Vibration of Reinforced Concrete Chimneys.[1]

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With Plates I—VI.

1. Introduction. The stability of different structures against the earthquake motion much depends on the length of their proper oscillation periods. Thus a railway-bridge pier, even when very tall and 100 feet or so in height, makes an oscillation in less than 0.5 sec., which is shorter than the period of the destructive earthquake motion, namely, 1.0 to some 1.5 sec., and therefore belongs to the category of a " short column " and is weakest at the base. On the other hand, a high brick factory chimney forms a " tall column " and has a comparatively long oscillation period of 2 sec. or more, and is fractured by the earthquake shock at about two-thirds of the height. As reinforced concrete chimneys, rapidly increasing in number, differ in several respects from those of brick, it became necessary to investigate their stability against winds and earthquakes, and I was recently fortunate enough to find the opportunity of carrying on the measurement of the vibrations, amongst the others, of the new great chimney at Saganoseki.

(1) Translation, with additions, of the present author's articles on the vibration of reinforced concrete chimneys published in the Toyo Gakugei Zasshi, March and April, 1917.

2. Utility of a reinforced concrete column. Suppose there are two circular uniform-section columns i and ii (fig. 1), fixed to the ground, of homogeneous material and of equal external dimensions, of which one is solid and has a diameter of $2x_0$, while the other is hollow and has the external and internal diameters respectively of $2x_0$ and $2x_1$. The values of the stability of the two columns against the fracture by the earthquake motion at a section $S\,S$ are expressed by the accelerations, α_1 and α_2, as follows[1]:—

(i) Solid column:

$$\alpha_1 = \frac{gFx_0}{2w \cdot \overline{2f}^2};$$

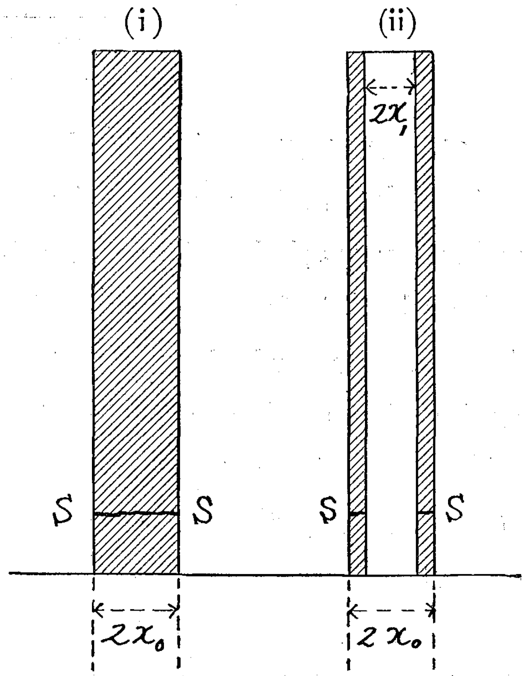
(ii) Hollow column:

$$\alpha_2 = \frac{gF(x_0^2 + x_1^2)}{2x_0\, w \cdot \overline{2f}^2} = \alpha_1 + \frac{gFx_1^2}{2x_0\, w \cdot \overline{2f}^2};$$

$2f$ being the height above the plane of fracture; w the weight of unit volume, and F the effective tensile strength, of the material of the columns; and g the acceleration due to the gravity. We have:—

$$\alpha_2 - \alpha_1 = \frac{g\,F\,x_1^2}{2\,x_0\, w \cdot \overline{2f}^2}$$

Fig. 1.



If the diameter $2x_0$ be comparatively large and the inner diameter $2x_1$ not much different from $2x_0$, then we have approximately:—

$$\alpha_2 - \alpha_1 = \alpha_1$$

or,

$$\alpha_2 = 2\,\alpha_1$$

Thus the seismic stability of the hollow column is always greater than that of the solid one, the ratio reaching the ultimate limit of 2 : 1 for the case of a very thin wall. This conclusion is

(1) See the *Publications of the Imp. Earthquake Investigation Committee*, No. 4.

legitimate only when the latter is sufficiently massive so as to warrant the employment of the fracture formulæ which apply to single columns. With respect to a brick or stone column, the thickness of the hollow wall can not be too much reduced. In the case of a reinforced concrete column, however, the thickness of the wall can be made very small, thereby combining the economy of material with the increase of the seismic stability. Thus reinforced concrete chimneys may be regarded as a class of structures suitable for earthquake countries.

The apparent anomaly of the inferiority of the stability of the solid column in comparison to the hollow one may be explained as follows. The seismic destructive force is equivalent to the product of the mass of a given structure multiplied with the maximum acceleration of the earthquake motion, and is not an entirely external force like that of the wind pressure. Hence the destructive force, which is proportional to the mass and which is resisted by the tensile strength of the section of fracture, is greater for the solid column than for the hollow column; the increase of the mass in the former being more effective than the decrease of the sectional area in the latter.

THE 567 FEET CHIMNEY OF KUHARA MINING COMPANY AT SAGANOSEKI.

3. The great Saganoseki chimney. The newly erected great reinforced concrete chimney of Kuhara Mining Company at the Smelting Plant of Saganoseki, in the Ōita prefecture, Kyushu, is the greatest in the world, and the main shaft has the height of 550 feet, being 40 feet taller than the similar one previously built at the Hitachi Mine of the same company, in the province of Hitachi. The foundation, composed of reinforced concrete, is circular, being 17 feet in thickness and 95 feet in diameter. The outer diameter of the main shaft is 42 feet 8 inches at the base and 27 feet 5 inches at the top, and the wall thickness varies from 29½ inches at the base to 7 inches at the top, the steel rods being embedded in the concrete at the depth of 3 inches from the outside surface. (See fig. 2.) The chimney has been designed by the Weber Chimney Company of Chicago, and the work of construction has been carried on by the Oriental Compressol Company of Tokyo. All the reinforcements consisted of the corrugated Johnson bars and the concrete had the composition of 1 : 2 : 3.5.

The main chimney shaft has a tapering form, the diameter, the wall thickness, the height of the centre of gravity, and the volume, of the different portions being as follows :—

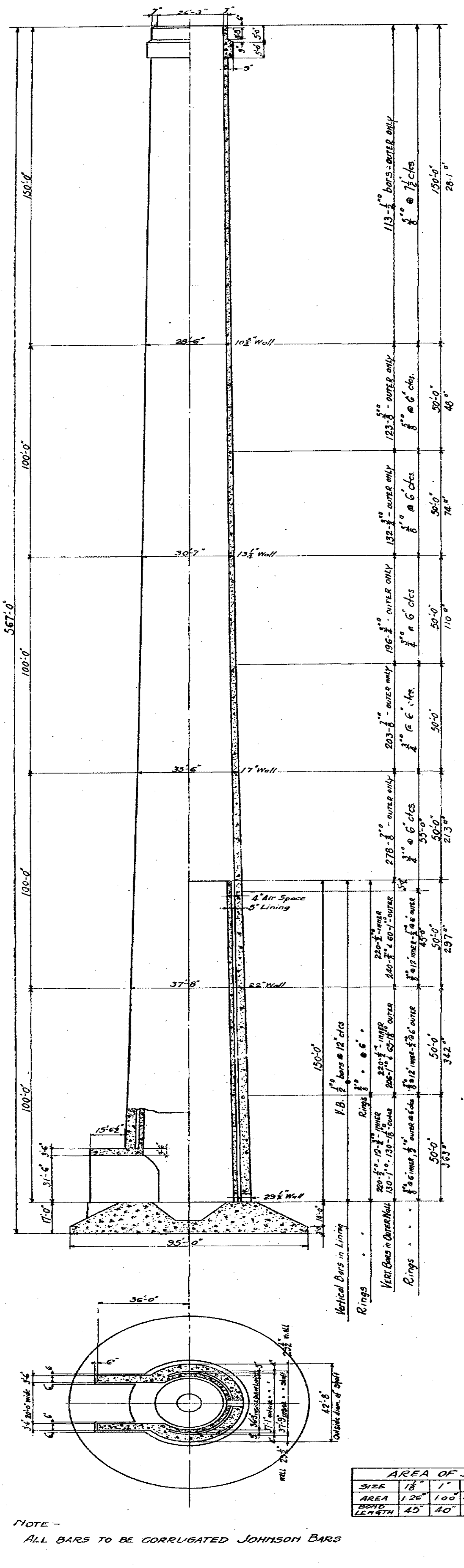
Height above Ground.	External Diameter.	Wall Thickness.	Portion of the main shaft.	Height Limits.	Height above Ground of Centre of Gravity of each portion.	Volume.
				ft. ft.	ft.	c.ft.
Top.	27′ 5″	7″	Highest	400—550	469.4	9437
400 ft.	28 6	10¾	4th	300—400	347.7	8932
300	30 7	13¼	3rd	200—300	247.2	12206
200	33 6	17	2nd	100—200	147.0	17377
100	37 8	22	Lowest	0—100	46.6	25700
Base.	42 8	29½	Total.	0—550	194.2	73652

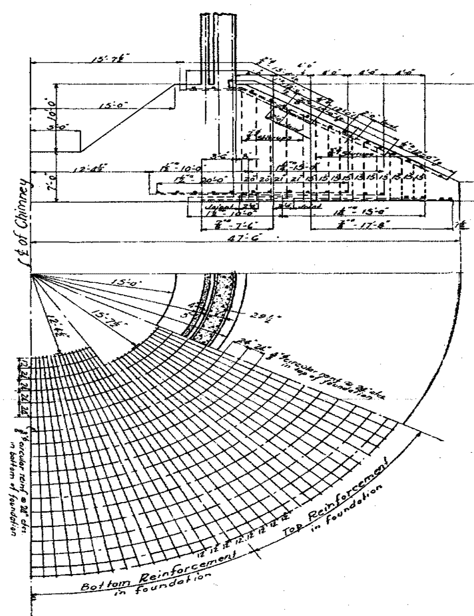
The main shaft exerts a pressure of 3 tons per square foot on the ground and has its centre of gravity at 194.2 feet from the latter, namely, at about 2/5th of the height of the structure. The amount of the materials used in the construction of the great chimney was as follows :—

Pl. I.

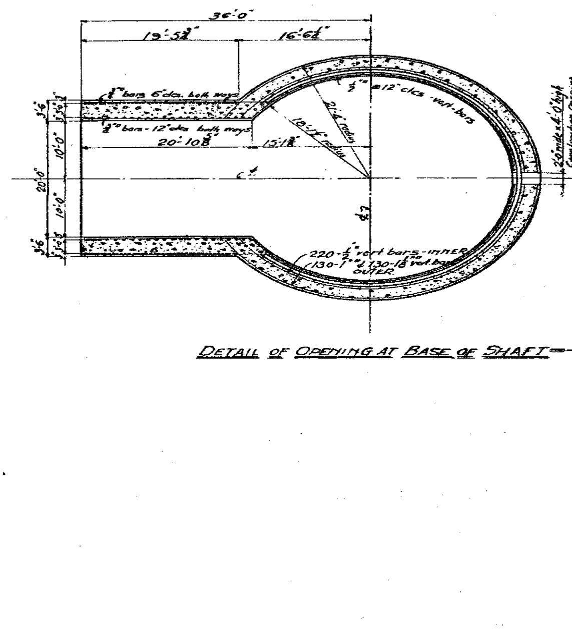
Fig. 2.

REINFORCED CONCRETE CHIMNEY
567'-0" HIGH x 26'-3" DIAM.
FOR THE
KUHARA MINING CO.
AT
SAGANOSEKI, JAPAN.





DETAIL OF FOUNDATION



DETAIL OF OPENING AT BASE OF SHAFT

AREA OF SQUARE BARS							
SIZE	1⅛"	1"	⅞"	¾"	⅝"	½"	⅜"
AREA	1.26"	1.00"	.766"	.563"	.391"	.25"	.141"
BOND LENGTH	45"	40"	35"	30"	25"	20"	15"

NOTE –
ALL BARS TO BE CORRUGATED JOHNSON BARS

The Oriental Compressol Co. Ltd.
ENGINEERING DEPARTMENT

The 567 Feet Reinforced Concrete Chimney at Saganoseki.

Fig. 3. Vibration Recorder mounted on the top of the reinforced concrete chimney shaft.

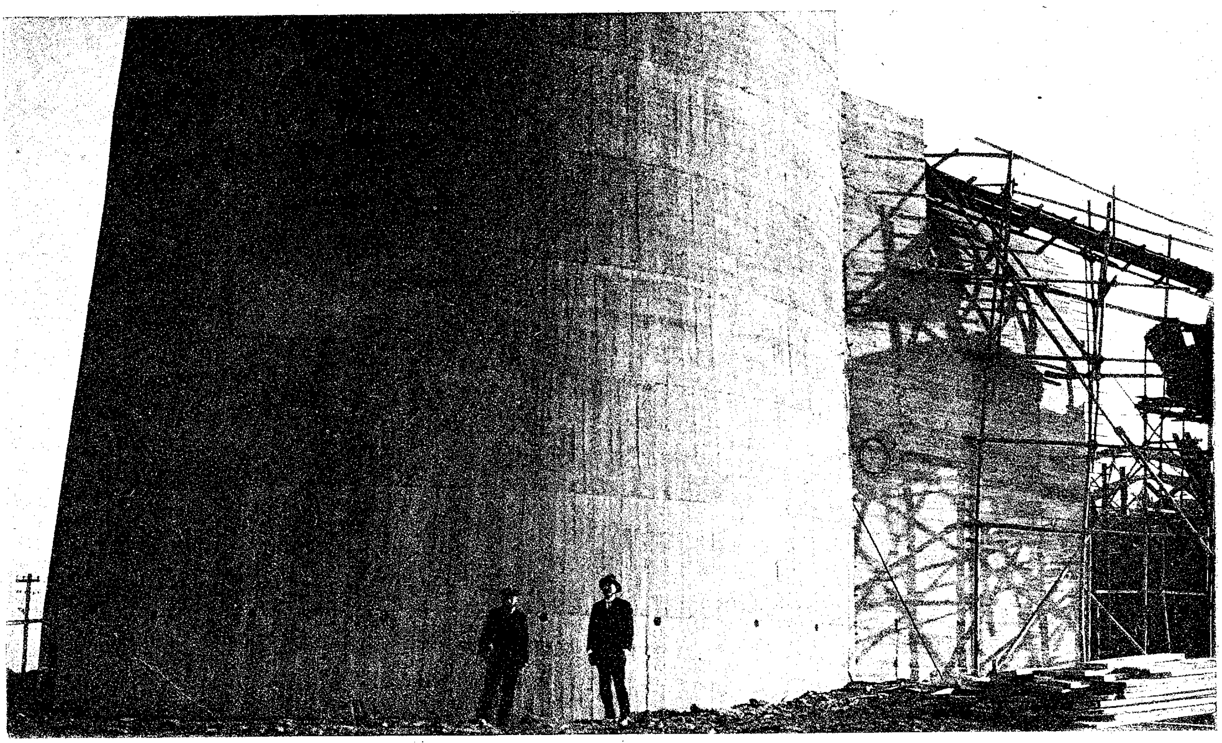


Fig. 4. The base of the great chimney.

Chimney.	Steel.	Concrete.	
		(Volume)	(Weight)
Foundation.	111 tons	341 cubic *tsubo*(1)......	4603 tons
Main Shaft.	316 „	336 „	4536 „
Total.	427 „	677 „	9139 „

As 1 cubic foot of the concrete weighs 140 lbs., the total weight of the reinforced concrete used in the main shaft is 4852 tons, of which 4536 tons is concrete and 316 tons is steel. The work of the foundation construction was started on April 16th, 1916, and the main shaft, built 5½ feet height successively, has been completed in the course of the 190 days between June 15th and Dec. 20th (night) of the same year. As the chimney stands on the top of the rocky Saganoseki promontory of a hard Paleozoic formation, the seismic movement of the ground would be comparatively weak and probably have an intensity less than 500 mm/sec^2. even in the case of the occurrence of a submarine destructive earthquake from the vicinity.

The top and the base of the chimney are respectively about 1000 and 450 feet above sea-level. Consequently the wind velocity at the top is generally much greater than at the base. Thus, on Dec. 22nd, 1916, at about 4 p.m., the wind velocity at the base was only 8 or 9 m/sec., while the anemometer mounted at the top of the chimney indicated a velocity of 24 m/sec. It is likely that in storms the wind velocity at the top will generally be at least twice as high as that at the base.

4. Method of experiment. The measurement of the movement of the chimney caused by winds has been carried on during the 5 days, Dec. 22nd to 26th, 1916, namely, a few days after the

(1) 1 *tsubo*=212 cubic feet.

completion of the structure ; the ascension to the top having being effected by means of a sort of elevator mounted on the temporary timber frame-work, which had been erected inside the shaft and which had supplied the means of carrying up the work men and the building materials during the course of construction, no exterior staging having been employed. The motion was registered mechanically with ink on white paper by a portable single-component horizontal vibration-recorder of 2 to 30 times magnification (fig. 3), and another of half-size reduction, fixed on the top of the steel-concrete wall of the chimney shaft, used respectively when the weather was calm and when it was rough. As the prevailing strong winds were from the W.W.N., the instruments, oriented so as to indicate the vibration in the radial or in the tangential direction, were set up generally on the opposite, or the E.E.S., side, being thus situated vertically above the junction of the chimney with the steel-concrete flue, whose course is also nearly parallel to the W.W.N.-E.E.S. direction. The wall thickness of the flue is 3 feet 6 inches and the opening at the base is 20 feet in width and 21 feet in height, with a semi-circular top of 10 feet radius. On Dec. 23rd, when the winds were weak, the measurement has been made at the N. N. E. portion of the chimney top. In every case, each of the recording instruments was properly protected by covers so that the steady mass and the writing index received no direct disturbances from the winds. The wind velocity was read off from a Robinson's anemometer set up on the chimney top observed each time during a few seconds interval. At the top of the chimney was provided a sort of plank flooring to accommodate the people engaged in the measurements.

The existence of the interior scaffolding, $12' \times 12'$ feet in size and composed of 4 corner posts $6'' \times 6''$ for the lower 400 feet and

4″×4″ for the upper 150 feet, which was at 50 feet height intervals propped against the interior of the wall of the chimney by means of two horizontal rectangular wooden beams, would not sensibly interfere with the vibration of the chimney shaft, as it was slender and its total weight was only 70 tons, namely, 1/70th of that of the latter. The movement of the elevator steel rope of 0.36 inch diameter, carrying, with the maximum speed of 300 feet in 1 minute, at each end a large iron bucket of 1/4 ton load capacity, produced no indication on the vibration-recorder set up at the top of the reinforced concrete chimney shaft.

5. Weather during the experiments. On the afternoon of the 22nd of December, the wind at the chimney top reached the force of a strong gale and had the velocity of 24 m/sec. On the 23rd to the 25th the weather was fine and there was practically no wind at the ground surface, while the wind velocity at the top of the chimney did not exceed 7 m/sec., so that the vibration-recorders indicated only slight movements, which were insensible. On the 26th the weather was, fortunately for the purpose of the experiment, very stormy and the wind which had the force of a hurricane at the chimney top indicated there a velocity of 35 m/sec.

6. Vibration of the chimney. On Dec. 22nd, when the wind velocity was 24 m/sec. at the top of the chimney shaft, the latter made well pronounced movements of about 1 inch, causing a sensation like that experienced in a shaky bogie railway carriage. The complete period of the oscillation as actually felt and measured with a stop-watch was 2.5 sec., as follows:—

At 3.30 p.m. : 10	large	distinct	oscillations	in	24.5 sec.
3.50 „ : 10	„	„	„	„	24.5 „
3.55 „ : 10	„	„	„	„	24.5 „

In strong gales and hurricanes the air circulation about the chimney top seems to be complicated. Thus, on the same afternoon, when the N. N. W. gales were steadily blowing, small balloons and paper pieces thrown from the chimney top at the lee side were at first hurled precipitously and vertically down along the shaft for some 150 feet and then gradually carried toward the S. S. E.

The movements of the chimney measured at the top with the vibration-recorders, illustrated in figs. 5, 6, 7, and 8, are indicated in the following two tables :—

Date and Time (Dec. 1916).	Wind Velocity.	Vibration of Chimney *Normal* to the Direction of Flue and Wind.	
		Range of Motion.	Complete Period.
23rd ; 9–12 a.m.	6.9 m/sec.	0.18 mm	2.55 sec.
	6.7	0.13	2.58
	5.5	0.17	2.55
,, 2.15 p.m.	4.5	0.14	2.54
24th ; 2.30 p.m.	1.0	0.13	2.53
,, 10.00 a.m.	4.5	0.46	2.56
25th ; 11.00 a.m.	1.8	0.72	2.54
26th ; 3.00 p.m.	35.0	186.00	2.56

Date and Time (Dec. 1916).	Wind Velocity.	Vibration of Chimney *Parallel* to the Direction of Flue and Wind.	
		Range of Motion.	Complete Period.
22nd ; 3.30 p.m.	22.0 m/sec.	20.00 mm	2.56 sec.
24th ; 1.00 p.m.	1.0	0.47	2.52
,, 11.00 a.m.	1.0	0.24	2.53
26th ; 3.30 p.m.	35.0	20.00	2.54

According to the above tables it will be seen that the vibrations of the chimney, which were quite insignificant for the wind velocity under 6 m/sec., much increased in amount with the augmentation of the wind velocity, the ratio being one much quicker than that of the square of the latter. Thus, the range of motion or double amplitude, was about 1 inch at the strong gale of 24 m/sec. speed, but it reached 7.7 inches (=186 mm) at the hurricane wind blowing 35 m/sec. Should the wind velocity amount to 50 m/sec. at the chimney top, the motion of the latter would at least be 15 inches. The period (complete) of the chimney oscillation, whose mean value was 2.53 and 2.55 sec. in the directions respectively parallel and normal to the wind, did not vary with the amplitude within the range of the present experiment, probably because the motion was well below the elastic limit of the reinforced concrete structure.

7. Relation between the wind direction and the vibration of the chimney. Standing on the chimney top it has been distinctly observed that the shaft oscillated much oftener and to a considerably greater extent in the component at right angles, than in that parallel, to the wind direction. According to the instrumental measurements indicated in the two above tables, the maximum vibration of the former category was 7.7 inches, while that of the latter was only about 1 inch. This peculiar behaviour of the chimney was due partly to the greater facility of motion transversal to the direction of the gale or hurricane, whose pressure must bend the column, rendering it difficult for the latter to oscillate against the wind. As a somewhat analogous instance, may be mentioned the case of a flexible bamboo stick fixed in a stream, which does not much oscillate against the running water, but is easily thrown into transverse movements.

8. Effect of the flue on the vibration. The existence of the flue opening at the base, with the height of 31 ft, and with the width of 20 ft, equal nearly to half of the diameter of the lower portion of the chimney, may cause the shaft to oscillate more easily in the direction transversal, than in one parallel, to the course of the flue. The slight superiority of the length of the period of the transverse oscillation (=2.55 sec.) over that of the parallel one (=2.53 sec.) may be attributed to this circumstance. As, however, in the present experiment the strong winds were blowing in the direction of the flue, the point in question can not be made clear. The peculiar relation to the wind direction considered in the foregoing § is probably the principal agency in causing the predominance of the transversal oscillation of the chimney. Still it is always necessary to limit the size of the opening at the base of a chimney, in order not to lessen the seismic stability of the shaft.

9. Succession of strong oscillations. According to the instrumental records, the chimney made alternations of groups of large and small vibrations at intervals of a few seconds or about a dozen seconds, there having been no case in which the motion was steadily large for several minutes. According to the following table, which relates to the motion of the chimney transverse to the direction of the wind recorded during the storm on Dec. 26th, the number of the successive strong vibrations of the chimney was generally 4 to 13, with the mean of 7 ; the total duration of each maximum group being 10 to 32 sec., with the mean of 18 sec. In the case of the exceptionally large vibrations, the number of repetitions was 20 to 22, extending over 51 to 56 sec. The duration here considered may be regarded as approximately indicating the time length during which the violent wind continued to blow, steadily and without cessation, on the occasion of the experiment on Dec. 26th.

Number of Strong Successive Vibrations.	Total Duration.	Maximum Motion.
4	10 sec.	128 mm
4	10	90
5	13	56
5	13	108
5	13	59
5	13	156
	13	130
5½	13	184
6	15	94
6½	16	168
7	18	93
7	18	166
7½	18.5	138
8	20	162
10	25.5	180
11	28	182
11	28	122
13	32	184
4½ } continuous.	11.5 }	123
8½ } continuous.	21.5 }	185
10 } ”	25.5 }	110
6 } ”	15 }	132
5½ } ”	14 }	72
7 } ”	18 }	150
20 } ”	51 }	184
22	56	184

10. Accumulation of motion. The motion of the chimney caused by the winds began invariably with small movements which were gradually increased to the maximum range, as shown in the following table relating to the motion transverse to the wind direction observed on Dec. 26th.

Number of vibrations of successively increasing amplitude.	Total Duration.	Limits of increase in the range of motion.
4	10 sec.	8 mm to 33 mm
4	10	8 42
4	10	5 59
5	13	8 93
5	13	15 107
7	18	6 168
7	18	7 128
4½	11.5	9 123
6	15	11 162
7	18	16 166
4	10	29 180
4	10	36 184
5	13	38 156
6½	16	40 184
5	13	40 184
4	10	46 130

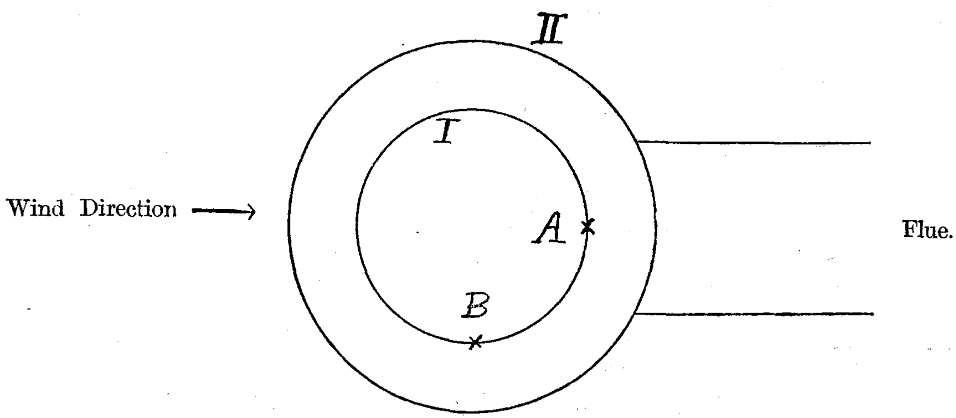
According to the above table, the vibration of the chimney increased from the small range of 5 to 46 mm to the maximum limit of 30 to over 180 mm after the repetition of 4 to 7 vibrations in the course of 10 to 18 sec., giving on the average the vibration number of 5 in 13 sec. This increase rate of the range of motion may partly be due to the more or less gradual augmentation of the force of the wind, but seems in the main to be the effect of the accumulation of motion. The motion occurring more or less conspicuously at the commencement of each vibration group may probably denote the effect of the direct impulsive force of the wind, and varied from 29 to 46 mm (about 2 inches), increasing nearly as the square of the wind velocity, according to the measurements on the 22nd and the 26th, December, as follows:—

(Dec.)	Wind Velocity.	Square of Velocity Ratio.	Initial Motion.	Amplitude Ratio.
26th:	35 m/sec.	......2.1	about 2 inches	2
22nd:	24 ,,		,, 1 ,,	

The maximum or accumulation motion in the vibration groups reached 4 times the range of the initial effect here considered. Thus, in the discussion of the vibration of a tall chimney caused by force of winds, it is necessary to investigate also the time relation of the latter.

11. Period of vibration. In the following table are given the wind velocity, the maximum range of vibration, and the average period found in the different experiments; the positions (*A*) and (*B*) denoting respectively the E.E.S. and the S.S.W. part of the top of the reinforced concrete shaft, as indicated in fig. 9. The period of the vibration transverse to the flue and the wind seems to be a little slower than that of the motion parallel to these latter.

Fig. 9.



Plan of the Chimney. I····Top. II····Base.

Motion *Parallel* to the Flue.			Motion *Transverse* to the Flue.		
Wind Velocity.	Max. Motion.	Average Period.	Wind Velocity.	Max. Motion.	Average Period.
Position (A).			**Position (A).**		
1.0 m/sec.	0.24 mm	2.53 sec.	1.0 m/sec.	0.13 mm	2.53 sec.
1.0	0.47	2.52	4.5	0.46	2.56
24.0	20.0	2.55	1.8	0.72	2.54
35.0	20.0	2.54	24.0	20.4	2.65(1)
			35.0	186.0	2.56
Mean.	—	**2.54**	Mean.	—	**2.57**
			Position (B).		
			6.9 m/sec.	0.18 mm	2.55 sec.
			6.7	0.13	2.58
			5.5	0.17	2.55
			4.5	0.14	2.54
			Mean.	—	**2.56**

(1) Measured on the top of the interior scaffolding.

12. Vibration of the interior scaffolding. The interior scaffolding which projected about 20 feet above the top of the chimney, was easily set into oscillations of a few inches and of period of 0.36 sec., when shaken powerfully by two or three men mounted on the timber frame. This caused, however, only a trifling effect on the reinforced concrete shaft, which was indicated on vibration-recorder diagrams as small tremors of 0.06 mm (period=0.66 sec.) and also of 0.18 mm (period=2.55 sec.). On the diagrams of the vibrations caused by the violent winds on Dec. 22nd and 26th, no trace of the effects due to the shaking of the scaffolding is to be found.

13. Tables. Tables I to VI give in detail the elements of motion of the great chimney, namely, the maximum range ($=2a$) and the average complete period ($=T$) indicated in different conspicuous parts of the vibration diagrams.

Vibration of the 550 Feet Reinforced Concrete Chimney at Saganoseki.

Half Size. Dec. 26th, 1916. Wind Velocity at the Chimney Top=35 m/sec.

Pl. III.

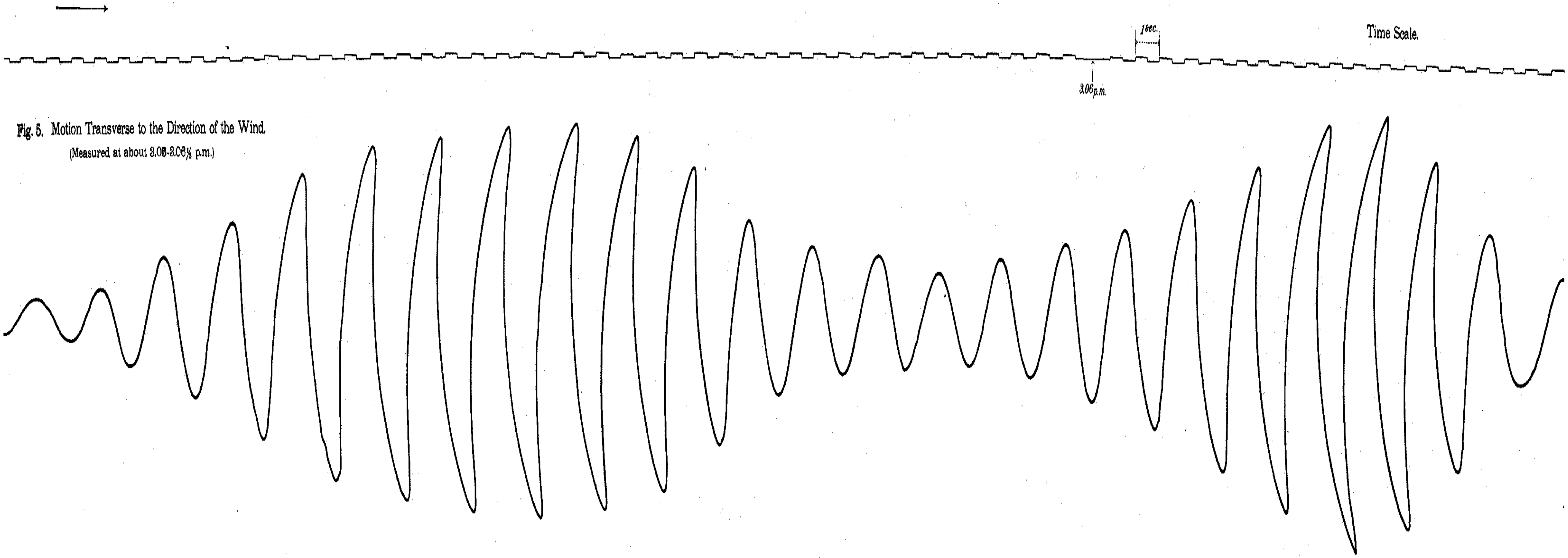
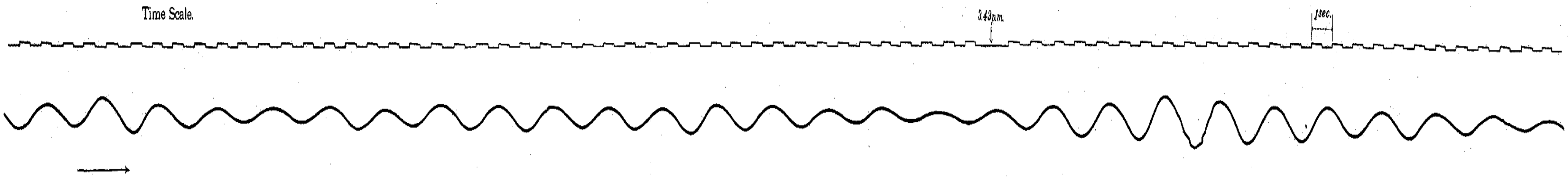


Fig. 5. Motion Transverse to the Direction of the Wind.
(Measured at about 3.05-3.06½ p.m.)

Fig. 6. Motion Parallel to the Direction of the Wind.
(Measured at about 3.42-3.43½ p.m.)



Vibration of the 550 Feet Reinforced Concrete Chimney at Saganoseki.

Motion Transverse to the Direction of the Wind. Half Size. Dec. 26th, 1916. Wind Velocity=35 m/sec.

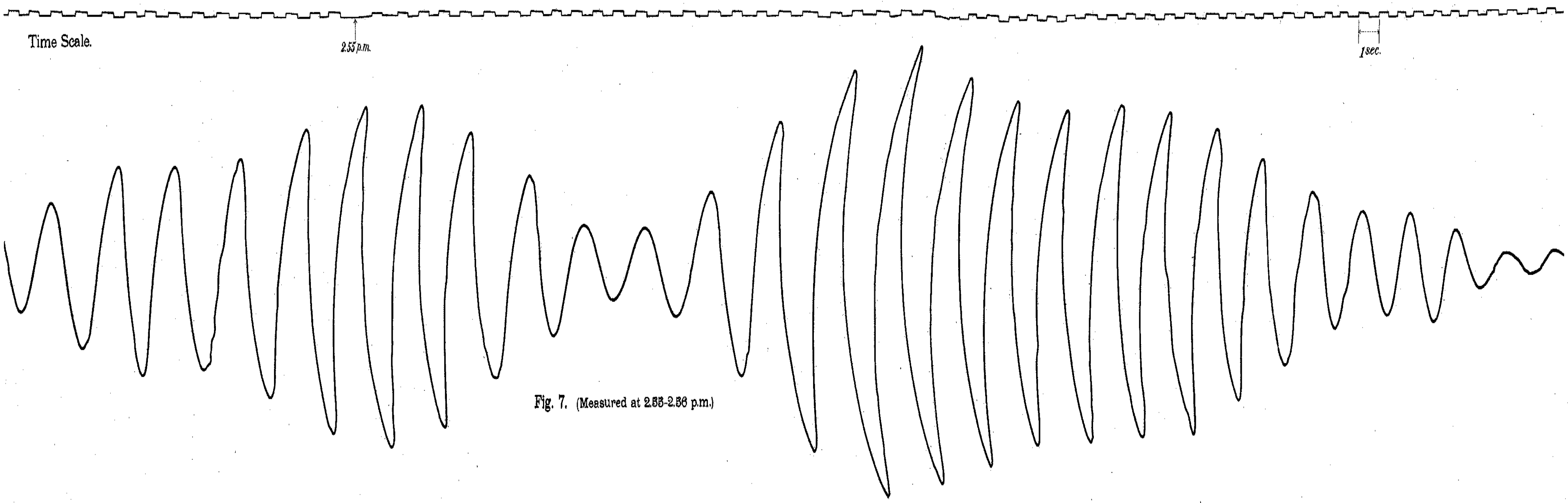


Fig. 7. (Measured at 2.55-2.56 p.m.)

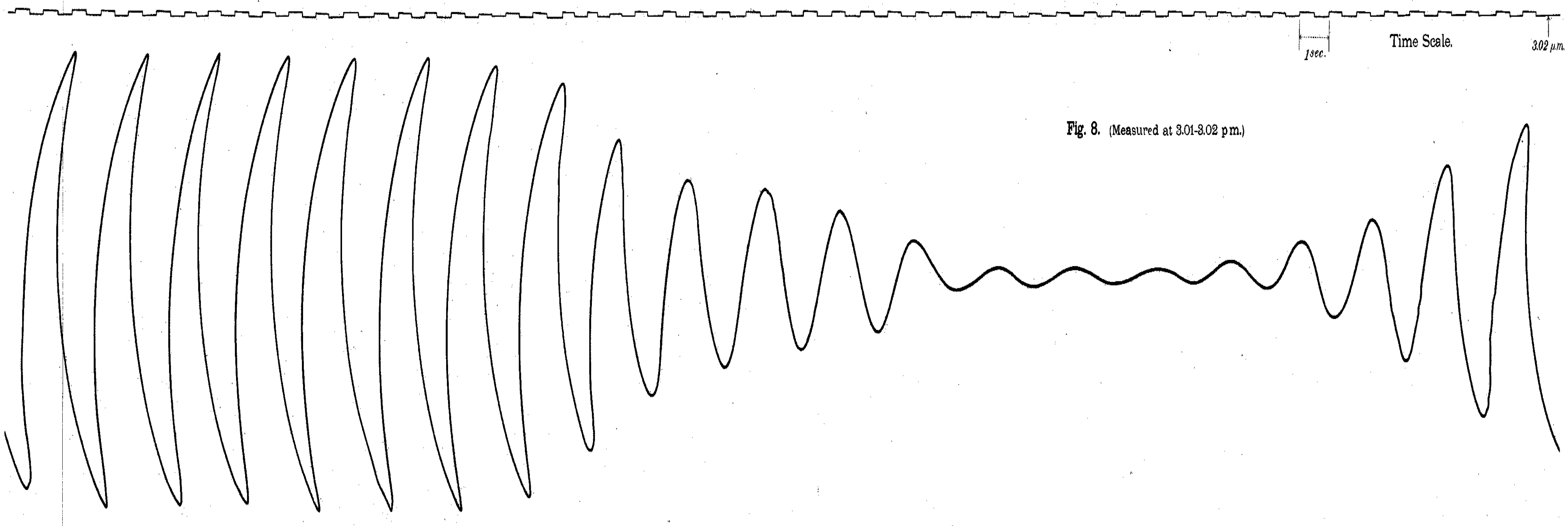


Fig. 8. (Measured at 3.01-3.02 p.m.)

TABLE I. VIBRATION OF THE GREAT SAGANOSEKI CHIMNEY.

Dec. 26th, 1916.

(Measured at the E.E.S. part of the top of the Concrete Shaft.)

A. Motion *Transverse* to the Direction of the Flue. 2½–3½ p.m.; N.N.W. wind,3 4½–35 m/sec.

2a	T	2a	T
128 mm	2.57 sec.	59.6 mm	2.55 sec.
8	2.58	12	2.54
184	2.45	182	2.56
40 (minimum)	2.52	138	2.60
163	2.62	109	2.57
16 (minimum)	2.73	10 (minimum)	2.46
130	2.56	119.4	2.57
186	2.45	49 (maximum)	2.60
124	2.57	12 (”)	2.49
109	2.61	15 (”)	2.63
162	2.62	169.4	2.50
7.2 (minimum)	2.82	4.4 (minimum)	2.60
185	2.59	22 (maximum)	2.60
185	2.59	44 (”)	2.50
36 (minimum)	2.62	12.4 (”)	2.55
183	2.57	18.2 (”)	2.49
155	2.54	77.2 (”)	2.48
88	2.54	20	2.46
39 (minimum)	2.63	16 (maximum)	2.52
128	2.55	101	2.53
14 (minimum)	2.53	177.2	2.50
184	2.70	184	2.59
149	2.62	79	2.55
71	2.54	57.6	2.52
13.2	2.60	5.2 (minimum)	2.52

B. Motion *Parallel* to the Direction of the Flue. 3½–3¾ p.m.; N.N.W. wind, 35 m/sec.

2a	T	2a	T
4 mm	2.56 sec.	20 mm	2.54 sec.
20	2.53	10	2.50
13.2	2.56	7	2.50
5.2	2.57	7.2	2.57
8.2	2.50	6	2.52

TABLE II. VIBRATION OF THE GREAT SAGANOSEKI CHIMNEY, *Transverse* TO THE DIRECTION OF THE FLUE.

Motion Measured at the E.E.S. Part of the top of the Concrete Shaft.

2a	T	2a	T
Dec. 24th, 2–3 p.m.; S. wind, 1 m/sec.		Dec. 25th, 11–12 a.m.; W. wind, 1.8 m/sec.	
0.13 mm	2.58 sec.	0.72 mm	2.58 sec.
0.05	2.51	0.31	2.57
0.09	2.56	0.15	2.53
0.06	2.48	0.26	2.49
		0.31	2.57
		0.05	2·58
Dec. 25th, 10–11 a.m.; S. wind, 4½ m/sec.		0.14	2.50
0.23 mm	2.55 sec.	0.05	2.51
0.46	2.55	0.16	2.50
0.35	2.52	0.33	2.53
0.13	2.62	0.09	2.51
0.20	2.57	0.17	2.58
0.24	2.57	0.14	2.53
0.27	2.53	0.33	2.55
0.09	2.54	0.13	2.49

TABLE III.

Motion Measured at the S.S.W. Part of the top of the Concrete Shaft.
Dec. 23rd, 1–2½ p.m.

Wind Velocity.	2a	T	Wind Velocity.	2a	T
6.7 m/sec.	0.13 mm	2.64 sec.	6.9 m/sec.	0.18 mm	2.53 sec.
	0.12	2.56		0.13	2.55
	0.10	2.55		0.13	2.53
5.5	0.10	2.62		0.17	2.50
	0.12	2.49		0.13	2.55
	0.07	2.52		0.13	2.50
	0.17	2.57		0.14	2.65
	0.13	2.55		0.13	2.58
4.5	0.12	2.44		0.16	2.58
	0.14	2.54			
	0.10	2.64			

VIBRATION OF THE GREAT SAGANOSEKI CHIMNEY.

TABLE IV. MOTION MEASURED ON DEC. 22ND, 1916.

3–4 p.m. Motion *Parallel* to the Flue measured on the E.E.S. part of the top of the concrete shaft.

Wind Velocity.	2a	T
21 m/sec.	3.0 mm	2.65 sec.
	11.0	2.58
22	1.9	2.43
	6.0	2.60
	5.8	2.55
	6.1	2.54
	4.0	2.45
	9.5	2.58
	”	2.47
	5.4	2.58
	8.1	2.58
	3.3	2.52
	5.2	2.67
	8.7	2.70
	20.0	2.63
	2.6	2.52
	5.4	2.58
	6.9	2.55
	2.4	2.45

4–5 p.m. Motion *Transverse* to the Flue measured on the scaffolding.

Wind Velocity.	2a	T
	11.2 mm	2.60
	19.	2.61
22.1 m/sec.	20.	2.70
”	”	2.63
	”	2.76
	20.	2.58
	9.6	2.52
	10.7	2.81
	20.	2.46
	20.	2.75
	”	2.70
	”	2.76
23.5	20.4	2.79
	20.4	2.69
	20.	2.64
	”	2.66
	20.3	2.70
	11.6	2.87
	20.	2.70
	”	2.57
24.0	”	2.64
	20.4	2.59
	”	2.50
22.5	”	2.51
	”	2.53
	”	2.64

TABLE V. MOTION *PARALLEL* TO THE DIRECTION OF THE FLUE.

(Dec. 24th, 1916. Measured at the E.E.S. part of the top of the concrete shaft.)

2a	T	2a	T
11 a.m.; S. wind, 1.0 m/sec.		1 p.m.; S. wind, 1.0 m/sec.	
0.10 mm	2.51 sec.	0.47 mm	2.54 sec.
0.12	2.60	0.30	2.54
0.24	2.50	0.08	2.48
0.17	2.50	0.23	2.55
		0.12	2.47

TABLE VI. VIBRATION OF THE GREAT SAGANOSEKI CHIMNEY CAUSED BY SHAKING THE INTERIOR SCAFFOLDING.

2a	T	Remarks.
Dec. 23rd, 8–9 a.m. Motion transverse to the Flue, measured on the scaffolding.		
0.90 mm	0.35 sec.	Impetus applied at about 1.8 sec. intervals.
0.10	0.26	
2.1	0.37	Impetus applied every 0.8 sec.
„	0.37	
Dec. 23rd, 10 a.m. Motion transverse to the Flue, measured at the S.S.W. part of the top of the concrete shaft. Wind velocity, 4½–6.9 m/sec.		
0.02 mm	0.67 sec.	
0.06	0.66	
0.03	0.65	
0.03	0.66	
0.05	0.68	
0.06	0.66	
0.04	0.67	
Dec. 25th, 10–11 a.m. Motion transverse to the Flue, measured at the E.E.S. part of the top of the concrete shaft. S. wind, 1.8–4.5 m/sec.		
0.30 mm	0.68 sec.	
0.21	0.66	
0.74	2.49	Slow oscillations following the direct shaking effects.
0.62	2.66	
0.15	0.64	
0.67	0.65	
0.37	(Slow)	
0.03	0.66	
0.08	0.65	
0.03	0.68	
0.10	0.64	
Dec. 24th, 1 p.m. Motion *parallel* to the Flue, measured at the E.E.S. part of the top of the concrete shaft. S. wind, 1.0 m/sec.		
0.04 mm	0.67 sec.	

100 FEET REINFORCED CONCRETE CHIMNEY AT SKEGAWA.

14. 100 feet Skegawa chimney. The 100 feet reinforced concrete chimney at Skegawa (fig. 10), built in the summer of 1916 by the Kuhara Mining Company, is circular in section, the dimensions being as follows:—

(Shaft.)	External Diameter.	Inner Diameter.
Base:—	5.7 feet.	4.5 feet.
Top:—	4.0	3.5

The thickness of the shaft, which is 0.75 foot for the lowest 30 feet, is then successively reduced for the upper three portions and becomes 0.5 foot for the topmost 25 feet. The shape of the chimney much approaches that of a cylinder, and the centre of gravity of the shaft is 37.2 feet above the ground, namely, at about 1/2.7 of the whole height. The volume and the height of the centre of gravity of the successive portions of the chimney are as follows:—

Successive Portion of the Shaft.	Height of Centre of Gravity, above the ground.	Volume.
Topmost 25 feet.	87.5 feet.	157.1 c. ft.
3rd 25 „	62.1	175.0
2nd 20 „	39.4	188.2
Lowest 30 „	14.6	362.0
Total	42.3	882.3

The material used in the construction of the chimney shaft and the foundation was as follows:—

	Volume of Concrete and Steel.	Percentage amount (weight) of Reinforcement.
Chimney Shaft:—	882 c. ft.	1.27
Foundation:—	975 „	0.225

The vertical steel rods were embedded at the depth of 2.4 inches from the outer side of the concrete shaft. The flue opening at the N.W. base of the chimney shaft is 6 feet in height and $3\frac{1}{2}$ feet in width.

15. Vibration measurement. For the convenience of the vibration experiments, executed on Jan. 30th and 31st, 1917, a temporary staging was erected around, but clear of, the chimney shaft whose use has been suspended during the two days. The vibration-recorder, which was one of the instruments previously used at Saganoseki, and had a magnification of 5 to 30 times, was fixed on the top of the concrete shaft, and registered the motion in the radial or tangential direction with ink on a white paper band wrapped round a roller. On the days of the experiments the weather was unfortunately clear and calm, such that it was not possible to ascertain the relation between the velocity of wind and the magnitude of the vibration. The chimney was, however, comparatively shaky and was easily thrown into vibrations of considerable amplitude by causing the shaft to be moved by a man mounted on the top.

16. Wind velocity. The velocity of the wind, measured with a Robinson's anemometer set up on the chimney top, had a mean of less than 10 m/sec., as follows:—Jan. 30th, 2 p.m.; N.W. wind; the mean velocity=9.6 m/sec. Jan. 30th, 3–$3\frac{1}{2}$ p.m.; N.W. wind; the velocity varied between 14.3 and 3.6 m/sec., with the mean of 7.6 m/sec. Jan. 31st, 11–$11\frac{1}{2}$ a.m.; S.S.E. wind; the velocity varied between 10.0 and 3.6 m/sec., with the mean of 5.8 m/sec.

17. Movements of the chimney. The results of the experiments, illustrated in figs. 11 and 12, for the case of the vibration parallel and for that transverse, to the direction of the flue were as follows:—

(Max. 2a = Maximum range of motion; T = Complete period.)

Date and Time. (Jan. 1917)	Wind Velocity.	Vibration of the chimney top *transverse* to the flue.			
		Natural motion caused by winds.		Motion produced by the artificial shakings.	
		Max. 2a	T	Max. 2a	T
30th, 3–3½ p.m.	N.W. wind: 7.6 m/sec. (average) 14.3 (max.)	0.95 mm	0.81 sec.	4.3 mm	0.84 sec.
31st, 10⅚–11⅙ a.m.	S.S.E. wind: 5.8 m/sec. (average) 10.0 (max.)	0.70	0.81	5.0	0.81
31st, 11½–12 a.m.	*Do.*	0.90	0.82	over 8.4	0.82
Mean.	——	——	0.81	——	0.82

Date and Time. (Jan. 1917)	Wind Velocity.	Vibration of the chimney top *parallel* to the flue.			
		Natural motion caused by winds.		Motion produced by the artificial shakings.	
		Max. 2a	T	Max. 2a	T
30th, 2–2½ p.m.	N.W. wind: 9.6 m/sec. (average)	1.0 mm	0.81 sec.	{ 3.4 mm 0.3	0.81 sec. 0.18
30th, 2½–3 p.m.	N.W. wind: 7.6 m/sec. (average) 14.3 (max.)	0.68	0.81	2.3	0.81
31st, 9½–10½ a.m.	Nearly calm.	0.74	0.79	{ over 5.5 0.18	0.82 0.17
31st, 10½–10⅔ a.m.	Very feeble.	0.70	0.79	{ 3.3 ——	—— 0.17
Mean.	——	——	0.80	——	{ 0.81 0.17

Vibration period. The vibration period was 0.8 sec. on the average. It seems to be only slightly longer in the direction transverse, than in that parallel, to the course of the flue. The existence of the opening at the base of the shaft exercises, therefore, no very great influence on the strength of the chimney.

Magnitude of motion. The oscillation of the chimney reached, even for the wind velocity of less than 10 m/sec., a range or double amplitude of 0.7 to 1.0 mm, being considerably greater than in the case of the great chimney at Saganoseki. The range of shaking produced by a man mounted on the top was a few millimetres or even over 1 cm; the period of the vibrations thus caused was 0.81 or 0.82 sec., being the same as that of the natural movement of the chimney. The artificial motion was mixed up with the small quick tremors of 0.17 sec. These were produced also by the passage of a railway train close by.

Duration of motion. The number of the more or less well-defined vibrations of the chimney caused by the winds, was, as shown in the following table, 8 to 18½, with the mean of 13.3, corresponding to the total duration of 10.8 sec. This latter probably indicated the approximate interval during which the wind continued to blow steadily. In the case of the experiments at Saganoseki, when the wind velocity reached 35 m/sec., the time interval under question was on the average about 18 sec. It is likely that the wind continues to blow steadily longer in storms than in ordinary weathers.

Number of successive well-defined Vibrations.

Jan. 30th.		Jan. 31st.	
10	14	8	16
10	14	9	18½
11	15	10	
11½	16	12	
12	17	15	
12	18½	15	
13		15	

18. Tables. Tables VII and VIII give in detail the elements of motion of the Skegawa 100 feet chimney, namely, the maximum range (=2a) and the average period (=T) indicated in different conspicuous parts of the vibration diagrams.

TABLE VII. VIBRATION OF THE 100 FEET REINFORCED CONCRETE CHIMNEY AT SKEGAWA.

(Measured at the top of the concrete shaft, Jan. 30th–31st, 1917.)

Motion *transverse* to the Flue.	
2a	T
Jan. 30th, 3–3½ p.m.	
0.90 mm	0.81 sec.
0.21	0.80
0.91	0.82
0.30	0.81
0.55	0.82
0.26	0.81
0.15	0.80
0.45	0.82
0.95	0.82
Jan. 31st, 10.50–11.10 a.m., wind velocity 5.6 m/sec.	
0.70 mm	0.81 sec.
0.25	0.82
0.64	0.81
0.23	0.80
Jan. 31st, 11½–12 a.m., wind velocity 5–6 m/sec.	
0.15 mm	0.82 sec.
0.90	0.80
0.30	0.84

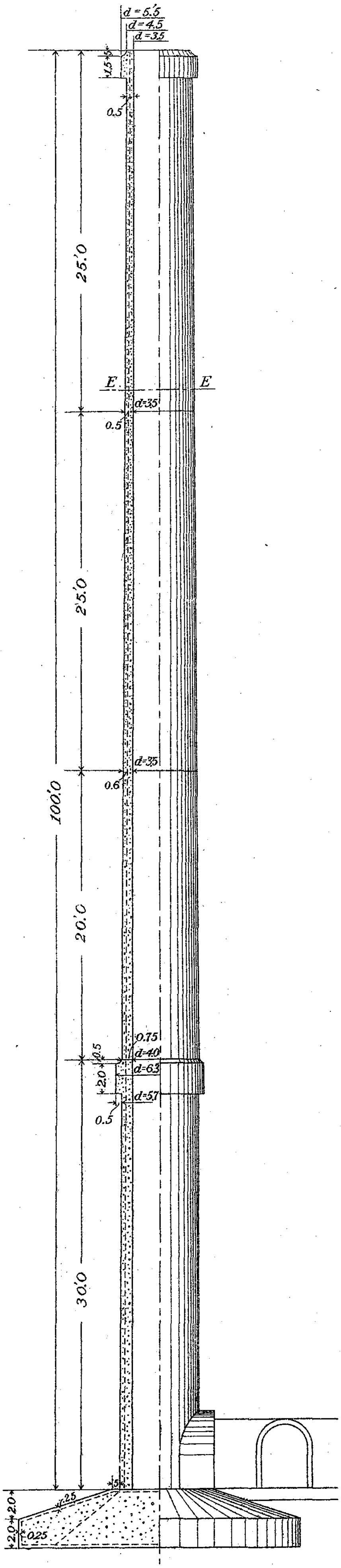
Motion *parallel* to the Flue.	
2a	T
Jan. 30th, 2–2½ p.m.	
0.75 mm	0.81 sec.
1.01	0.81
0.47	0.82
0.51	0.80
0.57	0.82
0.33	0.82
0.59	0.80
0.74	0.82
0.74	0.82
0.17	0.81
Jan. 30th, 2½–3 p.m., west wind.	
0.25 mm	0.81 sec.
0.55	0.81
0.30	0.80
0.19	0.80
0.68	0.82
Jan. 31st, 9½–10½ a.m., wind velocity 1–2 m/sec.	
0.51 mm	0.78 sec.
0.46	0.81
0.74	0.78
0.40	0.80
0.70	0.78
0.25	0.82
0.49	0.79
0.47	0.79
0.16	0.78
0.06	0.79
Jan. 31st, 10½–10⅔ a.m., wind weak.	
0.5 mm	0.79 sec.
0.7	0.80
0.6	0.80
0.44	0.80
0.2	0.78

TABLE VIII. VIBRATION OF THE 100 FEET REINFORCED CONCRETE CHIMNEY AT SKEGAWA, DUE TO THE SHAKING OF THE TOP OF THE SHAFT CAUSED BY A MAN MOUNTED ON IT.

(Measured at the top of the concrete shaft, Jan. 30th and 31st, 1917.)

Date, Time.	Wind Velocity.	2a	T	Remarks.
	m/sec.	mm	sec.	
Jan. 30th.* 2–3 p.m.		3.4	0.80	Mixed with movements of 2a = 0.13 mm, T = 0.18 sec.
		3.4	0.82	
		2.25	0.81	
Jan. 31st,* $9\frac{1}{2}$–$10\frac{1}{2}$ a.m.	1–2	1.92	0.80	Max 2a after the cessation of the artificial shaking = 2.24 mm.
		2.45	0.80	Mixed with small vibrations:—
		2.95	0.82	2a = 0.18 mm, T = 0.17 sec.; 0.14, 0.17; 0.04, 0.16; 0.05, 0.17
		3.26	0.82	
		2.69	0.81	
		2.84	0.85	Maximum amount of the motion = about 5.5 mm.
Jan. 30th, 3–$3\frac{1}{2}$ p.m.		3.40	0.84	
		4.33	0.85	
		1.50	0.82	
Jan. 31st, 10.50–11.10 a.m.	5.6	2.24	0.79	
		4.65	0.82	
		3.40	0.83	
		4.80	0.81	
		3.63	0.80	
		5.00	0.82	
		4.00	0.80	
Jan. 31st, $11\frac{1}{2}$ a.m.	5–6	4.20	0.80	
		2.10	0.83	
		1.30	0.83	

(*) These relate to the motion parallel to the flue, the others relating to that transverse to the latter.



Scale 1 : 150

Fig. 10.
100 Feet Reinforced
Concrete Chimney
at
Skegawa.

Vibration of the 100 Feet Reinforced Concrete Chimney at Skegawa.

Motion Transverse to the Direction of the Flue. Magnification = 20. Jan. 31st, 1917.

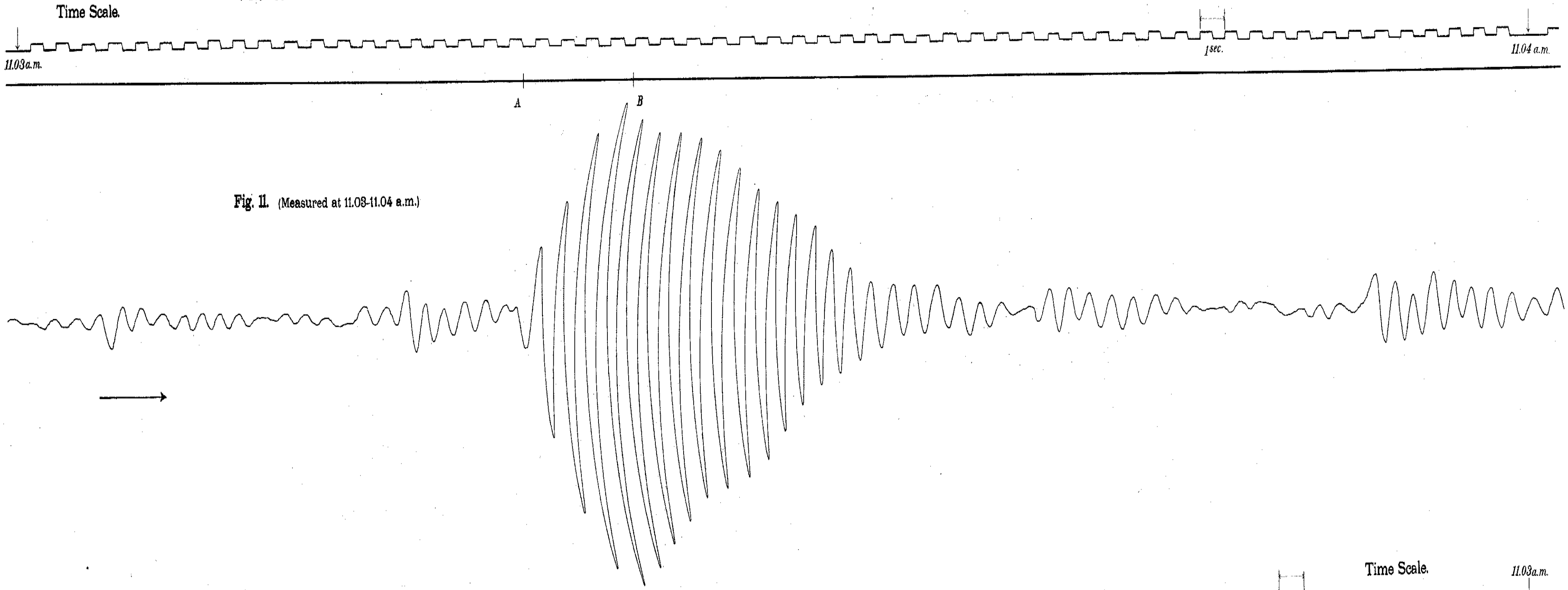


Fig. 11. (Measured at 11.03-11.04 a.m.)

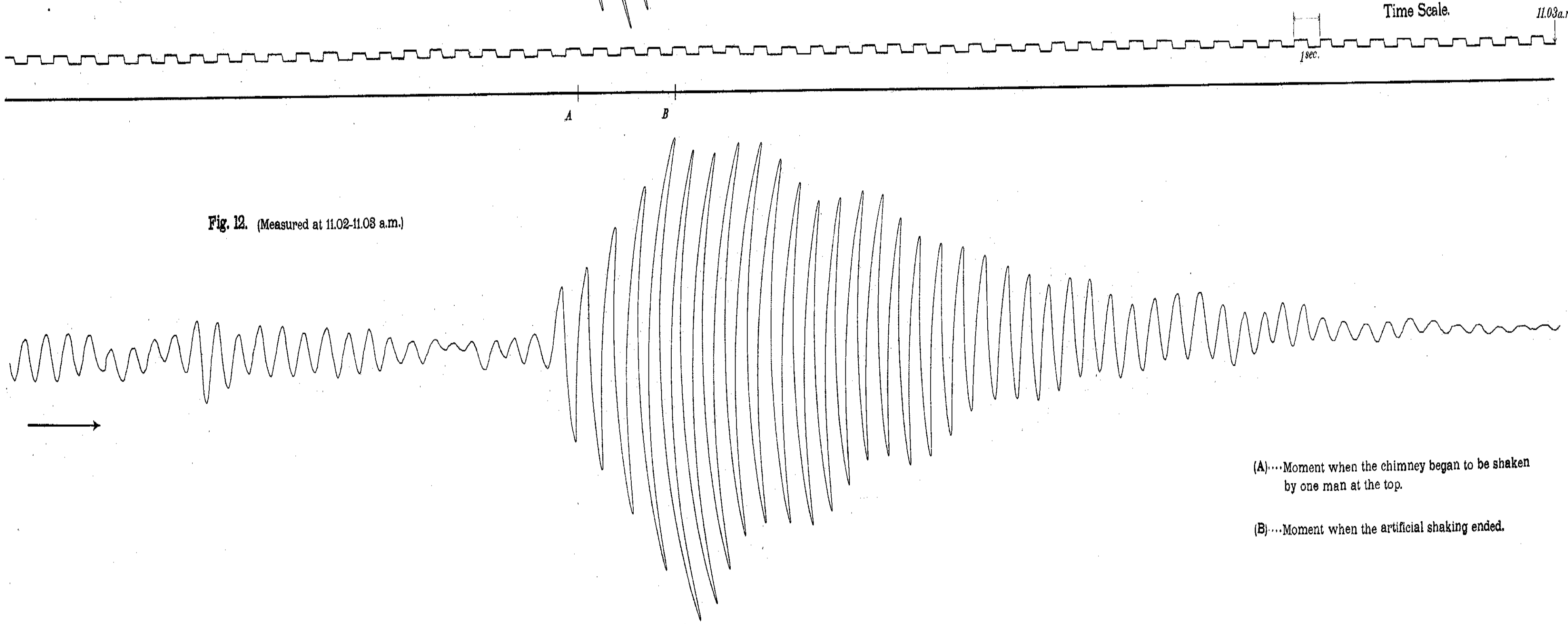


Fig. 12. (Measured at 11.02-11.03 a.m.)

(A)····Moment when the chimney began to be shaken by one man at the top.

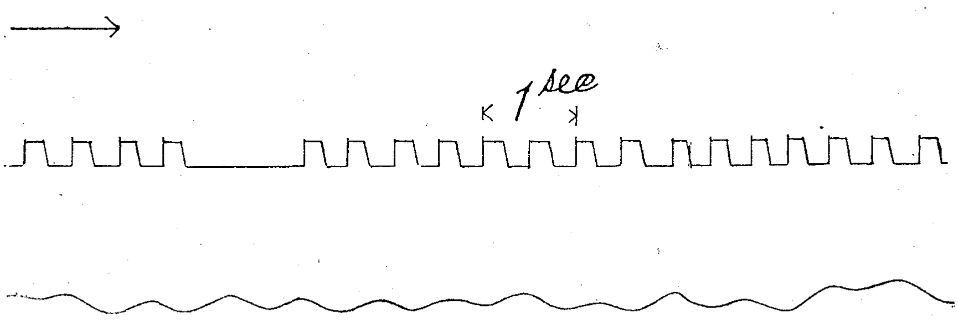
(B)····Moment when the artificial shaking ended.

100 FEET REINFORCED CONCRETE CHIMNEY OF THE MEDICAL COLLEGE, TOKYO.

19. The cylindrical reinforced concrete chimney of the Medical College, Tokyo Imperial University, completed in 1915, is 100 feet in height, and has an uniform internal diameter of $5'$ $6''$, being lined with an internal brick shaft, $4''\frac{1}{2}$ in thickness. The thickness of the outer, or concrete, shaft is 9 inches for the lowest 15 feet, then becomes 7 inches, being gradually reduced to 5 inches at the top. The outer diameter of the chimney is $7'$ $1''$ at the latter and $7'$ $9''$ at the ground. The foundation is 23 feet in diameter and $4'\,\frac{1}{2}''$ in thickness.

The tremor-recorder, which was the same as one of the instruments used in the cases of the Saganoseki and Skegawa chimneys, was set up on the iron platform around the top of the chimney, the ascent having been effected by means of the iron ladder steps fixed to the external side of the main shaft.

Fig. 13. Vibration of the 100 Feet Reinforced Concrete Chimney of the Medical College, Tokyo Imperial University.
(Magnification = 20.)



On the afternoon of March 8th, 1916, when the measurement was carried on, the wind was moderately strong, with the velocity of some 5 to 6 m/sec., yet the chimney was thrown only into very small movements, as shown in fig. 13. The vibration period was 0.85 sec., with the maximum motion of 0.2 mm.

SUMMARY OF THE RESULTS.

20. Comparison of the chimney at Skegawa with those at Saganoseki and at the Tokyo Imperial University. The comparatively large amount of vibration of the 100 feet chimney at Skegawa may partly depend on the slender form of the shaft whose base has an external diameter of 5.7 feet and bears to the height a ratio of 1 : 17.5. The 100 feet chimney of the Tokyo Imperial University has the external base diameter of 7′ 9″, whose ratio to the height is 1 : 12.9. Again, the base dimension of the great Saganoseki chimney is 42′ 8″ and is 1/12.9 of the height. The two latter chimneys are thus much more stable in form than the first. It may be also that in the case of the Skegawa chimney the execution of work was not perfect. Should the foundation be not sufficiently solid, the entire chimney would become shaky.

21. Intensity of motion. The maximum motion (=2a) of the great Saganoseki chimney, observed on Dec. 26th, 1916, was 7.7 inches or 186 mm, with the period of 2.55 sec. This gives the maximum acceleration of 565 $mm/sec.^2$, which is larger than the intensity of 444 $mm/sec.^2$ at Hongo (Tokyo Imp. University) on the occasion of the semi-destructive Tokyo earthquake of June 20th, 1894. The motion of the chimney top observed on Dec. 22nd, 1916, was about 1 inch or 25 mm, with the maximum acceleration of about 80 $mm/sec.^2$; this being already sufficiently intense. Should the wind velocity reach 50 m/sec. at the chimney top, the vibration of the latter would acquire at least an acceleration of over 1000 $mm/sec.^2$ It thus appears that in a locality where the earthquake motion is not very violent and has an acceleration, say, of under 500 mm/sec.^{2}, the effect of the wind pressure on a tall chimney becomes more important than that of the seismic motion.

In the erection of a chimney, a wall, a bridge pier, etc., the structure is to be so designed as to be able to withstand the earthquake motion likely to be expected at the place concerned. This seismic intensity may be estimated from the nature of the ground and also from the knowledge of the position of the neighbouring earthquake zones, along which destructive shocks take place.

22. Conclusion. The vibration period of the 100 feet chimney at Skegawa was 0.81 sec., and that of the cylindrical 100 feet chimney in the Tokyo Imperial University was 0.85 sec. Thus a reinforced concrete chimney of height between 100 and 150 feet seems to make a complete vibration in about 1.0 sec., while the period of one, some 200 feet in height, will not much exceed 2.0 sec.; that is to say, in these different cases the natural oscillation of the structure is not sensibly slower than the motion of the ground in destructive earthquakes, whose period is included mostly between about 1.0 and about 1.5 sec. Hence a reinforced concrete chimney of height under some 200 feet must be regarded as a "short column" and is, in relation to the seismic motion, weakest at the base. It is thus desirable, for the chimneys of this category, to reduce the height of the centre of gravity as much as possible, and to make the lower portion of the shaft sufficiently strong.

On the other hand, the vibration period of the 550 feet Saganoseki chimney was found to be 2.55 sec.; that of the 1000 feet chimney projected by the Kuhara Mining Company to be built at the Hitachi Smelting Plant will probably be 4 to 5 sec.

Thus a reinforced concrete chimney, 500 feet or more in height, oscillates sensibly slower than the destructive earthquake vibration, and is accordingly to be regarded as a "tall column," which is seismically weakest, not at the base, but at about two-thirds of the height. It is hereby to be remarked that, in the usual chimney construction, the centre of gravity of the whole structure is at about 1/3rd of the height, while that of the upper one-third portion alone is nearly at the middle of its height, causing the shaft to be comparatively weak near the top. This point must be kept in view when designing a tall reinforced concrete chimney. For instance, it is very desirable to design a reinforced concrete chimney, 500 to 1000 feet in height, in such a way that the centre of gravity is at 1/4th of the height for the whole structure as well as for the upper portion alone; this rendering the chimney one of uniform strength against the earthquake shock. If, however, the centre of gravity of the whole structure be at 1/4th of the total height, while that of the upper 1/3rd portion be nearly at 1/2 of the height of the latter, the result is to render the chimney weakened at the very place where it is seismically weakest.

A reinforced concrete chimney 200 to 300 feet in height is intermediate between a "short column" and a "tall column." Its seismic stability must, therefore, be calculated for the base as well as for the 2/3rd height, and the smaller of the two values is to be adopted as indicating its strength.

The great chimney of Saganoseki stands on a hill of Paleozoic schistose rocks, while the 100 feet chimneys of Skegawa and Tokyo Imperial University are situated on the hard natural ground. The vibration of a reinforced concrete chimney erected on a very soft soil, such as the low town parts of Tokyo and

Osaka, may possibly be much larger than those in the cases here described.

In conclusion I must tender my warmest thanks to Messres. Miyanaga, Matsuda, Sato, Kishimoto, and Kobayashi, engineers, of the Kuhara Mining Company, for the various facilities afforded me in carrying out the measurement of the vibration of the different chimneys.

May 1917. Seismological Institute.