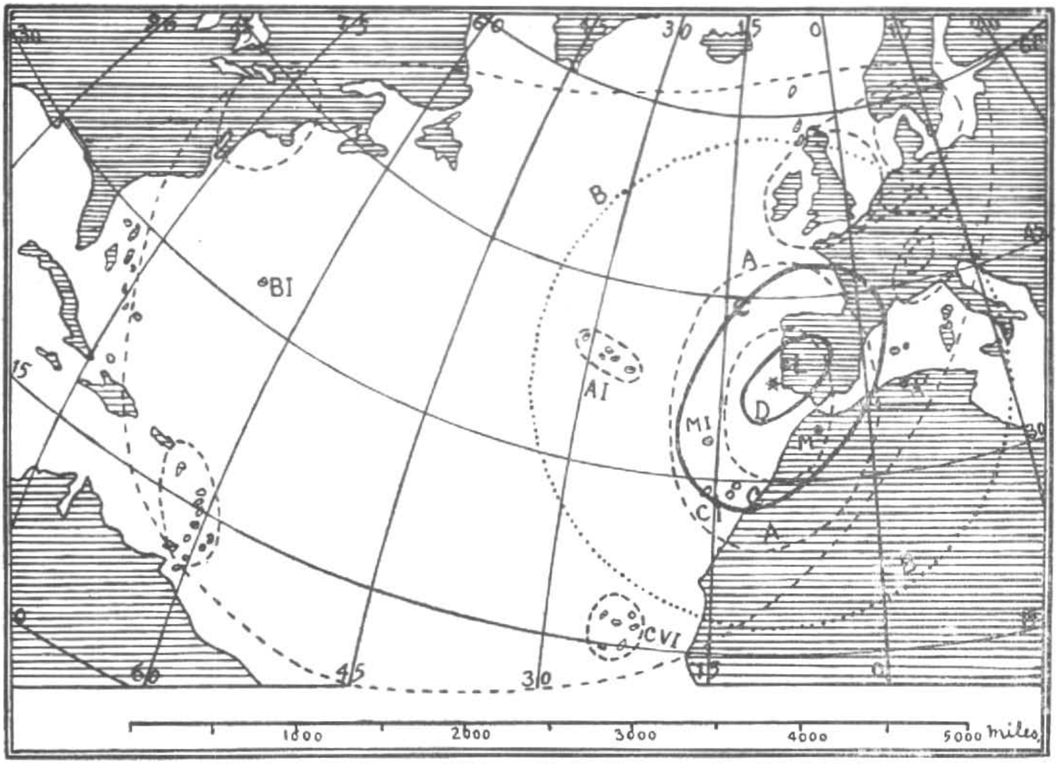

Fig. 1. Areas of perceptibility due to the Lisbon earthquake of 1755
L=Lisbon, M=Mequinez, A′=Algiers

According to Davison the maximum distance where the Lisbon earthquake was definitely felt and also the minimum distance of observation of true seiches was 610 miles (that of Bordeaux). The shock was probably perceptible and also the seiches were observed at Angouleme at a distance of 675 miles from Lisbon. This is the maximum distance of perceptibility of the shock. On this consideration and keeping in mind that the position of the epicentre might have been a few miles away from Lisbon in some southwesterly direction, it would be preferable to adopt a mean of the values obtained from Woerle's curve A and the upper limit, due to Davison, for the estimated value of the radius of perceptibility for calculation of the depth of focus. This is 1120 km (696 miles). This is also the mean of the values due to Woerle (curve A), Tarr and Martin, Davison and Mukherjee. The total felt area may be adopted as 1·5 million square miles.

The values of the depth of focus of the Lisbon earthquake (h_2), calculated from equations 11, 12 and 13 (with r=1120 km) are, 12, 20 and 23 km respectively. The mean is 18 km.

The values of the depth of focus of the Assam earthquake calculated from these equations (with r=1030 km) are 11, 18 and 21 km. The mean is 17 km.

The value obtained from microseismic data of the Assam earthquake and the average depth of its after shocks are about 14 km (Pramanik and Mukherjee 1953, Tandon 1954, Tillotson 1951). For the sake of homogenity we will use the values obtained from microseismic data for both the earthquakes.

5. Duration of the maximum wave group near the epicentre—t_0

We may not be far out from facts if we take for t_0 the observed value of duration of the principal portions of sensible shakings due to the two earthquakes.

Following are some of the observations of the duration of the Lisbon earthquake. These are more dependable than others. The distances considered here are from a point some 50 miles to a southwesterly direction from Lisbon.

Station	△ (*miles*)	Duration (*min*)	No. of observa-tions
Lisbon	50	6 or 7	5
Cadiz	170	5	1
Oporto	200	6 or 7	1
Madrid	325	8	1

The mean of the five observations at Lisbon is about 6·5 min and the mean from other stations is about 6·1 min.

Three phases due to the Lisbon shock were clearly recorded at Lisbon, Cadiz and Funchal in Madeira. "At Lisbon the first consisted of rapid vibrations too slight to cause alarm and lasting for about a minute. Then after about 30 seconds there came a shock, also composed of rapid vibrations, but so violent that houses began to fall. This lasted a little more than two minutes. Then after a pause of less than a minute, the nature of the movement changed and buildings were jerked upward like a wagon driven violently over rough stones. This phase lasted for 2 or 3 minutes and laid in ruins all the houses, churches and public buildings in Lisbon with the loss of thousands of lives". This graphic description of the different phases will lend additional support to the duration of the shock as estimated above.

Many observations of the durations of the Assam earthquake near the epicentre are available. The frequencies of the different observations according to the range of distances of the observing stations are shown below—

Durations (*min*)	Number of observations at △=90 to 120 miles	Number of observations at △=130 to 350 miles
3.0	1	2
4.0 to 4.5	3	7
5.0 to 6.0	8	8
6.5 to 7.0	5	–
7.0 to 7.5	..	2
8.0 to 8.5	..	2
9.0	1	..

The values for the two earthquakes may be summarised as follows—

Range of distance (*miles*)	t_0 due to the Assam earthquake (*min*)	t_0 due to the Lisbon earthquake (*min*)
50—120	5.5(18)	6.5(5)
125—350	5.1(21)	–
220—375	..	6.1(3)

The number of observations is shown within brackets. Following are some of the individual observations relating to the Assam earthquake which may be considered more reliable than others.

Station	△ (*miles*)	Duration (*min*)
Digboi	90	4.5
Rima	100	4.5
Tezpore	266	4.3
Lumding	279	5.0
Silchar	345	5.0
	Mean =	4.7

The duration at Digboi was as indicated by a recording gauge. The total duration of the Lisbon earthquake may therefore be taken from 6 to 6½ minutes and that of the Assam earthquake from 4½ to 5½ minutes.

6. The period of vibration near the epicentre—T_0

For practical purposes, the same value may be taken for both the shocks. A functional relation has been shown, between the magnitude (M) and the period of vibrations of a shock, as follows (Gutenberg and Richter 1942):

$$\text{Log } T_0 = -1 \cdot 5 + 0 \cdot 22M \quad (14)$$

Let us take the lower limit of the value for the magnitude which has been assigned to the Lisbon earthquake by Gutenberg and Richter. This value is $8\frac{3}{4}$. Magnitude of the Assam earthquake has been found to be 8·6. With these values, T_0 for Lisbon and Assam earthquakes are 2·6 sec and 2·5 sec. It may be added that the period of the Tokyo-Yakohama earthquake of 1 September 1923 (magnitude 8·2) as recorded by the seismograph at Tokyo, was 2 seconds.

7. Maximum distance of observations of seiches—$\triangle_1$, $\triangle_2$, etc

The maximum and minimum distances where seiches due to the Lisbon and the Assam earthquakes were observed with names of places of observations are given in Table 3. Places of observations in columns (2) and (3) are the same. The maximum distances and places where oscillations of hanging objects were observed and the earthquakes reported felt, have also been given in the same table. The ratios of the distances are shown in columns (5) and (6). The nearness of the ratios relating to the different phenomena is striking. It appears that the values of the ratios in column (6) are slightly more consistent with one another than the other series. This would appear to suggest that the probable position of the epicentre was 50 to 100 miles in some southwesterly direction from Lisbon. Nearness of the ratios would also suggest that the same cause (probably the effect of the surface waves) was operative in producing the varied phenomena under review.

Following points appear to emerge from the study. Conspicuous seiches are generated by exceptionally strong earthquakes (probably when the magnitude exceeds 8·5) of small focal depths. Sources of water within the felt area may be disturbed differently, depending on the distance of the source from the epicentre and strength of the shock. True seiches generally start within but very near the outermost limit of the felt area and extend over a distance,

TABLE 3

Phenomena	Lisbon earthquake: Distance from Lisbon (*miles*)	Lisbon earthquake: Distance from point 38°N 10°W (*miles*)	Assam earthquake (distances from epicentre) (*miles*)	Col 2 / Col 4	Col 3 / Col 4	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1. Maximum distances of seiches	(*i*) 1820* (River Dal)	1920	1120 (Bah, Agra)	1.63	1.71	*Davison
	(*ii*) 2074** (River Aurosaki, Finland)	2174	Do.	1.85	1.94	**Reid
2. Minimum distances of seiches	610 (Bordeaux)	710	450 (Monywa)	1.36	1.58	
3. Maximum distances of oscillation of hanging objects	1390 (Rendsberg)	1490	900 (Fyzabad, U.P.)	1.54	1.66	
4. Maximum distances where the earthquake was felt	1415 (Hamburg)	1515	950 (Lucknow)	1.49	1.59	

outside this area, which depends on the strength of the shock. Seiches are generally observed over the latter area just outside the felt area but isolated seiches may be generated at any distance beyond this area when the shock is exceptionally strong.

A shock is generally perceptible over the so called 'felt area'. The extent of this area is generally dependent on the focal depth and magnitude of the shock. Very strong shocks are perceptible at isolated places over a region even beyond the felt area. The extent of the former region and the number of reporting stations appear to be a function of the strength of the shocks of small focal depths. It will be clear from a glance at the map in Fig. 1 that the nature of the country plays an important part in regard to perceptibility of the effects of a shock. The area over which the seiches are generally observed and the shock is perceptible, beyond the felt area, is common. The breadth of the former is however greater than that of the latter. Data given in Table 1 will illustrate this point.

8. Energy (E_1, E_2) and magnitude (M_1, M_2) of the Assam and Lisbon earthquakes

For calculation of the ratio of the energies of the Assam and Lisbon earthquakes from equation (10), we may assume that $h_1=h_2$ and $T_1=T_2$. The value of $h_2^2T_1^2/h_1^2T_2^2=1$. Uncertainty lies in what value should be taken for t_1 and t_2. Taking $4\frac{1}{2}$ to $5\frac{1}{2}$ minutes for t_1 and 6 to $6\frac{1}{2}$ minutes for t_2, the value of $t_2\triangle_2/t_1\triangle_1$ will lie between 1·85 and 2·45. The possibility of occurrence of other values of t_1 and t_2 cannot be precluded altogether. The value of t_1 at Digboi ($\triangle$=90 miles) is available from the trace of an autographic recorder and is $4\frac{1}{2}$ minutes; 4 to $4\frac{1}{2}$ minutes may relate to the principal vibrations. Three phases of the Lisbon earthquake were clearly observed at Lisbon. From the graphic description given with durations of the different phases and intervals between them, the period of the most violent shaking may be taken as 5 minutes. At any rate, this could not have been less than $4\frac{1}{2}$ minutes. Thus taking the second limiting value for t_1 and t_2 as 4 to $4\frac{1}{2}$ minutes and $4\frac{1}{2}$ to 5 minutes respectively, the lower and upper limits for $t_2\triangle_2/t_1\triangle_1$ are 1·7 and 2·45.

We will use either of the following relations, connecting energy with magnitude of an earthquake, for calculation of the energy and magnitude of the Lisbon earthquake.

$$\text{Log } E=11\cdot3+1\cdot8M \text{ (Gutenberg and Richter 1942)} \quad \ldots.(15)$$

$$\text{Log } E=12+1\cdot8M \text{ (Gutenberg and Richter 1949)} \quad \ldots.(16)$$

The value of M for the Assam earthquake is 8·6. Let M_1 and M_2 stand for the magnitudes of the Assam and Lisbon earthquakes. Substituting 8·6 for M_1 in equation (15), we get $E_1 = 6\times10^{26}$ erg. Then E_2 should lie between $1\cdot7\times6\times10^{26}$ and $2\cdot45\times6\times10^{26}$ erg or 10^{27} and $1\cdot5\times10^{27}$ erg. With these values of E_2, the limit of M_2, from equation (15) comes out between 8·73 and 8·82. The most probable value of the magnitude of the Lisbon earthquake therefore lies between 8·7 and 8·8.

The value of E_1 from equation (16) is 3×10^{27} erg. The limit of E_2 from this value is 5×10^{27} to $7\cdot4\times10^{27}$ erg. This gives the same values of M_2 as from the other equation.

Taking 6×10^{26} to 3×10^{27} erg for E_1 and 10^{27} to 7×10^{27} erg for E_2, we find that the energy of the Lisbon earthquake was double of that of the Assam earthquake.

Various methods are in use for calculation of the energies of earthquakes. A comparative discussion of some of these is being made elsewhere with a view to get a better approximation of the energies of these earthquakes.

9. Acknowledgement

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REFERENCES

Blake, A.	1941	*Bull. seism. Soc. Amer.*, **31**, 3, pp. 225–231.
Davison, C.	1936	*Great Earthquakes* (Thomas Murby and Co., London).
Gutenberg, B. and Richter, C.F.	1942	*Bull. seism. Soc. Amer.*, **32**, 3, pp. 163-191.
	1949	*Seismicity of the Earth and associated phenomena* (Princeton Univ. Press)
Milne, D.	1841	*New. Phil. J.*, **31**, pp. 37–40.
Oldham, R.D.	1899	*Mem. Geol. Surv. India*, **29**, p. 376.
Pramanik, S.K. and Mukherjee, S.M.	1953	A compilation of papers on the Assam Earthquake of August 15, 1950, p. 26 (Central Board of Geophysics, India, Publication No. 1).
Reid, H.F.	1914	*Bull. seism. Soc. Amer.*, **4**, 2, pp. 53-80.
Tandon, A.N.	1954	*Indian J. Met. Geophys.*, **5**, 2, pp. 95-137.
Tarr, R.S. and Martin, L.	1912	*U.S. geol. Surv.*, professional paper No. 69, p. 128.
Tillotson, E.	1951	*Nature*, **167**, pp. 128-130.