# MEASUREMENT OF VIBRATION OF GOJUNOTOS, OR 5-STORY BUDDHIST STUPAS (PAGODAS).

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*With Plates* XXIX–XLIV.

**1. Introduction.** The gojunotos or 5-story Japanese Buddhist stupas (pagodas) form an interesting class of tall wooden structure which is peculiarly earthquake-proof. In the present note I give the results of the vibration measurement of the following six old towers:—

| Locality of Gojunoto. | Date of Construction. | Remarks. |
|---|---|---|
| (1) Horyuji, near Nara, Yamato. | 15th year of Empress Suiko, 607 A.D. | |
| (2) Toji, in Kyoto. | 1641 | In 1692, the central post was cut short by 1.3 shaku. |
| (3) Toshogu, Ueno, Tokyo. | 1639 | Great repair in 1918. |
| (4) Hommonji at Ikegami, near Tokyo. | 1608 | |
| (5) Nikko. | About 1820 | Great repair in 1918. |
| (6) Asaksa, in Tokyo. | 1692 | Repaired in 1886. |

The construction details of the different gojunotos will be seen from figs. 3 to 10, which have been reproduced from the original drawings kept in the Bureau of Religions of the Department of Education or in the Institute of Architecture of the Tokyo Imperial University.

**2. Gojunotos.** A gojunoto consists essentially of the following two parts: (i), the *shinbashira*, or large vertical central post, generally of *hinoki* (*Chamaecyparis obtusa*) or *keyaki* (*Zelkowa acuminata*) timber, which extends through the whole height of the tower, and supports and is prolonged to fit into the *kurin*, or "nine rings," a high nine-ringed bronze hollow column projecting above the topmost roof; and (ii), the tower body, generally built of *hinoki* timber, whose successive stories, slightly decreasing in area upwards, is each composed of 4 inner and 12 external strong vertical columns well joined together. (See fig. 2.) The shinbashira, usually jointed at one or more different heights may, or may not, be in contact with the tower body, which simply rests on the foundation stone blocks. (See figs. 12 and 13.) The roofs of the Nikko and Asaksa gojunotos are covered by copper plates, and those of the others by tiles.

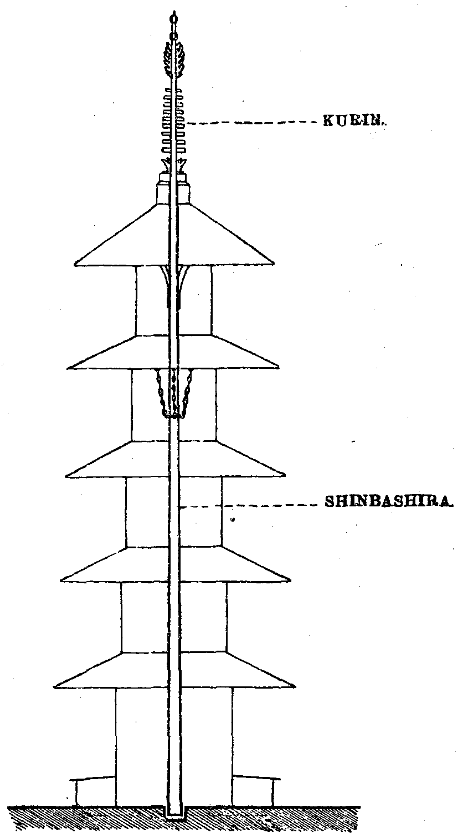

Fig. 1. Diagram showing the construction of Nikko Gojunoto.

The Horyuji temple, which at present comprises 28 buildings under the state protection, was founded by the Empress Suiko and the Prince Imperial Shotoku in the year 607 A.D. In spite of the several catastrophes in the course of the subsequent 13 centuries, the kondo (main hall), the gojunoto, the centre gate, and the galleries escaped destruction. These buildings are thus the oldest wooden architecture not only in Japan, but in the whole world. The stupa. 105.2 shaku[1] in height, stands on a double stone-foundation, the ground story measuring 21.2 shaku square. The "skirting roof" is a subsequent addition. Among the five other

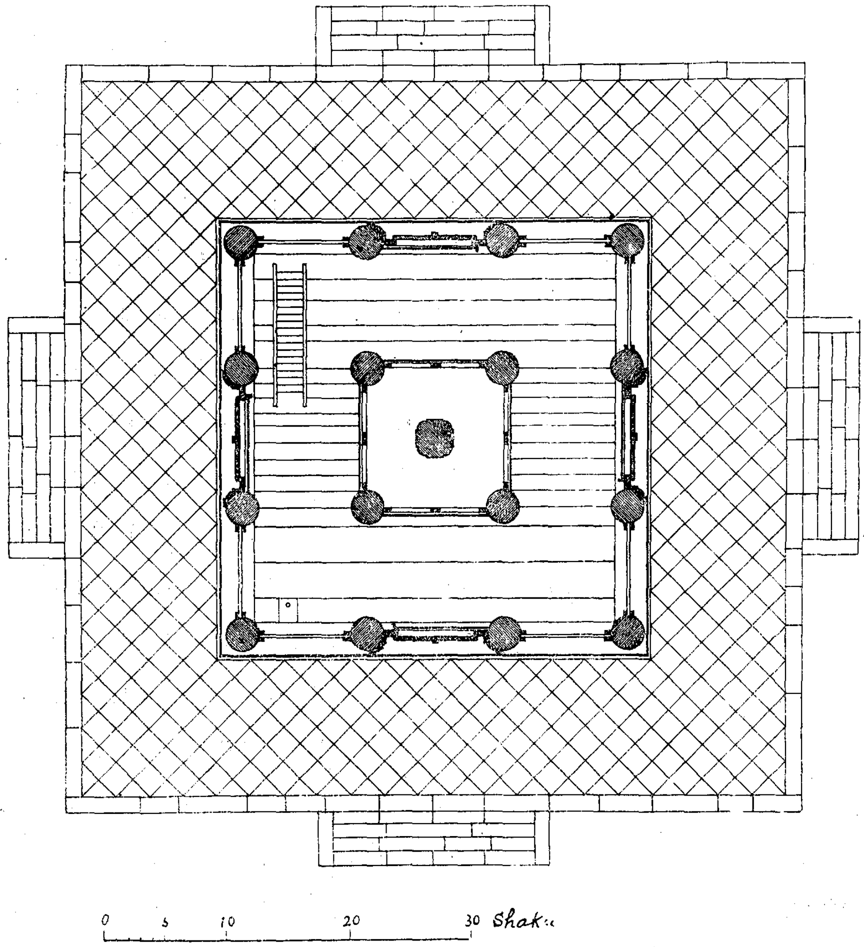


Fig. 2. Ground Plan of the Toji Gojunoto. (According to the drawing made by the late Mr. Y. Horiike. Scale in shaku (1 shaku=0.994 foot).

gojunotos, none of which has a skirting roof, the oldest is the Hommonji stupa, built 313 years ago, namely, in 1608, or 1001 years after the date of completion of the Horyuji temple.

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1) 1 *shaku*, or Japanese foot=0.994 English foot=$\frac{1}{33}$×metre.

The great stupa of Toji, built in 1641 by Tokugawa Iyemitsu, is the grandest among the existing gojunotos of Japan and has the total height of 183.7 shaku. The height of the kurin is 50.2 shaku and that of the tower body is 133.5 shaku. Of the five towers of Nikko, Horyuji, Ueno, Asaksa, and Hommonji, the first is the tallest with the total height of 114.8 shaku, and the last the shortest with the total height of 99.3 shaku. The other three have approximately equal height of 105.2 to 107.4 shaku. In Table I are given the dimensions of the different gojunotos.

TABLE I. Dimensions of the Different Gojunotos.

(1 shaku=0.994 foot.)

| Gojunoto. | Horyuji. | Toji. | Ueno. | Hommonji. | Nikko. | Asaksa. |
|---|---|---|---|---|---|---|
| Height. | | | | | | |
| | shaku. | shaku. | shaku. | shaku. | shaku. | shaku. |
| Kurin. | 31.9 | 50.2 | 27.0 | 20.6 | 27.0 | 25.7 |
| Tower Body. | 73.3 | 133.5 | 79.5 | 78.7 | 87.8 | 81.7 |
| Total. | 105.2 | 183.7 | 106.5 | 99.3 | 114.8 | 107.4 |
| Dimension of the Different Stories. | | | | | | |
| 1st Story. | 20.7 | 31.5 | 16.0 | 15.9 | 16.0 | 16.0 |
| 2nd ,, | 18.4 | 29.0 | 14.6 | 15.0 | 14.5 | 14.6 |
| 3rd ,, | 16.2 | 26.0 | 13.2 | 13.5 | 12.8 | 13.0 |
| 4th ,, | 13.7 | 24.3 | 11.8 | 12.3 | 11.5 | 11.6 |
| 5th ,, | 10.6 | 22.2 | 10.3 | 10.8 | 9.7 | 10.0 |
| Height of the Different Stories. | | | | | | |
| 1st Story. | 19.4 | 20.5 | 15.5 | 14.5 | 16.3 | 17.6 |
| 2nd ,, | 13.0 | 23.0 | 13.4 | 12.2 | 15.1 | 13.3 |
| 3rd ,, | 12.6 | 22.5 | 13.4 | 12.6 | 15.3 | 13.3 |
| 4th ,, | 12.0 | 22.0 | 13.6 | 12.7 | 15.2 | 13.7 |
| 5th ,, | 10.2 | 21.5 | 13.4 | 12.4 | 15.2 | 14.0 |
| 5th Roof. | 5.6 | 21.8 | 11.0 | 11.5 | 10.0 | 10.5 |
| Size of Shinbashira (Central Post). | | | | | | |
| At Bottom. | 3.3 | 3.0 | 1.85 | 1.25 * | 1.96 | 1.6 |
| ,, Top. | 1.5 | 3.0 | 1.85 | 1.16 | 1.58 | 1.3 |

(*) Size at the 2nd Story.

The four gojunotos of Ueno, Hommonji, Nikko, and Asaksa are nearly equal to one another in the dimensions of the sectional area, which is 16 shaku square at the 1st story and successively diminishes upwards, becoming about 10 shaku square at the 5th story. The size of the great stupa of Toji is nearly double that of the other towers, having the sectional area of 31.5 and 22.0 shaku square respectively at the 1st and the 5th stories. The tower-body of the Horyuji gojunoto is of proportionally large size, and the area of the 1st story is 20 shaku square, while that of the 5th is about 10 shaku square as is the case with the Nikko tower. The ratio of the height of the tower body to the dimension of the 1st story is as follows:—

| | | | |
|---|---|---|---|
| Horyuji | 3.5 | Hommonji | 4.9 |
| Toji | 4.2 | Nikko | 5.5 |
| Ueno | 5.0 | Asaksa | 5.1 |

Thus the stupa of Horyuji has the most stable form, while that of Nikko is the most slender of all.

**3. Shinbashira, or central post.** The ratio of the height of the tower body to the length of the kurin is as follows:—

| | | | |
|---|---|---|---|
| Horyuji | 2.3 | Hommonji | 3.8 |
| Toji | 2.7 | Nikko | 3.3 |
| Ueno | 2.9 | Asaksa | 3.2 |

The length of the kurin is longest in the Horyuji and Toji stupas, in each of which the shinbashira is of large size and stands on a foundation stone. The shinbashira of the Horyuji tower, which is in contact with the tower body at two intermediate heights, has the diameter of 3.3 shaku at base and of 1.5 shaku at top. In the great stupa of Toji the shinbashira supporting the tall kurin is entirely isolated from the tower body, and is of an uniform section 3 shaku square in area, jointed at two heights.

The shinbashira of the Ueno stupa, jointed at two places, is of a uniform section 1.85 shaku square in area. It stands on a foundation stone, while the top is secured in position by means of two horizontal iron rods passing through it at right angles to one another. It will be observed that the shinbashira, which is not very stiff, forms a sort of a heavy vertical column, supported at base and loosely fixed at top. This peculiar method of construction converts the central post into a sort of pendulum mass whose inertia prevents to a certain extent the free motion of the tower body.

The shinbashira of the Hommonji stupa, jointed at one place, is erected, not directly from the ground, but from the strong cross beams of the floor of the 2nd story, being otherwise not in contact with the tower body. It is octagonal and much smaller than the central posts in the other cases, with the diameters of 1.25 and 1.16 shaku respectively at base and at top. The shinbashira here forms a sort of an elastic inverted pendulum fixed to the main structure.

In the Nikko and Asaksa stupas, the central posts do not stand on, or touch the ground, but are suspended respectively from the 4th story and from the top of the tower body. In each of these cases, therefore, the shinbashira and the kurin form actually a pendulum system, which tends to keep its place when the tower body is shaken by a strong earthquake. The central post of the Nikko gojunoto is large in size, having the diameters of 1.96 and 1.58 respectively at bottom and at top. The post of the Asaksa stupa is a little smaller, and has the diameters of 1.6 and 1.3 shaku respectively at bottom and at top.

**4. Vibration measurement.** The measurement of vibration of the Horyuji gojunoto was made in 1910, while those relating to the others were carried on in the course of the two years 1919 and 1920. The dates and the conditions of the weather at the times of the experiments were as follows:—

Horyuji ...............July 18th, 1910; fore-noon. Very light winds.

Toji .....................March 19th, 1920; 11.50 A.M.–0.55 P.M. Heavy rain; slight winds.

Ueno .................June 26th, 1920; after-noon. Slight rain; no winds.

Hommonji ...........June 15th, 1920; 10.50 A.M.–1 P.M. Strong S.E. winds.

Nikko .................Feb. 28th–March 1st, 1919: very light winds.

Asaksa.................July 3rd, 1919; 1–3 P.M. Slight rain; very feeble winds.

On the occasion of the experiments with the Hommonji gojunoto there were strong winds, which caused the structure to deviate into distinct movements. On the dates of the measurement in the five other stupas, however, the weather was calm, there having been only very light winds or no wind at all, so that it was necessary to put the towers in oscillation by artificial means. The latter consisted in pushing the shinbashira, or central post, at the 4th or 5th story with hand horizontally from one direction several times successively at an interval of some $1\frac{1}{2}$ second. The tower body itself was thus gradually set in motion, which was easily caused to become intense enough to be sensible.

The tower vibration was measured by means of a portable tremor-recorder, with two horizontal components oriented at right angles to one another, whose writing pointers registered the motion in ink on white paper wrapped round a roller driven by means of a clock work.* The component horizontal pendulums had each a natural oscillation period of about 3 seconds, and the magnification ratio of the pointers varied between 5 and 30. The instrument was set up either on the inside floor or on the outside verandah of the 5th story. Illustrative diagrams are given in figs. 17 to 25, (Pls. XXXVII to XLIV).

In Tables II to XVI, which embody the results of the measurements, are given the maximum motion (2a) and the average value of the complete period (T), found from a number of well-defined and prominent consecutive vibrations at different stages of the diagrams of motion.

**5. Horyuji gojunoto.** The gojunoto† of the Horyuji temple, near Nara, has the total height of 105.2 shaku, the kurin and the tower body being respectively 31.9 and 73.3 shaku high. The sectional dimension of the tower body is 20.7 shaku at base and 10.6 shaku at the 5th story. The shinbashira, which rests on the foundation stone, is round in section, and tapers from the diameter of 3.3 shaku at base to 1.5 shaku at the 5th story, being further reduced to the diameter of 1.5 shaku at the foot of the kurin.

The shinbashira is evidently either not very stiff or not rigidly fixed to the foundation, as at the foot of the kurin it can be pushed with hand and displaced 1 cm. in any direction against the edge of the aperture through which it passes. Except for the existence of this latter limiting arrangement, the central post could naturally be thrown into a much larger deviation.

On July 18th, 1910, when the vibration measurement was made, there were very slight winds, which caused the tower to

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* My thanks are due to my assistant Mr. T. Kato, and mechanists Messres. K. Wakimoto, Y. Takahashi, K. Kato, and Y. Wada, who conducted the actual works of the measurements.

† Figs. 3 and 4 giving the elevation and sectional details of the gojunoto of Horyuji are after Dr. C. Ito, who made valuable investigations on the architecture of this ancient temple.

execute very small unfelt movements. of the average period of 1.26 sec. The motion of the tower produced by one man walking about on the roof of the 5th story had the same period (1.24 sec.) with the maximum 2a of about 0.7 mm. in each of the E.W. and the N.S. directions. The forced oscillations of the tower caused by shaking with hand the central post at the 5th story floor or at the foot of the kurin, which had the max. 2a of 1.02 and 1.40 mm. in the two horizontal directions respectively, indicated a much longer period of 1.64 sec. But the period (=1.23 sec.) of the free oscillations which followed the forced movements was identical with that of the natural motion.

TABLE II. Motion of the Horyuji Gojunoto.

| Cause of Disturbance. | E.W. Component. | | N.S. Component. | |
|---|---|---|---|---|
| | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| In ordinary state. | 1.24 * | 0.05 | 1.26 * | 0.12 |
| | 1.23 * | 0 04 | 1.27 * | 0.17 |
| | 1.25 * | 0.23 | 0.49 * | 0.02 |
| | | | 0.50 * | 0.04 |
| Effect of slight wind. | 1.30 * | 0.09 | 1.29 * | 0.18 |
| One man walking on the N. roof. | 1.25 | 0.72 | - | 0.05 |
| *Do.* on the E. roof. | 1.15 | 0.17 | 1.26 | 0.67 |
| *Do.* on the E., N., or W. roof. | 1.25 | 0.23 | 1.30 | 0.28 |
| | 1.19 | 0.72 | 1.24 | 0.30 |
| Central Post shaken E.-W. (at the 5th floor). | 1.55 | 0.52 | 1.51 | 1.18 |
| | | | 1.37 | 0.82 |
| | 1.14 * | 0.08 | 1.27 * | 0.08 |
| *Do.* shaken E.-W. (at the 5th floor). | 1.25 | 0.48 | 1.25 | 0.20 |
| | 1.65 | 0.93 | 1.65 | 0.45 |
| | 1.65 | 0.62 | 1.69 | 0.23 |
| | 1.23 * | 0.13 | 1.25 * | 0.12 |
| *Do.* shaken E.-W. (at the foot of the kurin). | 1.17 | 0.77 | | |
| | 1.77 | 1.02 | 1.80 | 0.52 |
| | 1.76 | 0.95 | 1.77 | 0.78 |
| | 1.27 * | (small.) | 1.18 | (small.) |
| *Do.* shaken N.-S. (at the foot of the kurin). | 1.51 | 0.65 | 1.49 | 1.40 |
| | 1.23 * | 0.17 | 1.25 * | 0.06 |
| | | | 0.49 * | 0.03 |

* Free after-movement.

TABLE III. Motion of the Horyuji Gojunoto, grouped into Free and Forced Oscillations.*

| E. W Component. | | N. S. Component. | | | |
|---|---|---|---|---|---|
| T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| Ordinary or free oscillations, or those caused by walking on the top roof :— | | | | | |
| 1.14 | 0.08 | 1.18 | small. | 0.40 | 0.03 |
| 1.15 | 0.17 | 1.24 | 0.30 | 0.49 | 0.02 |
| 1.19 | 0.72 | 1.25 | 0.06 | 0.50 | 0.04 |
| 1.23 | 0.17 | 1.25 | 0.12 | **0.49** | |
| 1.23 | 0.13 | 1.25 | 0.20 | | |
| 1.24 | 0.05 | 1.26 | 0.12 | | |
| 1.25 | 0.72 | 1.26 | 0.67 | | |
| 1.25 | 0.23 | 1.27 | 0.17 | | |
| 1.25 | 0.48 | 1.27 | 0.08 | | |
| 1.25 | 0.23 | 1.29 | 0.18 | | |
| 1.27 | small. | 1.30 | 0.28 | | |
| 1.30 | 0.09 | **1.26** | | | |
| **1.23** | | | | | |
| Oscillations caused by the forced shaking of the central post :— | | | | | |
| 1.51 | 0.65 | 1.37 | 0.82 | | |
| 1.55 | 0.52 | 1.49 | 1.40 | | |
| 1.65 | 0.93 | 1.51 | 1.18 | | |
| 1.65 | 0.62 | 1.65 | 0.45 | | |
| 1.76 | 0.95 | 1.69 | 0.23 | | |
| 1.77 | 1.02 | 1.77 | 0.78 | | |
| **1.67** | | 1.80 | 0.52 | | |
| | | **1.61** | | | |
| 1.17 | 0.77 | | | | |

* Mean value is indicated by thick numerals.

**6. Toji gojunoto.** The total height of the great stupa* of the Toji temple, in Kyoto, is 183.7 shaku; the sectional dimension of the tower body, 133.5 shaku in height, being 31.5 shaku at base and 22.2 shaku at the 5th story. The kurin is 50.2 shaku in height. The shinbashira which is of uniform square section 3×3 shaku, and is isolated from the rest of the structure rises from the foundation stone and is composed of two pieces jointed at the 3rd story height by means of a number of strong vertical beams 24 shaku long, firmly secured around the post. Its upper end is jointed in the same strong method to the lower end of the wooden core of the kurin at the mean height of 108 shaku above the ground, or 24 shaku below the foot of the kurin. Each of the 16 round vertical columns of the base story has the diameter of 2.7 shaku. (See the ground plan, fig. 2.)

The vibration measurement was made on June 27th, 1920, between 11.50 A.M. and 0.55 P.M., when it rained heavily. The natural oscillation of the tower caused by the slight winds, which was very small and entirely unfelt, had the mean period of 1.81 sec., with the max. 2a of 0.10 to 0.17 mm., as shown in Tables IV and V.

The shinbashira is entirely free and nowhere in contact with the surrounding inner platforms of the tower building. The latter could, however, be thrown into movements of no insignificant size, and of sensible intensity, by shaking the former with hand at an upper part, possibly by the reaction through the body of the man, as the process required a great exertion of strength. The amount of motion of the central post thus produced was 3 to 5 cm. at the 5th floor, with the mean period of 1.27 sec., as follows:—

* Figs. 2 and 6, giving the construction details of the Toji gojunoto, are reproductions of the drawings made by the late Mr. Y. Horiike.

TABLE IV. Motion of the Toji Gojunoto, Kyoto, caused by shaking the Central Post at the 5th Floor.

(*)......After-movement.

| Central Post shaken from | E. W. Component. | | N. S. Component. | |
|---|---|---|---|---|
| | T (sec.). | 2a (mm.). | T (sec.). | 2a (mm.). |
| The E. side. | { 1.25<br>1.26 | 0.49 .........<br>0.58 ......... | 1.25<br>1.28 | 0.21<br>0.23 |
| *Do.* | { 1.24<br>*1.15 | 0.70 .........<br>0.10 | 1.26 | 0.40 |
| The N. side. | { 1.25<br>*1.12 | 0.30 .........<br>0.28 | 1 25 | 0.43 |
| *Do.* | 1.20 | 0.45 ......... | 1.20 | 0.43 |
| The E. side. | { 1.28<br>1.30<br>*1.12 | 0.87 ........<br>0.74<br>0.11 | 1.27 | 0.24 |
| The N. side. | 1.25 | 0.63 ......... | 1.25 | 0.60 |
| The E. side. | 1.28 | 0.92 ......... | 1.30 | 0.46 |

TABLE V. Motion of the Toji Gojunoto, Kyoto: Natural Oscillation caused by Winds.

| E. W. Component. | N. S. Component. |
|---|---|
| sec. | sec. |
| 1.75 (3) | 1.69 (1) |
| 1.80 (2) | 1.72 (1) |
| 1.82 (2) | 1.80 (3) |
| 1.83 (4) | 1.82 (2) |
| 1.85 (1) | 1.83 (2) |
| 1.81 (2a=0.10 mm.) | 1.84 (3) |
| | 1.85 (2) |
| The frequency of a given value of the period is indicated by the figure enclosed in brackets. | 1.88 (2) |
| | 1.81 (2a=0.17 mm.) |

Central Post shaken at the 5th floor

from the E. side,......47 times in 60.0 sec.
,, N. ,, ,......47 ,, 60.0
,, ,, ,, ,......48 ,, 60.0
,, ,, ,, ,......20 ,, 25.5

The consequent motion of the tower had the max. 2a of 0.92 mm., with the average period of 1.26 sec., which is identical with that of the artificial disturbances applied to the central post.

**7. Ueno gojunoto.** The gojunoto of the Toshogu temple in the Ueno park, Tokyo, is 106.5 shaku in height, the sectional dimension of the tower body being 16.0 shaku at base and 10.3 shaku at the 5th story. The central hinoki (*Chamaecyparis obtusa*) post, supporting the kurin 27.0 shaku in height, is uniform square in section, 2×2 shaku, and rests on the foundation stone and formes a column not very stiff, being composed of four pieces jointed by means of iron hoops, while the top is held in position by two horizontal iron rods or pins passing through it at right angles.

On June 26th, 1919, when the vibration experiment was carried on, it was slightly rainy and perfectly calm. The tower was easily put into considerable movement by pushing with hand the central post at the 4th story height from the N., E., or the S. side at successive time intervals of about 1 second. The movement of the post thus artificially produced was as follows:—

Motion parallel E.W.: Max. amount=2.0 cm.

31 oscillations in 31.0 sec.
32 ,, 30.5 ,,
38 ,, 36.0 ,,
} .....Mean Period=0.97 sec.

Motion parallel N.S.: Max. amount=0.8 cm.

18 oscillations in 16.5 sec.
21 ,, 36.0 ,,
} .....Mean Period=0.89 sec.

TABLE VI. Motion of the Toshogu Gojunoto, at Ueno, Tokyo: Period of Vibration.*

| E.W. Component. | | | N.S. Component. | | |
|---|---|---|---|---|---|
| Free Motion. | Forced Motion. | | Free Motion. | Forced Motion. | |
| sec. | sec. | sec. | sec. | sec. | sec. |
| 1.14(1) | 0.83(1) | 1.29(1) | 1.16(1) | 0.87(1) | 1.29(1) |
| 1.26(2) | 0.92(1) | 1.30(2) | 1.17(1) | 0.89(1) | 1.35(1) |
| 1.29(2) | 0.93(2) | 1.38(1) | 1.25(2) | 0.90(2) | 1.40(1) |
| 1.30(8) | 0.94(2) | 1.39(1) | 1.26(1) | 0.91(1) | 1.46(1) |
| 1.32(2) | 0.95(3) | 1.41(1) | 1.29(1) | 0.93(2) | 1.50(1) |
| 1.33(1) | 0.96(4) | **1.35** | 1.30(5) | 0.94(2) | 1.51(1) |
| 1.34(3) | 1.04(2) | | 1.31(2) | 0.95(3) | **1.42** |
| **1.30** | 1.10(2) | 1.65(2) | 1.32(2) | 0.96(5) | |
| | **0.97** | 1.70(1) | 1.35(3) | 1.04(2) | 1.90(2) |
| | | 1.90(1) | 1.40(1) | **0.94** | 1.77(1) |
| | 0.28(2) | **1.73** | 1.44(1) | | **1.88** |
| | 0.29(1) | | **1.30** | 0.30(2) | |
| | **0.28** | | | | |

* The frequency, or the number of occurrence, of a given value of the period is indicated by the figure enclosed in brackets. Mean value is indicated by thick numerals.

TABLE VII. Motion of the Toshogu Gojunoto, at Ueno, Tokyo: Period of Large Vibrations.

| E.W. Component. | | | | N.S. Component. | | | |
|---|---|---|---|---|---|---|---|
| 2a (mm.) | T(sec.) | 2a (mm.) | T(sec.) | 2a (mm.) | T(sec.) | 2a (mm.) | T(sec.) |
| 2.02...... | 0.96 | 2.24...... | 1.29 | 1.03...... | 0.96 | 1.03...... | 1.90 |
| 2.02 | 0.96 | | | 1.08 | 0.96 | 1.65 | 1.46 |
| 2.03 | 0.96 | | | 1.10 | 0.94 | 3.07 | 1.50 |
| 2.05 | 0.93 | | | 1.13 | 0.95 | | **1.62** |
| 2.21 | 0.95 | | | 1.20 | 0.93 | | |
| 2.23 | 0.92 | | | 1.27 | 0.96 | | |
| 2.45 | 0.96 | | | 1.39 | 0.95 | | |
| 2.51 | 0.95 | | | 1.50 | 0.91 | | |
| 2.98 | 0.93 | | | 1.52 | 0.90 | | |
| 3.08 | 0 94 | | | 1.53 | 1.04 | | |
| 3.43 | 0.95 | | | 1.78 | 1.04 | | |
| | **0.95** | | | | **0.96** | | |

Even without the artificial disturbance the tower was making small oscillations. I give in Tables VI and VII the results of the different measurements.

It is to be observed that the forced oscillation of the tower artificially produced had the mean period of 0.95 sec. which is equivalent to that of the proper shaking of the central post. As soon as, however, the latter action had been stopped, the motion became free, with the mean period of 1.3 sec., assuming the magnitude sometimes larger than that of the preceding forced portion. In Table VI the period of the forced and free oscillations are compared. According to Table VII, the largest oscillations of the tower principally belonged to the class of the forced motion.

The natural oscillation of the stupa, existing without the application of the man power shaking was as follows:—

Motion parallel E.W.......T=1.29 sec., 2a=0.07 mm.
,, N.S. ......T=1.44 ,, , 2a=0.08 ,,

Experiment No. 1. Central Post shaken from the N. Side.

| E. W. Component. * Free after-movement. | | | N. S. Component | |
|---|---|---|---|---|
| T (sec.) | 2a (mm.) | | T (sec.) | 2a (mm.) |
| 1.39 | 0.55 | ...... | {1.40 | 0.88 |
| | | | {0.90 | 0.25 |
| * — | — | | 1.40 | 0.95 |
| * 1.34 | 0.21 | ......... | 1.32 | 0.12 |
| * 1.26 | 0.57 | ......... | 1.26 | 0.05 |
| * 1.34 | 0.08 | ......... | 1.17 | 0 05 |
| * 1.26 | 0.05 | ......... | 1.16 | 0.07 |

The absolutely maximum motion of 2a=0.95 mm. (N.S. component) took place immediately after the cessation of the man power shaking of the central post.

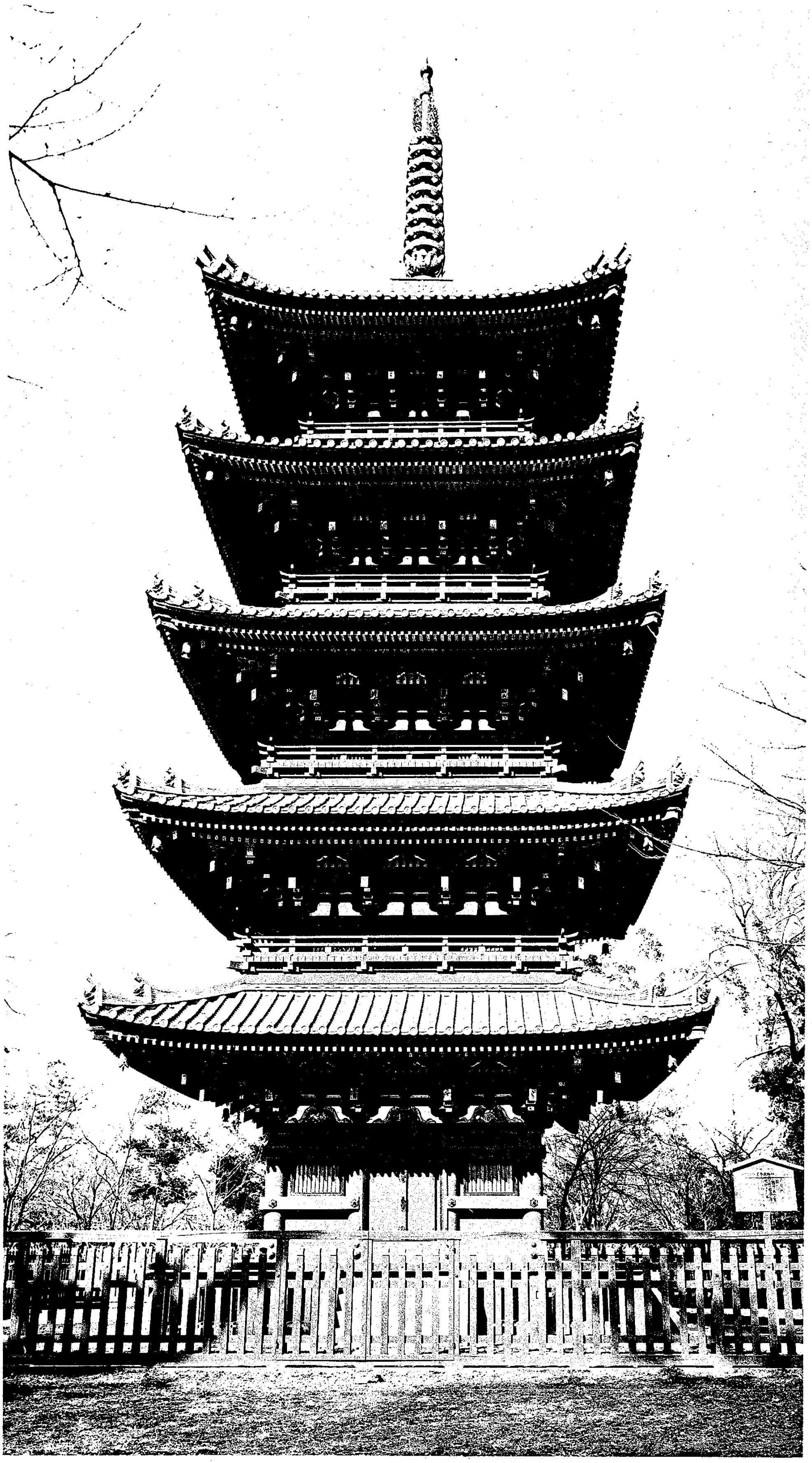


Fig. 3. The Gojunoto of Toshogu, at Ueno, Tokyo.

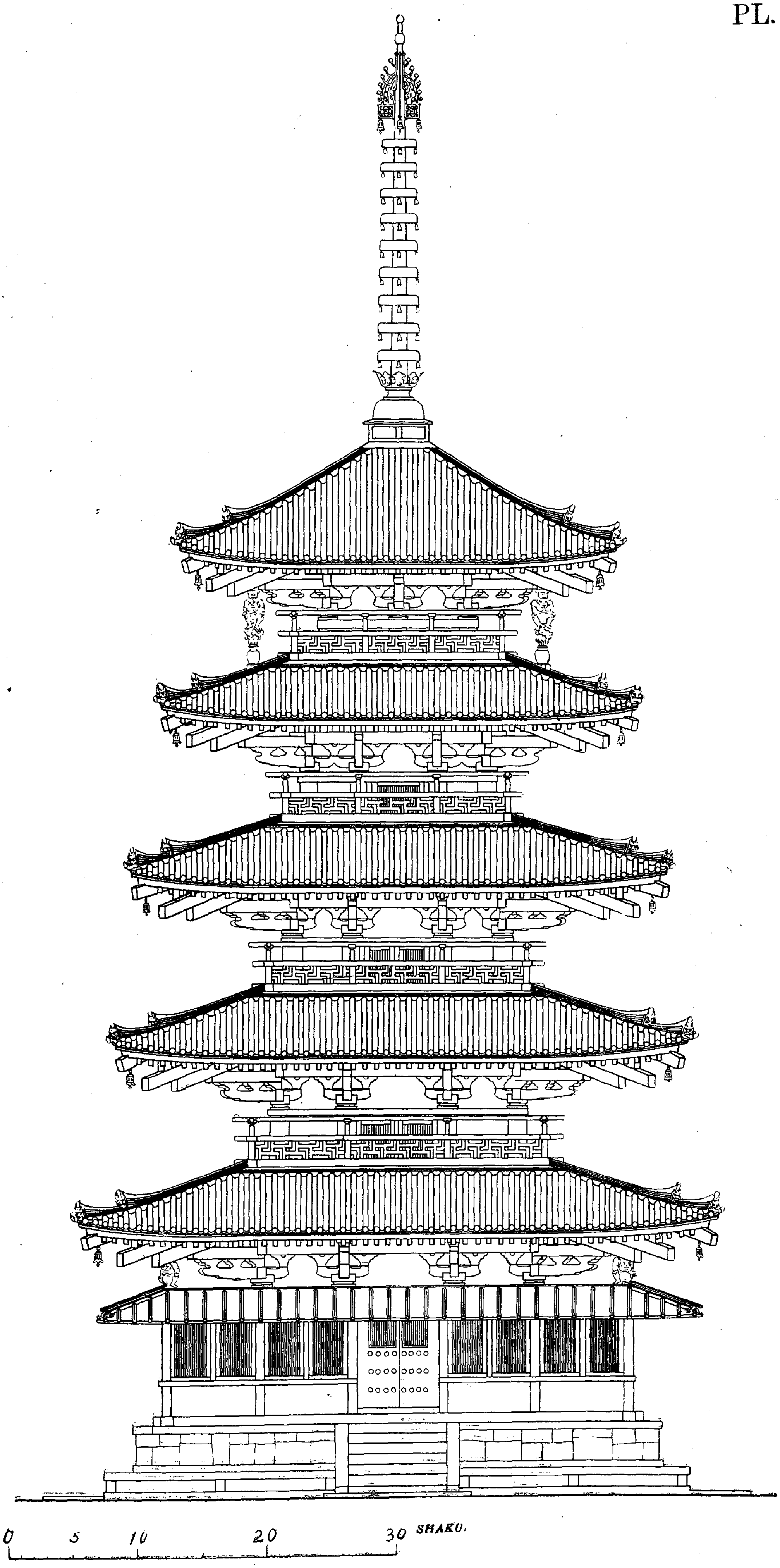



Fig. 4. The Gojunoto of Horyuji. Elevation
(From the drawings by Professor C. Ito.)

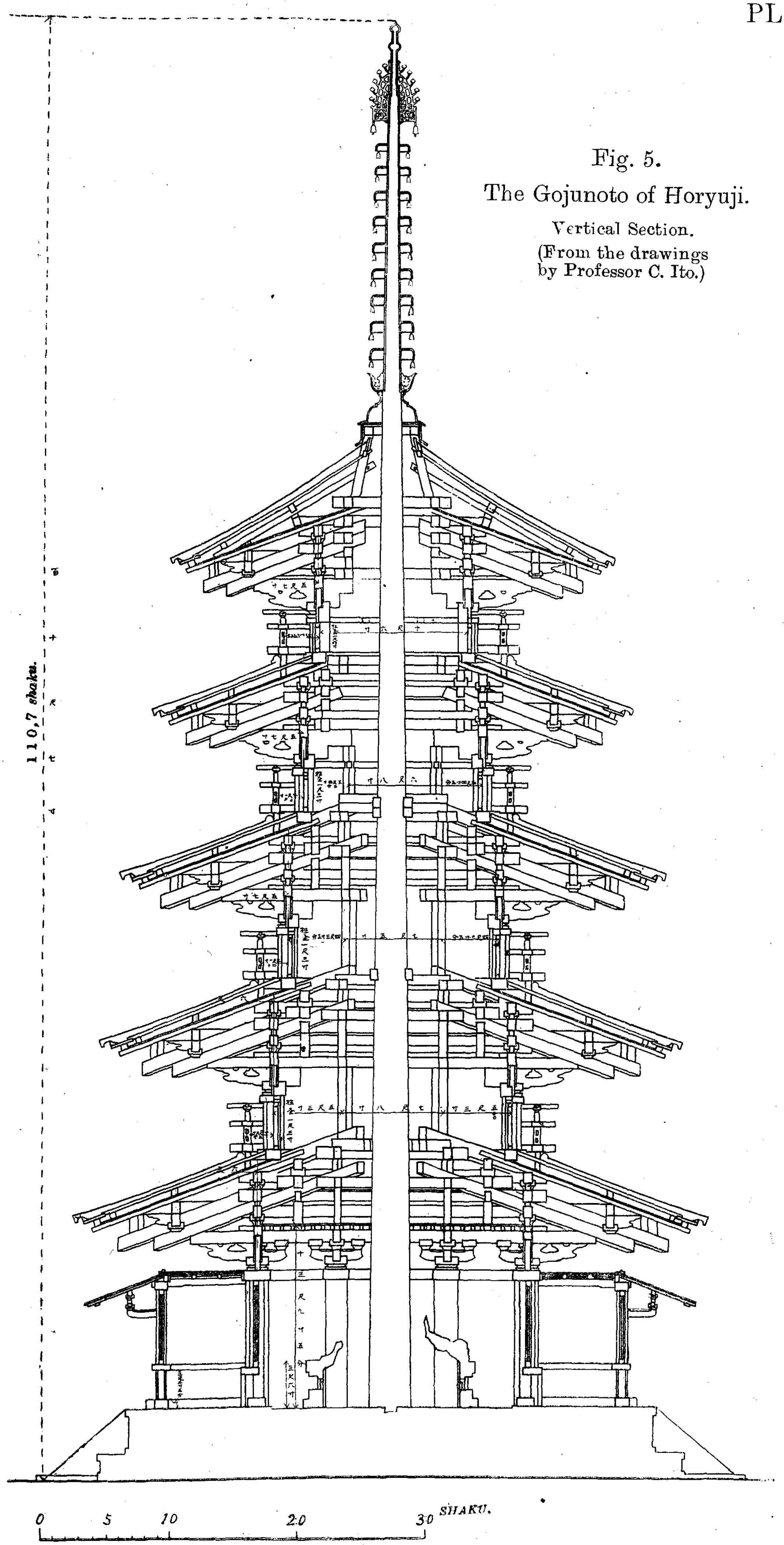



Fig. 5.
The Gojunoto of Horyuji.
Vertical Section.
(From the drawings
by Professor C. Ito.)

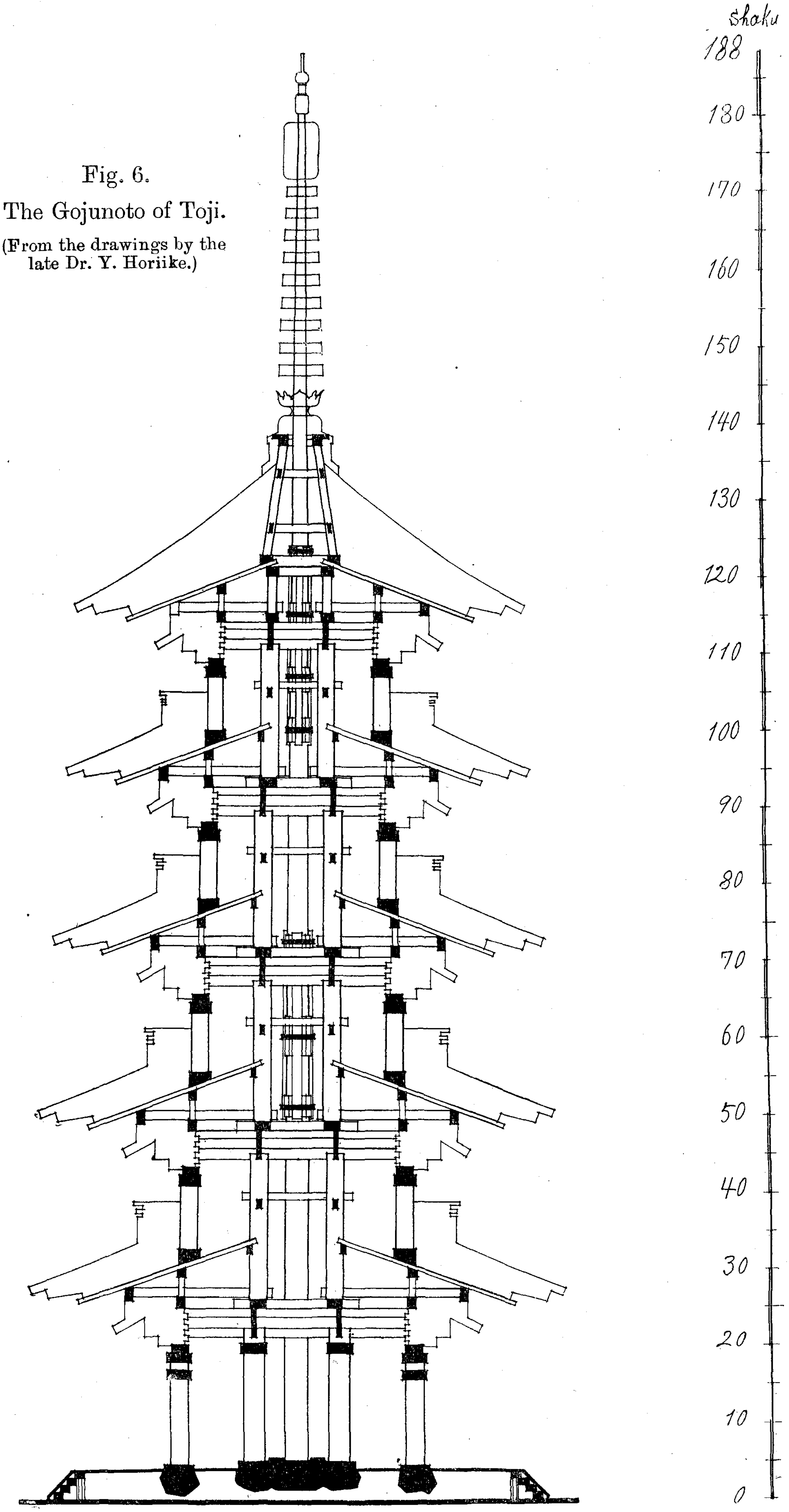



Fig. 6.

The Gojunoto of Toji.

(From the drawings by the late Dr. Y. Horiike.)

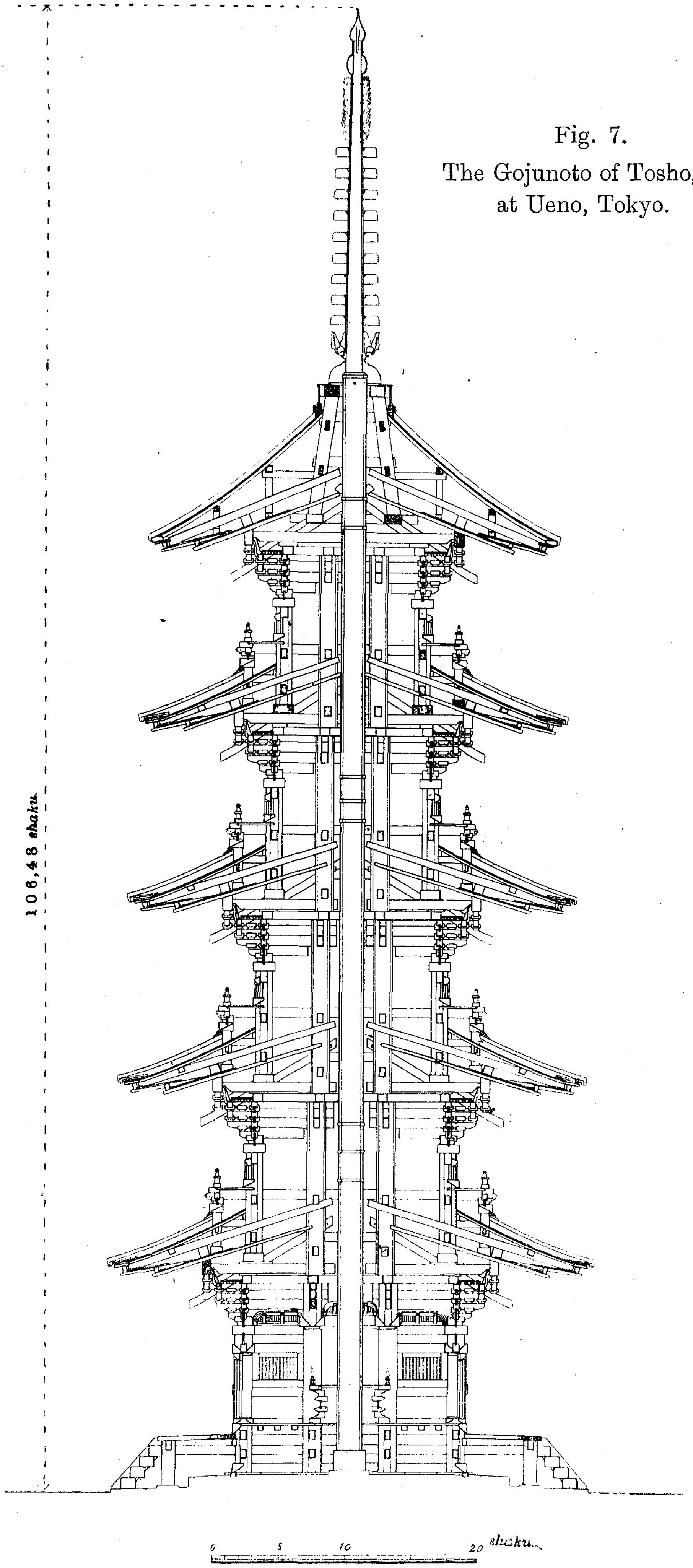
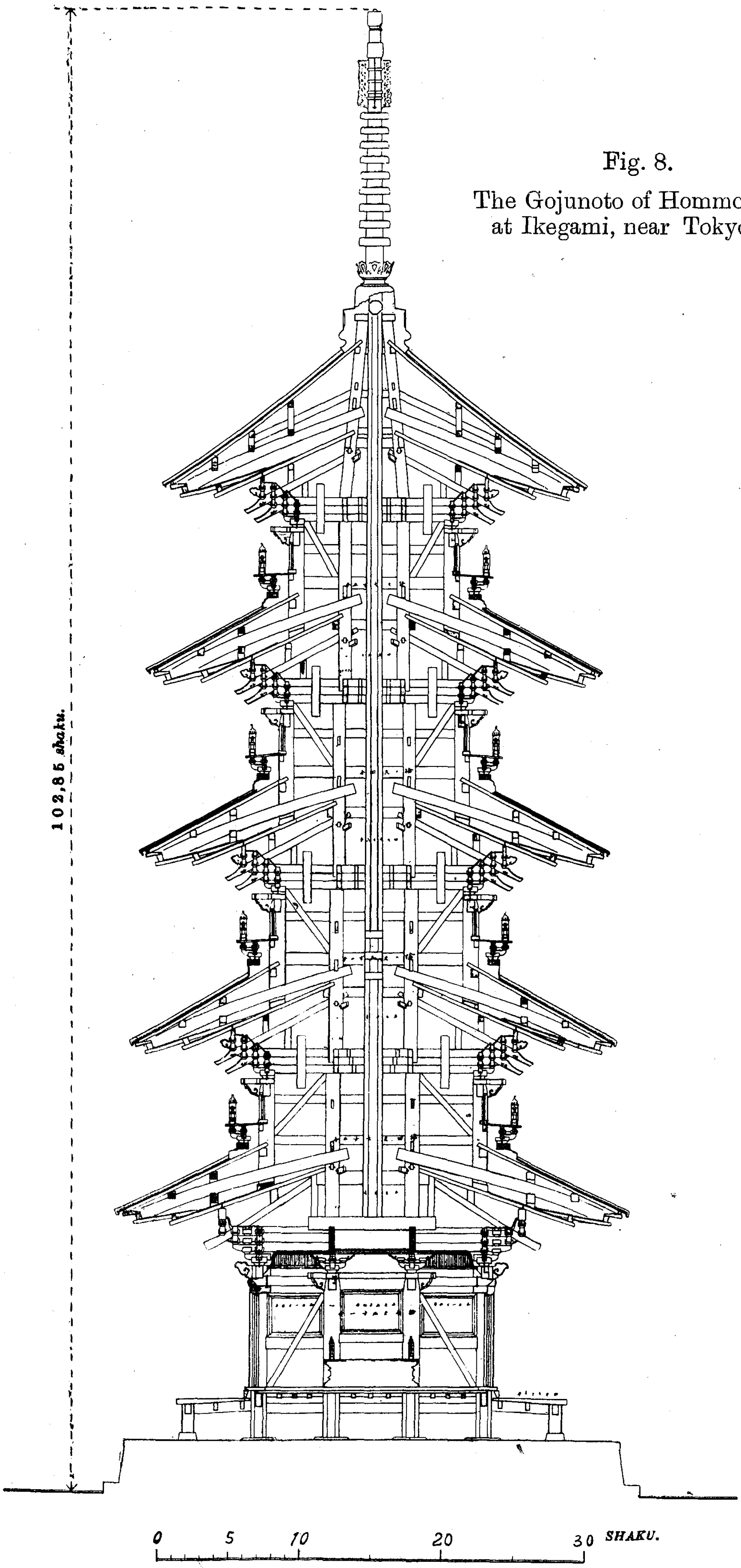



Fig. 7.
The Gojunoto of Toshogu,
at Ueno, Tokyo.

Fig. 8.
The Gojunoto of Hommonji,
at Ikegami, near Tokyo.



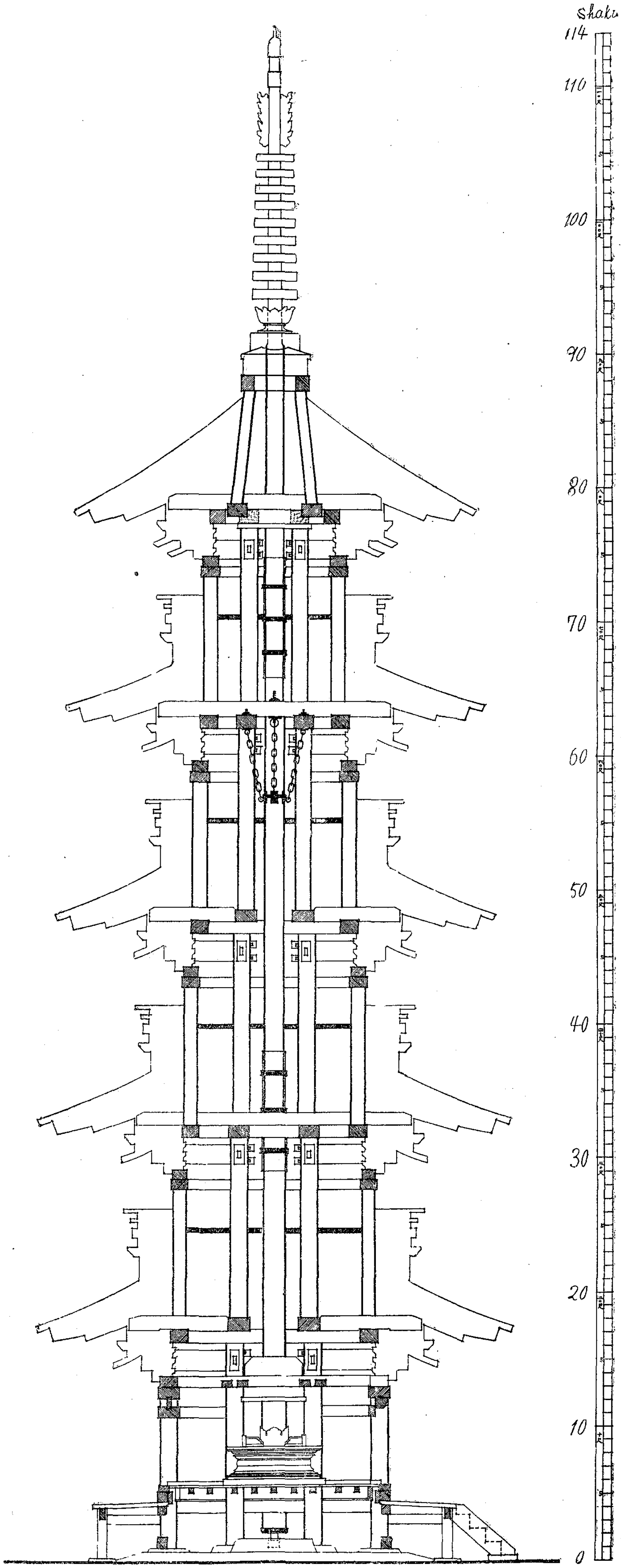



Fig. 9. The Gojunoto of Nikko.

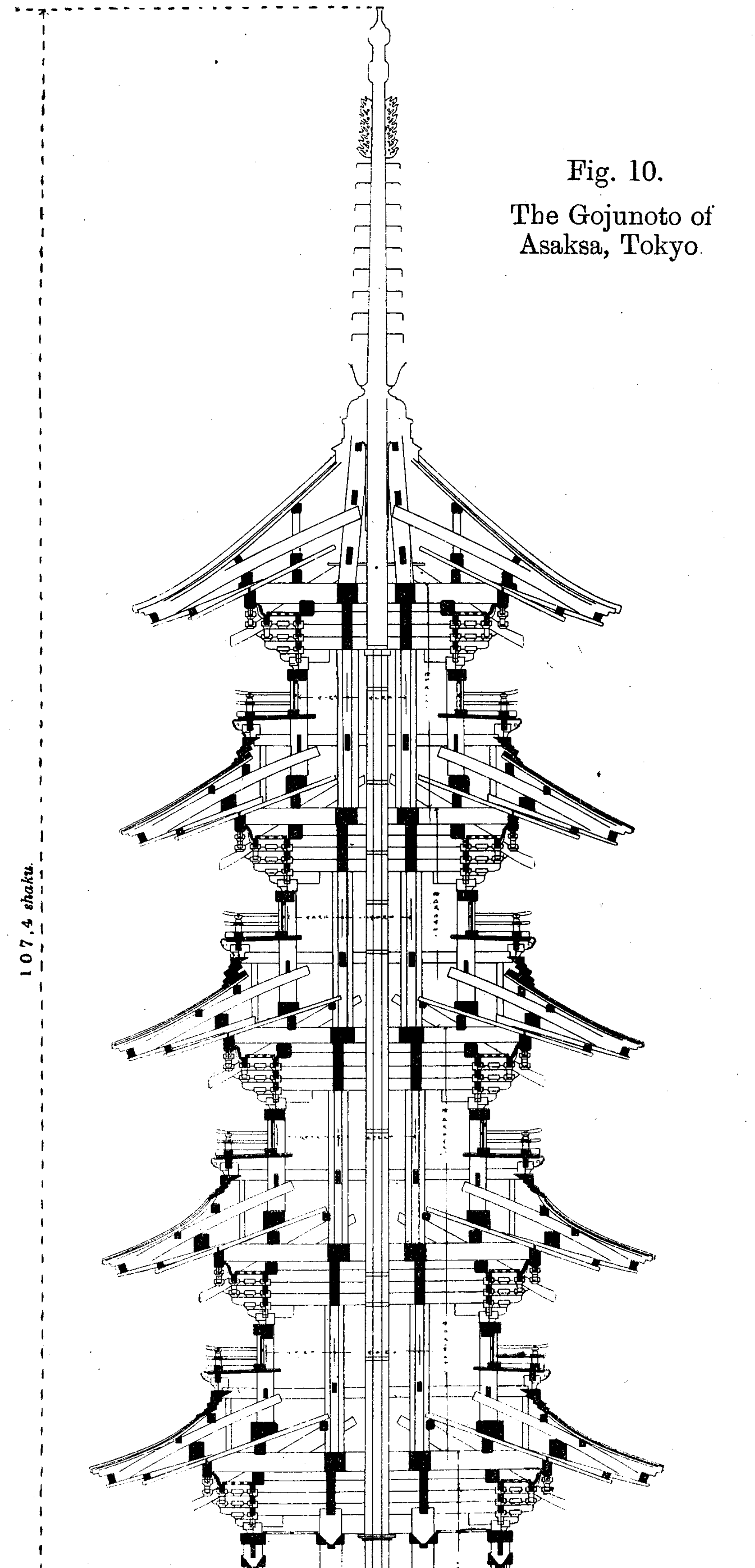



Fig. 10.
The Gojunoto of
Asaksa, Tokyo.

Experiment No. 3. Central Post shaken from the E. Side.

| E. W. Component. | | | N. S. Component. | |
|---|---|---|---|---|
| T (sec.) | 2a (mm.) | | T (sec.) | 2a (mm.) |
| 0.96 | 2.03 | ......... | 0.96 | 0.87 |
| * 1.30 | 1.83 | ......... | 1.29 | 0.40 |

The initial movements were as follows:—

1st displacement ......0.32 mm.→W.

2nd „ ......1.00 mm.→E., 0.1 mm →N.

3rd „ ......2.12 mm.→W., 0.28 mm.→S.

The vibrations during the shaking of the central post were alternately large (max. 2a=0.87 mm.) and small (max. 2a=0.43 mm.)

Experiment No. 4. Central Post shaken from the E. Side.

| E. W. Component. | | | N. S. Component. | |
|---|---|---|---|---|
| T (sec.) | 2a (mm.) | | T (sec.) | 2a (mm.) |
| 0.96 | 2.02 | ......... | 0.96 | 0.91 |
| * 1.30 | 2.23 | ......... | 1.30 | 0.29 |

The vibrations during the shaking of the central post were alternately large (2a=0.91 mm., T=1.08 sec.) and small (2a=0.38 mm., T=0.84 sec.).

The motion in the E.W. component decreased, after the cessation of the forced shaking of the central post, from 2a=2.23 mm. to 2a=0.03 mm. in the course of 16 complete oscillations. In the N.S. component the decrement was not so regular.

Experiment No. 5. Central Post shaken from the E. Side.

| E. W. Component. | | | N. S. Component. | |
|---|---|---|---|---|
| T (sec.) | 2a (mm.) | | T (sec.) | 2a (mm.) |
| 0.96 | 2.45 | ......... | 0.96 | {1.03 (T=1.04 sec.) / 0.28 (T=0.84 „ ) |
| * 1.30 | 2.03 | ......... | 1.25 | 0.47 |

* ......Free after-movement.

The initial motion was as follows:—

1st displacement......0.33 mm.→W.

2nd ,, ......1.28 mm.→E., 0.17 mm.→N.

3rd ,, ......2.45 mm.→W, 0.52 mm.→S.

Experiment No. 7. Central Post shaken from the E. Side.

| E. W. Component. | | N. S. Component. | |
|---|---|---|---|
| T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| 1.05 | 2.05 | 1.51 | 0.58 |
| 0.89 | 1.28 | 0.87 | 0.22 |
| 1.65 | 0.93 | 0.30 | 0.02 |
| 0.83 | | | |
| 1.10 | 1.68 ......... | {1.35<br>{0.30 | 0.33<br>0.33 |
| * 1.30 | 2.63 ......... | 1.30 | 0.52 |
| * 1.30 | 0.40 ......... | 1.31 | 0.15 |

In the E.W. component, the motion was reduced, after the stoppage of the shaking of the central post, from 2a=2.63 mm. to zero practically in the course of 16 complete oscillations.

Experiment No. 11. Central Post shaken from the E. Side.

| E. W. Component. | | N. S. Component. | |
|---|---|---|---|
| T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| 0.95 | 2.51 ......... | 0.95 | 0.83 |
| 1.29 | 2.24 ......... | 1.29 | 0.40 |
| * 1.32 | 0.55 ......... | 1.32 | 0.33 |

The initial movements were as follows:—

1st displacement......0.12 mm.→W., 0.07 mm.→S.

2nd ,, ......0.88 ,, →E., 0.13 ,, →N.

3rd ,, ......1.77 ,, →W., 0.28 ,, →S.

4th ,, ......2.67 ,, →E., 0.58 ,, →N.

The E.W. motion decreased, after the stoppage of the forced shaking, from 2a=2.23 mm. to zero in 16 complete oscillations.

* Free after-movement.

## Table VIII. Motion of the Toshogu Gojunoto at Ueno, Tokyo, caused by shaking the Central Post.

(*)......Natural after-movement.

Experiments Nos. 2, 6, 8, 9, 10, 12, 13, 14, 15, and 16.

| No. of Exprt. | Motion of Central Post. | | E. W. Component. T (sec.) | E. W. Component. 2a (mm.) | N. S. Component. T (sec.) | N. S. Component. 2a (mm.) |
|---|---|---|---|---|---|---|
| 2 | Shaken from N. | | 1.04 | 1.23 | 1.04 | 1.78 |
| | | | 1.04 | 1.05 | 1.04 | 1.53 |
| | | * | 1.32 | 0.97 | 1.31 | 0.63 |
| | | * | 1.29 | 0.18 | 1.25 | 0.17 |
| 6 | Shaken from S. | | 1.38 | 0.97 | 0.96 | 1.27 |
| | | | 1.65 | 0.57 | 0.89 | 1.03 |
| | | | 0.28 | 0.02 | — | (small.) |
| | | * | 1.34 | 0.97 | 1.35 | 1.73 |
| | | * | 1.14 | 0.10 | | |
| 8 | Shaken from E. | | {0.95 | 2.21 | 0.96... | {1.08 (T=1.12 sec.) 0.84 (T=0.48 „ ) |
| | | | {1.90 | (Trace) | 1.90 | |
| | | * | 1.30 | 1.73 | 1.30 | 0.35 |
| 9 | *Do.* | | 0.92 | 2.23 | 0.92 | 0.82 |
| | | | 0.94 | 1.90 | 0.94 | 0.65 |
| | | * | 1.30 | 1.34 | 1.30 | 0.42 |
| 10 | *Do.* | | 0.93 | 2.98 | 1.77 | 0.68 |
| | | | 0.96 | 2.02 | 1.90 | 1.03 |
| | | * | 1.30 | 1.88 | 1.30 | 0.38 |
| 12 | Shaken from N. | | 1.10 | 0.52 | {0.95 | 1.39 |
| | | | | | {1.50 | 3.07 |
| | | | 1.30 | 0.77 | 0.93 | 1.20 |
| | | | 0.29 | 0.07 | | |
| 13 | | | 1.30 | 1.09 | 0.91 | 1.50 |
| | | | {1.70 | 0.22 | 1.46 | 1.65 |
| | | | {0.28 | 0.05 | | |
| | | * | 1.33 | 0.42 | 1.35 | 1.87 |
| 14 | Shaken from S. | | 1.41 | 1.10 | 0.90 | 1.52 |
| | | * | 1.30 | 1.08 | 1.30 | 1.90 |
| 15 | Shaken from E. | | 0.95 | 3.43 | 0.95 | 1.13 |
| | | * | 1.30 | 2.18 | 1.30 | 0.37 |
| 16 | *Do.* | | 0.94 | 3.08 | 0.94 | 1.10 |
| | | * | 1.30 | 2.38 | 1.30 | 0.47 |

**8. Hommonji gojunoto.** The gojunoto of the Hokke sect temple Hommonji, at Ikegami, near Tokyo, has a total height of 99.25 shaku; the sectional dimension of the tower body, built of keyaki (*Zelkowa acuminata*) wood, and 82.23 shaku in height, being 16 shaku at the base and 11 shaku at the 5th story. The central octagonal post, supporting the kurin 20.62 shaku in height, does not rest on the ground, but rises from the ceiling of the 1st story, where the base is fixed to a strong cross beam, being otherwise not in contact with the tower structure. It is composed of two sugi (*Cryptomeria japonica*) solid pieces jointed at 18 shaku above the base level and has the height of 63.2 shaku, with a nearly uniform sectional area of the diameter varying from 1.25 at the base to 1.16 shaku at the top (fig. 11.).

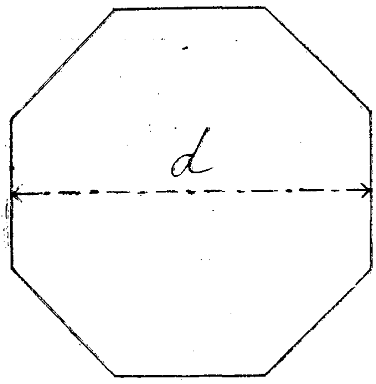



Fig. 11. Section of the Central Post of the Hommonji Gojunoto.
At the top... d=1.16 shaku
„ base.....d=1.25.

The vibration measurement was made on June 15th, 1290, between 10.50 A.M. and 1. P.M., when strong S.E. winds with the speed of some 10 m./sec. set the tower into the natural movement of considerable amplitude.* The central post could easily be thrown into oscillation by pushing its upper portion with hand at successive regular intervals such that the motion reached some 3 cm. range at the 5th story, the top striking against the hollow metal base (roban) of the kurin. The period of oscillation of the central post thus produced artificially was on the average 1.55 sec. as follows:—

* The wind speed and direction observed at the Central Meteorological Observatory in Tokyo, at the time of the experiment, were as follows :—

| | | | | | |
|---|---|---|---|---|---|
| 9 A.M. | 7.5 m./sec. | .........S.W. | 1 P.M. | 8.3 m./sec. | .........S.W. |
| 10 „ | 9.2 | ......S.S.W. | 2 „ | 8.3 | .........W. |
| 11 „ | 10.4 | ......... | 3 „ | 10.0 | ......... |
| Noon | 10.6 | ......... | 4 | 8.8 | ......... |

| | | | |
|---|---|---|---|
| 92 oscillations in | 60 sec. | | |
| 46 ,, | 30 ,, | | |
| 47 ,, | 30 ,, | | Mean Period = 1.55 sec. |
| 47 ,, | 30 ,, | | |
| 46 ,, | 30 ,, | | |

The oscillation of the central post produced usually no evident increase in the motion of the tower. The average period (=T) and the maximum range (=2a) of the natural motion caused by the winds, measured at the 5th story floor, are given in Tables IX,

TABLE IX. Motion of the Hommonji Gojunoto:
Free Motion* caused by Winds.

| E. W. Component. | | N. S. Component. | |
|---|---|---|---|
| T (sec.). | 2a (mm.) | T (sec. . | 2a (mm.) |
| 1.3 (3) | 0.62 | 1.24 (1) | 0.50 |
| 1.33 (1) | 0.29 | 1.32 (1) | 0.13 |
| 1.34 (3) | 0.75 | 1.33 (3) | 1.64 |
| 1.35 (3) | 2.03 | 1.34 (4) | 2.10 |
| 1.36 (2) | 1.40 | 1.35 (5) | 2.30 |
| 1.37 (1) | 0.30 | 1.36 (3) | 2.13 |
| 1.38 (4) | 2.20 | 1.37 (1) | 1.60 |
| 1.39 (3) | 1.92 | 1.38 (6) | 2.49 |
| 1.40 (7) | 2.20 | 1.40 (1) | 0.67 |
| 1.42 (1) | 0.83 | 1.42 (1) | 2.03 |
| 1.43 (1) | 2.97 | 1.43 (1) | 2.16 |
| 1.44 (2) | 1.62 | 1.45 (1) | 1.43 |
| 1.48 (1) | 1.97 | 1.48 (1) | 0.40 |
| 1.49 (1) | 1.77 | 1.36 | 2.49 (max.) |
| 1.38 | 2.97 (max.) | | |

* The frequency of the occurrence of the different periods is indicated by a figure enclosed in brackets.

TABLE X. Motion of the Hommonji Gojunoto:
Natural Motion caused by Winds.

| Time of Observation. | E.W. Component. | | N.S. Component. | |
|---|---|---|---|---|
| | T sec. | 2a (mm.) | T sec. | 2a (mm.) |
| 10.40—10.45 A.M. | 1.40 | 1.16 | 1.40 | 0.67 |
| | 1.30 | 0.37 | 1.24 | 0.05 |
| | 1.33 | 0.29 | — | — |
| | 1.44 | 0.65 | — | — |
| | 1.38 | 0.81 | 1.35 | 0.97 |
| | 1.34 | 0.47 | 1.34 | 0.27 |
| | 1.30 | 0.15 | 1.33 | 0.52 |
| | 1.36 | 0.07 | 1.36 | 0.20 |
| | 1.38 | 1.33 | — | — |
| | — | — | 1.45 | 1.43 |
| | 1.40 | 0.52 | 1.38 | 1.43 |
| | 1.40 | 0.10 | 1.38 | 1.33 |
| | 1.34 | 0.05 | — | — |
| | 1.39 | 0.20 | 1.32 | 0.13 |
| 10.50—11.05 A.M. | 1.35 | 2.03 | 1.33 | 1.64 |
| | 1.49 | 1.77 | 1.35 | 1.13 |
| | 1.43 | 2 97 | 1.48 | 0.40 |
| | 1.42 | 0.83 | — | — |
| | — | — | 1.38 | 1.16 |
| | 1.37 | 0.30 | — | — |
| | 1.76 | 0.20 | 1.65 | 2.95 |
| | 1.30 | 0.62 | 1.37 | 1.60 |
| | 1.40 | 0.12 | — | — |
| | — | — | 1.35 | 1.97 |
| | 1.44 | 1.62 | — | — |
| | 1.48 | 1.97 | 1.42 | 2.03 |
| | 1.35 | 1.97 | 1.38 | 2.49 |
| | 1.40 | 2.20 | 1.38 | 1.36 |
| | 1.40 | 0.23 | 1.34 | 0.46 |
| 11.06—11.20 A.M. | 1.36 | 2.20 | 1.33 | 1.13 |
| | 1.39 | 1.92 | 1.43 | 2.16 |
| | 1.34 | 0.75 | 1.36 | 0.63 |
| 11.25—11.45 A.M. | 1.35 | 1.79 | — | — |
| | — | — | 1.38 | 2.29 |
| | 1.38 | 1.16 | 1.35 | 1.05 |
| | — | — | 1.35 | 2.30 |
| | 1.36 | 1.40 | 1.36 | 2.13 |
| | 1.40 | 1.67 | 1.34 | 2.10 |
| | 1.39 | 0.68 | 1.34 | 0.89 |

Table XI. Motion of the Hommonji Gojunoto: Observation of Individual Vibrations.

| E. W. Component. | | N. S. Component. | |
|---|---|---|---|
| T (sec.) | 2a (mm.). | T (sec.) | 2a (mm.). |
| 1.76 | 0.20 | 1.65 | 2 95 |
| 1.75 | 1.43 | 1.75 | 1.03 |
| 1.60 | 2.62 | 1.50 | 1.53 |
| 1.60 | 2.39 | 1.60 | 1.00 |
| 1.70 | 1.31 | 1.80 | 0.80 |
| 1.75 | 1.47 | 1.70 | 1.82 |
| **1.68** | | **1.67** | |

Table XII. Motion of the Hommonji Gojunoto: Motion caused by shaking the Central Post.

| Duration of Shaking. | E. W. Component. | | N. S. Component. | |
|---|---|---|---|---|
| | T (sec.) | 2a (mm.). | T (sec.) | 2a (mm.). |
| 35 Sec. | 1.36 | 0.34 | 1.35 | 0.68 |
| 14 | 1.40 | 0.87 | 1.28 | 0.73 |
| 35 | 1.36 | 3.30 | 1.40 | 2.41 |
| 60 | 1.39 | 0.88 | 1.45 | 2.37 |
| 30 | 1.42 | 0.23 | 1.41 | 0.23 |
| 30 | 1.45 | 0.23 | 1.31 | 0.53 |
| 30 | 1.44 | 1.82 | 1.46 | 2.07 |
| | **1.40** | | **1.38** | |

and X, while the corresponding elements of motion observed under the addition of the artificial shaking of the central post are given in Table XII. The general mean period came out to be 1.38 sec., the max. 2a in the E.W. and the N.S. directions being each about 3 mm.

Table XI relates to the conspicuous vibrations which occurred singly in different otherwise minimum epochs of the motion. The period was longer, with the average value of 1.7 sec., due probably to the action of a solitary gust of wind which could put the structure in oscillation in the time interval dependent on its duration.

**9. Nikko gojunoto.** The gojunoto of the Nikko temple has the total height of 114.75 shaku, the kurin and the tower body being respectively 27 and 87.75 shaku high. The sectional dimension of the tower is 16.0 shaku at base and 9.7 shaku at the 5th story. The combined system of the kurin and the shinbashira does not rest on the ground but is suspended from the cross beams 61 shaku above ground at the floor of the 5th story by four iron chains, attached to the post at the height of 56 shaku, namely, at the level corresponding to the 4th story balustrade. Each of the chains is 5.5 shaku in length, and is composed of links 0.5 shaku long and 0.07 shaku thick. The central round post which is of keyaki wood and has the diameters of 1.96 shaku at base and of 1.58 shaku at top, namely, just below the roban, is composed of three pieces jointed at the heights of 32.5 and 69.0 shaku by means of vertical bamboo sticks 6 shaku long secured by three iron rings, 0.36 shaku in width and 0.035 shaku in thickness. The diameters of the outer and the inner vertical columns of the different stories are as follows:—

| | 1st Story. | 2nd to 5th Stories. |
|---|---|---|
| 12 outer posts. ... | ... Diameter = 1.36 shaku ; | Diameter = 1 20 shaku. |
| 4 inner posts. .... | ... Diameter = 1.50 „ ; | Diameter (Octagonal) = 1.4 „ |

The amount of the eccentric horizontal distances between the columns of the successive stories is 0.25 shaku for the inner and 0.75 shaku for the external series.

TABLE XIII. Motion of the Nikko Gojunoto: Period of Vibration.*

| E. W. Component. | | | | N. S. Component. | | | |
|---|---|---|---|---|---|---|---|
| Forced Shaking. | | Free Motion. | | Forced Shaking. | | Free Motion. | |
| T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| 1.20 (1)......... | 0.67 | 1.24 (1)......... | 0.07 | 1.20 (1)......... | 0.52 | 1.27 (3)......... | 0.19 |
| 1.21 (1) | 1.03 | 1.27 (1) | 0.05 | 1.25 (1) | 1.53 | 1.29 (1) | 0.23 |
| 1.26 (1) | 0.60 | 1.29 (2) | 0.22 | 1.28 (4) | 2.27 | 1.30 (1) | 0.20 |
| 1.27 (1) | 2.57 | 1.30 (3) | 0.77 | 1.29 (1) | 0.58 | 1.31 (3) | 3.12 |
| 1.30 (3) | 1.93 | 1.31 (2) | 1.62 | 1.30 (5) | 2.27 | 1.32 (4) | 1.30 |
| 1.31 (2) | 2.18 | 1.32 (3) | 1.23 | 1.31 (1) | 0.08 | 1.33 (3) | 1.97 |
| 1.32 (1) | 1.33 | 1.33 (2) | 1.97 | 1.34 (1) | 0.79 | 1.34 (4) | 1.40 |
| 1.34 (1) | 0.40 | 1.34 (6) | 2.43 | 1.35 (3) | 0.43 | 1.35 (3) | 1.85 |
| 1.35 (3) | 3.07 | 1.35 (1) | 0.77 | 1.36 (2) | 3.03 | 1.36 (2) | 0.77 |
| 1.36 (3) | 3.03 | 1.36 (2) | 1.92 | 1.37 (3) | 1.58 | 1.37 (1) | 0.67 |
| 1.37 (2) | 2.58 | 1.38 (1) | 3.28 | 1.39 (1) | 1.87 | **1.324** | |
| 1.38 (1) | 3.10 | 1.39 (1) | 2.53 | 1.40 (3) | 0.67 | | |
| 1.39 (2) | 3.83 | 1.40 (1) | 0.48 | 1.43 (1) | 0.84 | | |
| 1.41 (4) | 2.17 | **1.327** | | 1.44 (1) | 0.31 | | |
| 1.42 (1) | 1.30 | | | 1.45 (2) | 0.83 | | |
| 1.43 (1) | 1.92 | | | **1.342** | | | |
| 1.44 (1) | 1.22 | | | | | | |
| 1.46 (1) | 0.37 | | | 0.43 (3) | | | |
| 1.52 (1) | 0.70 | | | 0.44 (2) | | | |
| **1.357** | | | | 0.46 (2) | | | |
| | | | | 0.47 (1) | | | |
| 0.25 (1) | | | | 0.49 (1) | | | |
| 0.24 (1) | | | | **0.45** | | | |
| 0.25 (1) | | | | | | | |
| **0.25** | | | | | | | |

* The frequency of a given value of period is indicated by the figure enclosed in brackets. Mean value is indicated by thick numerals.

The different roofs were covered by copper plates, 1.2×4.0 shaku in size, weighing, for the 5th roof, 4.96 lbs. per piece. For each of the four other roofs, the weight in question is 4.96 lbs. for the single layer along the edge, but 3.14 lbs. for the rest of the area. Thus, the copper plate covering on the top roof was about 1 lb. per sq. foot, and for the lower roofs about $0.7\frac{1}{2}$ lb. per sq. foot. The substitution of the copper plates for tiles materially contributes to reduce the weight of the tower.

On Feb. 28th and March 1st, 1919, when the vibration measurement was made, it was found that the small wooden dowel, 0.5 shaku in diameter, projecting downward from the bottom face of the central post (fig. 12.), was in touch on the N.W. side with the inner wall of the cavity excavated in the granite foundation, leaving a separation of 0.1 shaku on the S.E. side. Consequently it was not possible to set the pendulum system into free motion by pushing it with hand. When pushed or struck at lower parts, below the centre of gravity, the column made simply some slight shivering tremors. Shaking, however, the column near the top, it was caused to move sensibly with slow proper period.

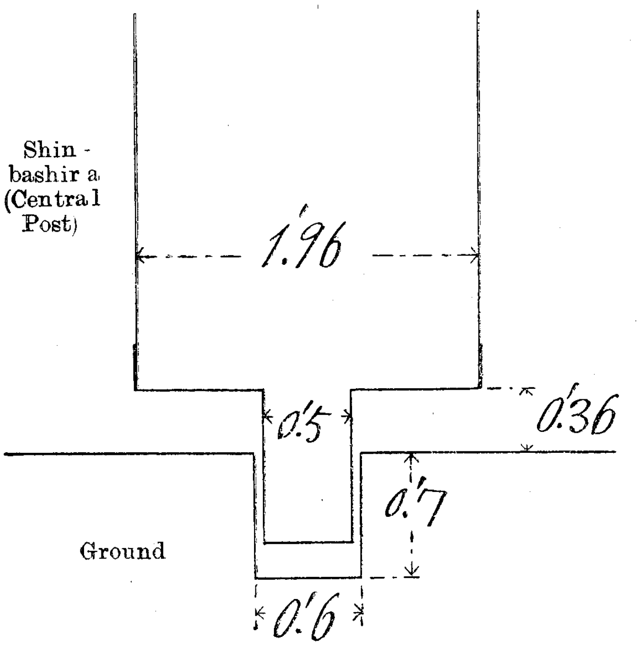



Fig. 12. Section showing the lower end of the Central Post Pendulum of the Nikko Gojunoto.

At the time of the experiment there prevailed very light winds, which caused no tree leaves to move. The tower was, however, making small unfelt oscillations.

As will be seen from Tables XIII and XIV, the period of the forced oscillation of the tower was 1.35 sec. and identical with that of the free oscillation. The max. movements in the two classes of motion were respectively 3.8 and 3.2 mm. It is hereby to be noted that the period of the natural oscillation caused by winds was the same as that of the movements which followed the forced man power shakings.

TABLE XIV. Motion of the Nikko Gojunoto, caused by shaking the Central Post.

(* .....Free after-movement.)

| Motion of the Central Post. | E. W. Component. | | N. S. Component. | |
|---|---|---|---|---|
| | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| Natural Oscillation. (Very slight wind) | 1.32 | 0.20 ............... | 1.30 | 0.13 |
| | 1.35 | 0.17 | 1.25 | 0.05 |
| Shaken E.-W. | 0.25 | 0.08 | 0.43 | 0.09 |
| | 1.20 | 0.67 | 1.30 | 0.20 |
| ,, N.-S. | 1.33 | 0.19 | 1.20 | 0.57 |
| | — | — | 1.14 | 0.40 |
| | — | — | 1.20 | 0.52 |
| | 1.29 | 0.25 | 1.15 | 0.47 |
| | 1.36 | 0.19 | 1.04 | 0.20 |
| | — | — | 0.43 | 0.07 |
| | 0.24 | 0.01 | 0.42 | 0.08 |
| | * 1.34 | 0.13 | 1.35 | 0.04 |
| ,, E.-W. | 1.41 | 2.13 ............... | 1.37 | 0.97 |
| | 1.38 | 3.10 | 1.37 | 1.58 |
| | 1.41 | 2.17 | 1.36 | 1.07 |
| | 1.44 | 1.22 | 1.30 | 0.53 |
| | * 1.31 | 0.26 | 1.32 | 0.57 |
| | * 1.24 | 0.07 | 1.27 | 0.07 |
| | * 1.33 | 1.97 | — | — |
| | * 1.34 | 0.43 | 1.36 | 0.30 |
| | * 1.39 | 2.53 | 1.35 | 1.85 |
| | * 1.33 | 1.73 | 1.32 | 1.15 |
| | * 1.32 | 0.10 | 1.33 | 0.10 |
| ,, E.-W. | 1.52 | 0.70 ............... | 1.31 | 0.09 |
| | 1.36 | 3.03 | 1.35 | 0.22 |
| | 1.39 | 3.83 | 1.39 | 1.83 |
| | 1.42 | 1.30 | 1.40 | 0.67 |
| | 1.35 | 1 33 | 1.30 | 1.33 |
| | 1.32 | 1.33 | 1.30 | 1.37 |
| | * 1.35 | 0.77 | 1.33 | 1.97 |
| | * 1.34 | 0.93 | 1.34 | 1.40 |
| | * 1.32 | 0.57 | 1.32 | 1.30 |

| Motion of the Central Post. | E. W. Component. | | N. S. Component. | |
|---|---|---|---|---|
| | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| Shaken N.-S. | 1.46 | 0.37 | 1.45<br>0.47 | 0.83<br>0.18 |
| | — | — | 0.49 | 0.27 |
| | 1.35 | 0.50 | 1.45 | 0.80 |
| | 1.34 | 0.40 | 1.40<br>0.46 | 0.54<br>0.07 |
| | 1.36 | 0.07 | 1.35 | 0.20 |
| | 1.41 | 0.05 | 1.40<br>0.46 | 0.21<br>0.10 |
| | * 1.30 | 0.23 | 1.30 | 0.20 |
| | * 1.27 | 0.05 | 1.27 | 0.13 |
| | * 1.40 | 0.48 | 1.36 | 0.77 |
| | * 1.29 | 0.22 | 1.27 | 0.19 |
| | * 1.29 | 0.10 | 1.29 | 0.23 |
| ,, E.-W. | 1.41 | 1.53 | 1.35 | 0.43 |
| | 1.43 | 1.92 | 1.43 | 0.84 |
| | * 1.36 | 1.92 | 1.34 | 1.10 |
| | 1.37 | 2.58 | 1.37 | 1.13 |
| | 1.35 | 3.07 | 1.36 | 3.03 |
| | * 1.32 | 1.23 | 1.31 | 3.12 |
| | * 1.34 | 0.15 | 1.32 | 0.30 |
| | * 1.35 | 0.27 | 1.32 | 0.07 |
| | — | — | 0.44 | 0.12 |
| | — | — | 1.31 | 0.19 |
| | 1.34 | 0.77 | 1.34 | 0.74 |
| | 0.26 | 0.05 | — | — |
| | 1.31 | 1.62 | 1.32 | 0.77 |
| ,, E.-W. | 1.36 | 2.43 | 1.29<br>0.43 | 0.58<br>(small.) |
| | 1.30 | 1.93 | 1.44<br>0.43 | 0.31<br>(small.) |
| | 1.39 | 2.11 | 1.34 | 0.79 |
| | 0.25 | 0.13 | — | (small.) |
| | — | (small.) | 0.44 | 0.10 |
| | 1.30 | 0.60 | 1.28 | 0.53 |
| | 0.25 | 0.09 | — | — |
| | 0.24 | 0.13 | — | — |
| | 1.37 | 0.73 | 1.02 | 0.14 |
| | 1.20 | 1.03 | 1.20 | 0.52 |
| | 1.27 | 2.57 | 1.28 | 2.27 |
| | 1.31 | 2.18 | 1.30 | 2.27 |
| | * 1.34 | 2.43 | 1.34 | 1.40 |
| | * 1.30 | 0.77 | 1.37 | 0.13 |
| | * 1.38 | 0.32 | 1.32 | 0.67 |
| | * 1.30 | 0.60 | 1.31 | 0.92 |
| ,, N.-S. | 1.26 | 0.61 | 1.25 | 1.53 |
| | 1.30 | 0.79 | 1.28 | 1.97 |
| | 1.31 | 0.64 | 1.28 | 1.27 |
| | * 1.36 | 0.09 | 1.33 | 0.10 |
| | * 1.34 | 0.09 | 1.35 | 0.06 |

**10. Asaksa gojunoto.** The gojunoto of the Asaksa temple, in the Asaksa park, Tokyo, has the total height of 107.4 shaku, the kurin and the tower body being respectively 25.7 and 81.7 shaku high. The sectional dimension of the tower is 16.0 shaku at the base and 10.0 shaku at the 5th story. The combined system of the kurin and the shinbashira does not rest on the ground, but is suspended from the roof frame of the 5th story by four strong flat iron springs and two horizontal iron bars passed through the post at right angles. The shinbashira, octagonal in section, is of larch-tree, (*Larix leptolepis japonica*) and is composed of 5 pieces or parts jointed together, the circumference being 5.5 shaku at the bottom and 4.4 shaku at the 5th story (fig. 13).

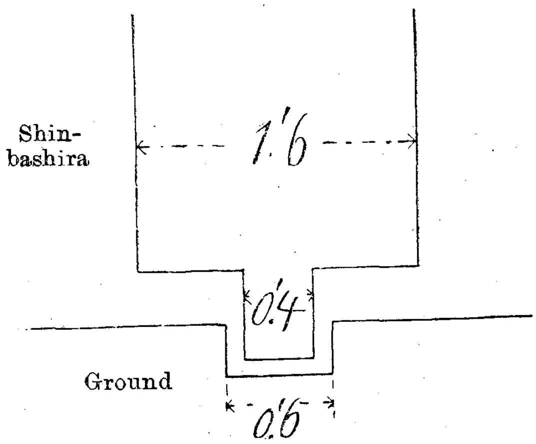



Fig. 13. Section of the lower end of the Central Post Pendulum of the Asaksa Gojunoto.

The kurin and the shinbashira form a pendulum, which could be put into movement by slight touches of hand at the lower end. The natural oscillation period was 3.05 sec., which is much shorter than the value corresponding to a simple free pendulum of the same dimensions. The amount of motion of the lower end of the post reached 0.25 and 0.20 shaku respectively in the N.S. and the E.W. directions. The proper pendulum oscillation might have been made larger but for the device for limitation, as shown in fig. 13; the small dowel at the bottom end of the post having the freedom of motion for only the amplitude of 0.1 shaku in the small hollow receptacle of stone fixed to the ground.

TABLE XV. Motion of the Asaksa Gojunoto:
Period of Vibration.*

| E. W. Component. | | N. S. Component. | |
|---|---|---|---|
| Forced Motion. | Free Motion. | Forced Motion. | Free Motion. |
| sec. | sec. | sec. | sec. |
| 1.25 (1) | 1.31 (1) | 1.30 (1) | 1.31 (2) |
| 1.30 (3) | 1.32 (2) | 1.31 (2) | 1.32 (2) |
| 1.31 (1) | 1.33 (1) | 1.32 (4) | 1.34 (1) |
| 1.32 (1) | 1.34 (2) | 1.33 (3) | 1.35 (5) |
| 1.34 (3) | 1.35 (9) | 1.34 (4) | 1.36 (2) |
| 1.35 (5) | 1.36 (7) | 1.35 (4) | 1.37 (1) |
| 1.36 (7) | 1.37 (1) | 1.36 (4) | 1.38 (3) |
| 1.37 (1) | 1.44 (1) | 1.38 (4) | **1.349** |
| 1.38 (3) | 1.45 (1) | 1.39 (1) | |
| 1.39 (1) | **1.356** | 1.40 (3) | |
| 1.40 (6) | | 1.41 (1) | |
| 1.41 (1) | | **1.352** | |
| 1.42 (2) | | | |
| 1.45 (2) | | | |
| 1.50 (1) | | | |
| **1.370** | | | |

On July 3rd, 1919, when the vibration measurement was made, it was calm, and the tree leaves were not appreciably moved; at the 5th story there being only slight easterly breeze. The tower was put into motion most effectively by shaking the shinbashira at the 5th story. The central post itself could be thrown into considerable movement by the man power disturbances applied at the 3rd story. This caused, however, no great motion of the tower structure. Similarly large oscillations of the post caused by pushing its lower free end produced only slight motion of the tower.

The forced oscillation of the tower had the average period of 1.36 sec., with the max. 2a of 4.1 mm. The free movement which set in after the cessation of the artificial shaking had also the identical period of 1.35 sec., with the max. 2a of 3.6 mm. (See Tables XV and XVI.)

* The frequency, or the number of occurrence, of a given value of the period is indicated by the figure enclosed in brackets.

TABLE XVI. Motion of the Asaksa Gojunoto, Tokyo, caused by man power shaking of the Central Post.

Experiment No. 1. Central Post shaken from the E. Side.

| Motion of the Central Post. | E. W. Component. | | N. S. Component. | |
|---|---|---|---|---|
| | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| Shaken at the 5th Floor. | 1.30 | 0.67 | 1.32 | 0.33 |
| | 1.36 | 1.47 | 1.32 | 0.27 |
| | 1.40 | 1.30 | 1.39 | 0.24 |
| | 1.36 | 2.03 | 1.35 | 0.49 |
| | 1.40 | 1.50 | 1.36 | 0.40 |
| | 1.44 | 1.57 | 1.33 | 0.23 |
| | 1.40 | 2.15 | 1.38 | 0.43 |
| | 1.45 | 2.05 | 1.38 | 0.33 |
| * | 1.36 | 1.90 | 1.38 | 0.23 |
| * | 1.36 | 1.90 | 1.32 | 0.37 |
| * | 1.36 | 0.92 | 1.38 | 0.55 |
| * | 1.31 | 0.23 | | |
| * | 1.35 | 1.25 | | |
| * | 1.36 | 0.28 | | |
| Shaken at the 4th floor. | 1.50 | 1.03 | 1.31 | 2.13 |
| | 1.41 | 0.88 | 1.40 | 0.10 |
| | 1.40 | 0.98 | 1 41 | 0.07 |
| * | 1.35 | 0 70 | | |
| Shaken at the 3rd floor. | { 1.39 | 1.17 | 1.38 | 0.07 |
| | { 0.46 | 0.06 | | |
| | 1.35 | 0.57 | 1.32 | 0.12 |
| | 1.36 | 0.31 | 1.33 | 0.15 |
| * | 1.32 | 0.99 | 1.32 | 0.33 |
| * | 1.35 | 0.35 | 1.35 | 0.25 |
| * | 1.36 | 0.41 | 1.34 | 0.23 |
| * | 0.39 | (small.) | | |

Experiment No. 2. Central Post thrown into Free Oscillation by shaking at the lowest story.

| | | | | |
|---|---|---|---|---|
| Shaken E.-W. | 1.34 | 0.28 | 1.31 | 0.10 |
| | 1.35 | 0.43 | 1.36 | 0.09 |
| | 1.34 | 0.13 | 1.38 | 0.25 |
| | 1.35 | 0.80 | 1.35 | 0.54 |
| | 1.32 | 0.23 | | (-mall.) |
| Shaken N.-S. | 1.36 | 0.21 | 1.35 | 0.12 |
| | 1.37 | 0.58 | 1.37 | 0.16 |

Experiment No. 3. Central Post shaken at the 5th Floor.

| Direction of Shaking. | E. W. Component. | | N. S. Component. | |
|---|---|---|---|---|
| | T (sec.) | 2a (mm.) | T (sec.) | 2a (mm.) |
| Shaken from the S. | 1.38 | 0.77 ............... | 1.40 | 2.00 |
| * | 1.35 | 0.72 | 1.35 | 2.10 |
| Shaken from the W. | 1.36 | 3.5 ............... | 1.35 | 0.23 |
| | 1.35 | 3.43 | 1.38 | 0.89 |
| *Do.* | 1.36 | 3.5 ............... | 1.34 | 0.34 |
| | 1.37 | 3.5 | —— | (small.) |
| *Do.* | 1.38 | 2.58 ............... | 1.36 | 0.46 |
| * | 1.35 | 2.50 | 1.36 | 0.73 |
| *Do.* | 1.36 | 2.97 ............... | 1.34 | 0.19 |
| | 1.34 | 2.27 | 1.33 | 0.22 |
| Shaken from the S. | 1.36 | 0.94 ............... | 1.34 | 2.70 |
| * | 1.35 | 1.03 | 1.35 | 2.47 |
| *Do.* | 1.40 | 0.14 ............... | 1.35 | 2.13 |
| | 1.35 | 0.41 | 1.36 | 2.07 |

Experiment No. 4. Central Post shaken at the 5th Floor.

| | | | | |
|---|---|---|---|---|
| Shaken from the E. | 1.45 | 2.25 ............... | 1.34 | 0.24 |
| | 1.44 | 2.46 | 1.40 | 0.13 |
| | 1.40 | 3.60 | 1.32 | 0.17 |
| * | 1.36 | 4.10 | 1.31 | 0.24 |
| Natural motion. * | 1.35 | 0.65 ............... | 1.31 | 0.20 |
| (without-special * | 1.35 | 0.79 | 1.30 | 0.14 |
| shaking.) * | 1.34 | 0.78 | 1.35 | 0.24 |
| * | 1.34 | 0.76 | 1.36 | 0.30 |
| Shaken from the W. | 1.25 | 0.82 | | |
| * | 1.44 | 0.48 | | |
| | 1.30 | 1.07 | | |
| * | 1.35 | 0.77 | | |
| | 1.38 | 0.63 | | |
| * | 1.33 | 0.45 | | |
| | 1.30 | 1.01 | | |
| * | 1.45 | 0.37 | | |
| | 1.31 | 1.40 | | |
| | 1.32 | 0.47 | | |

**11. Comparison of movements of the different gojunotos.** In Table XVII are given the elements of motion of the six gojunotos, together with the height and size of the towers.

*Natural vibration period.* The large gojunoto of Toji has the longest natural vibration period of 1.81 sec., while the Horyuji tower has the shortest value of 1.25 sec., the latter having the most stable form of construction. Of the four others, which are slender in form and whose dimensions do not much differ mutually, the vibration period varied from 1.28 sec. for the Ueno to 1.37 sec. for the Hommonji gojunoto. Taking the average from the four towers of Ueno, Hommonji, Nikko, and Asaksa, I get

Height of tower body = 81.9 shaku = H

Base dimension = 16.0 ,, = b

5th Story dimension = 10.2 ,,

Natural vibration period = 1.34 sec. = $\tau$

The base and the 5th story dimensions of the Toji tower body are very nearly equal to double of the average values for the four smaller ones here deduced; the height of the former being, however, only 1.7 times that of the latter. Now, the vibration period of a uniform section column fixed at the base varies inversely as the thickness and directly as the square of the height. Thus the vibration period ($=\tau'$) of the Toji gojunoto may roughly be estimated from that of the mean hypothetical smaller one, assuming all the different towers to be geometrically and constructively similar, as follows:—

$$\tau' = \frac{\tau \times \overline{138}^2 \times b}{H^2 \times 31.8} = 1.9 \text{ sec.},$$

which agrees fairly well with the actual value of 1.81 sec.

**12. Forced vibration period.** The period of the large forced tower body oscillations caused by the man power shinbashira shaking was found to be perfectly the same as that of the small or large free motion in the three cases of the Hommonji, Nikko, and Asaksa gojunotos, in the last two of which the central post and the kurin form a system suspended from the tower structure. The free oscillation period of the pendulum of the Asaksa gojunoto was 3.05 sec., that for the Nikko one being probably of the same order of magnitude. The trace of the existence of the slow movement of 3 sec. period was, however, not found in the instrumental records. Again, the vibration period (=1.55 sec.) of the central post of the Hommonji gojunoto, which is fixed to the floor of the 2nd story and is clear of the rest of the structure, is not shown in the motion of the tower.

In the gojunoto of Ueno, the heavy shinbashira, which rests on the ground and is supported at the top, has the short proper vibration period of 0.95 sec., which becomes the predominant element in the forced oscillation of the tower; the natural longer oscillation period (=1.28 sec.) of the latter being entirely obliterated when the central post is set in motion. This seems to be due to the relatively great mass of the shinbashira, whose upper end is in contact with the tower body.

In the case of the Horyuji gojunoto, the period of the small natural oscillation (=1.25 sec.) is much shorter than that of the larger movement (=1.64 sec.) caused by shaking the central post. This may be due to the fact that the latter is in contact with the tower body at two places about the middle of its height, thereby putting, in case of the shaking, the whole system in motion as one mass.

TABLE XVII. Maximum Movement and the Free and Forced Vibration Periods of the different Gojunotos.

| Gojunoto. | Height of Tower Body | Dimension of Base Story | Dimension of 5th Story | Natural Period | Forced Period | Max. 2a. |
|---|---|---|---|---|---|---|
| | shaku | shaku | shaku | sec. | sec. | mm. |
| Horyuji | 73.3 | 20.7 | 10.6 | 1.25 | 1.64 | 1.4 |
| Toji | 138.0 | 31.8 | 22.2 | 1.81 | 1.26 * | 0.92 |
| Ueno | 79.5 | 16 0 | 10.3 | 1.28 | 0.95 | 3.4 |
| Hommonji | 78.7 | 15.9 | 10.8 | 1.37 | 1.39 | 3.3 |
| Nikko | 87.8 | 16.0 | 9.7 | 1.33 | 1.35 | 3.8 |
| Asaksa | 81.7 | 16.0 | 10.0 | 1.35 | 1.36 | 4.1 |
| Mean from Ueno, Hommonji, Nikko, and Asaksa. | 81.9 | 16.0 | 10.2 | 1.34 | — | — |

For the Toji gojunoto, the period of the proper movement of the column composed of the shinbashira and kurin, which was not directly observed, may be estimated to be about $3\frac{1}{4}$ sec. from the comparison with that for the Hommonji gojunoto. Slow oscillation of this period, however, does not occur in the motion of the tower body, which is entirely isolated from the shinbashira.

The difference in character of motion of the five smaller gojunotos, as far as the natural and forced oscillations are concerned, may be diagrammatically illustrated as in fig. 14.

* The average period of the artificial shakings.

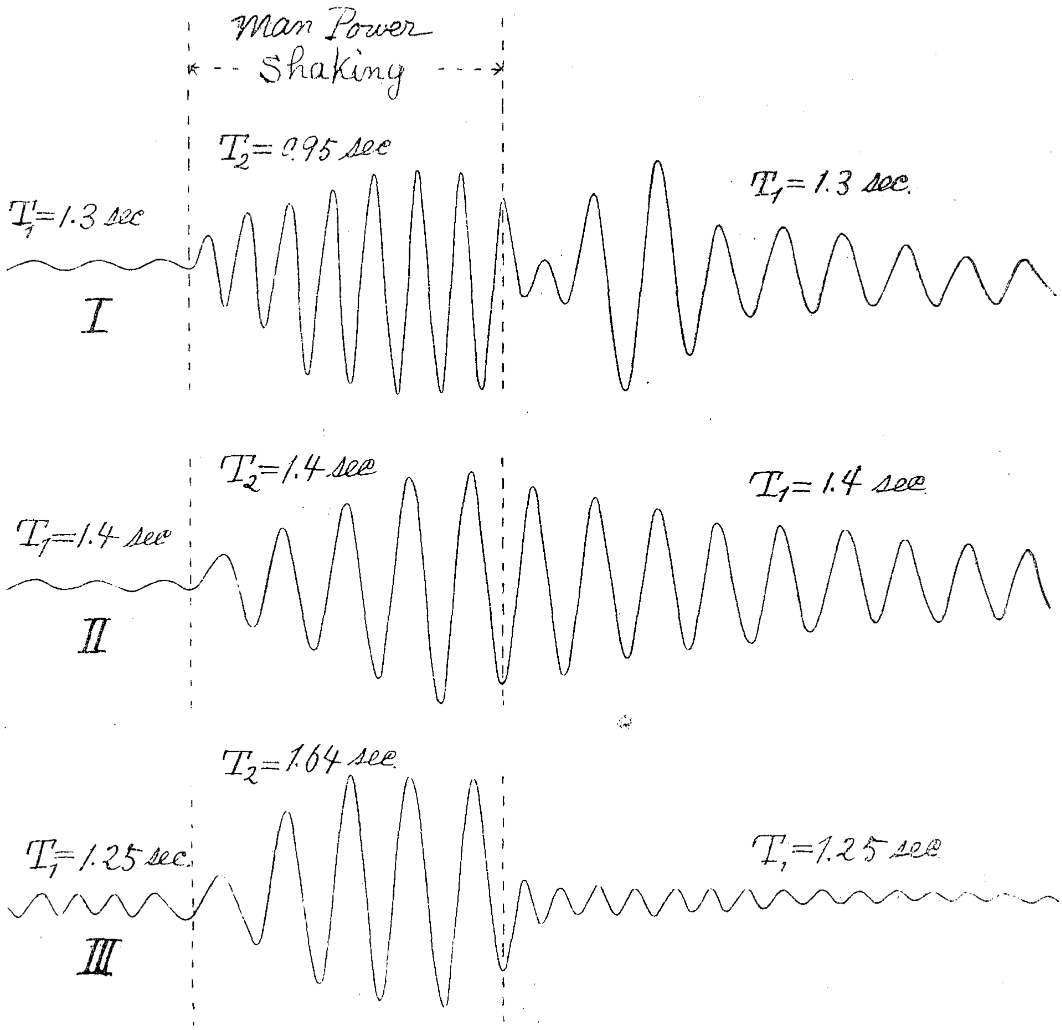



Fig. 14. Diagram illustrating the character of motion of the different gojunotos. $T_1$=Natural vibration period. $T_2$=Vibration period during the application of man power shaking to the shinbashira (central post).
I. Ueno Type.
II. Nikko, Asaksa, and Hommonji Type.
III. Horyuji Type.

In each of the three gojunotos of Ueno, Nikko, and Asaksa, the oscillations which occurred a short time interval after the cessation of the artificial shakings applied to the central post were often equally large or even larger than the preceding prominent movements. (See figs. 18, 19, and 21.) This fact may be due to the circumstance that the removal of the disturbing action transfers the moving system from the forced condition to the natural state, favouring thereby the production of large free oscillations.

The double amplitude, or range of motion, observed in the cases of Toji and Horyuji gojunotos was quite small, with the maximum amount of 0.92 and 1.4 mm. respectively. The motion of the four towers of Ueno, Hommonji, Nikko, and Asaksa produced by the artificial shaking or by moderately strong winds was about 4 mm. The actual oscillation of these gojunotos in violent storms or on occasion of a great earthquake would naturally be superior to that for the other two, and may amount to a few feet.

**13. Height of centre of gravity.** I reproduce here the results obtained by the students in the department of architecture of the Tokyo University, who worked, as examples in applied seismology, of the stability of the gojunotos of Nikko, Horyuji, and of Daigoji. Messres. Hamano and Suzuki have made estimates of the weight and the height of the centre of gravity of the Nikko gojunoto from its one-twentieth scale model kept in the museum of the Architectural Department of the Tokyo Imperial University, as follows:—

| | |
|---|---|
| Weight of the kurin ... ... ... ... ... | 3,500 lbs. |
| ,, the shinbashira . ... ... ... | 9,800 ,, |
| Total weight of the gojunoto ... ... ... | 276,000 ,, |
| Height of centre of gravity ... ... ... | 39 shaku. |

The point corresponding to the centre of percussion of the tower relative to the ground surface is at the height of about 52 shaku.

The results of the approximate estimations made of the Horyuji gojunoto, by Messres. K. Omori and D. Oka from Professor C. Ito's detail construction drawings, are as follows:—

| | |
|---|---|
| Weight of the kurin ... ... ... ... ... | 5,800 lbs. |
| ,, the shinbashira ... ... ... | 10,800 ,, |
| Total weight of the gojunoto ... ... ... | 1,006,000 lbs. |
| Height of centre of gravity ... ... ... | 36 shaku. |
| Height of the point corresponding to the centre of percussion ... ... ... ... | 49 shaku. |

The height of centre of gravity of the gojunoto of Daigoji, near Kyoto, is about 34.7 shaku, according to the estimation by Mr. S. Fujioka.*

Thus, the position of centre of gravity is in each case at the level of the 3rd story verandah or balustrade, being situated a little below the middle height of the tower body, as follows:—

| | Ratio of height of centre of gravity to the total height of tower body. |
|---|---|
| Nikko ... ... ... ... ... | $\frac{39 \text{ shaku}}{87.8 \text{ shaku}} = \frac{1}{2.26}$ |
| Horyuji ... ... ... ... | $\frac{36}{79.1} = \frac{1}{2.20}$ |
| Daigoji... ... ... ... ... | $\frac{34.7}{78.4} = \frac{1}{2.26}$ |

From the above statements it will be seen that the gojunotos of Nikko, Horyuji, and of Daigoji, are equivalent, as far as the simple overturning action is concerned, to large uniform section columns with the base of 16 to 21 shaku and with the height of 69 to 78 shaku. (See fig. 15.) The ratio of the base dimension to the height is 1/4.9 for the Nikko gojunoto which is appreciably smaller than the values for the other two, namely, 1/3.5 and 1/3.3. This is the reason why the Nikko stupa looks so slender.

* The dimensions of the Daigoji gojunoto are as follows:—

| | |
|---|---|
| Total height ............... | 119.7 shaku. |
| Height of kurin ... ...... | 41.3 ,, |
| ,, ,, tower body...... | 78.4 ,, |

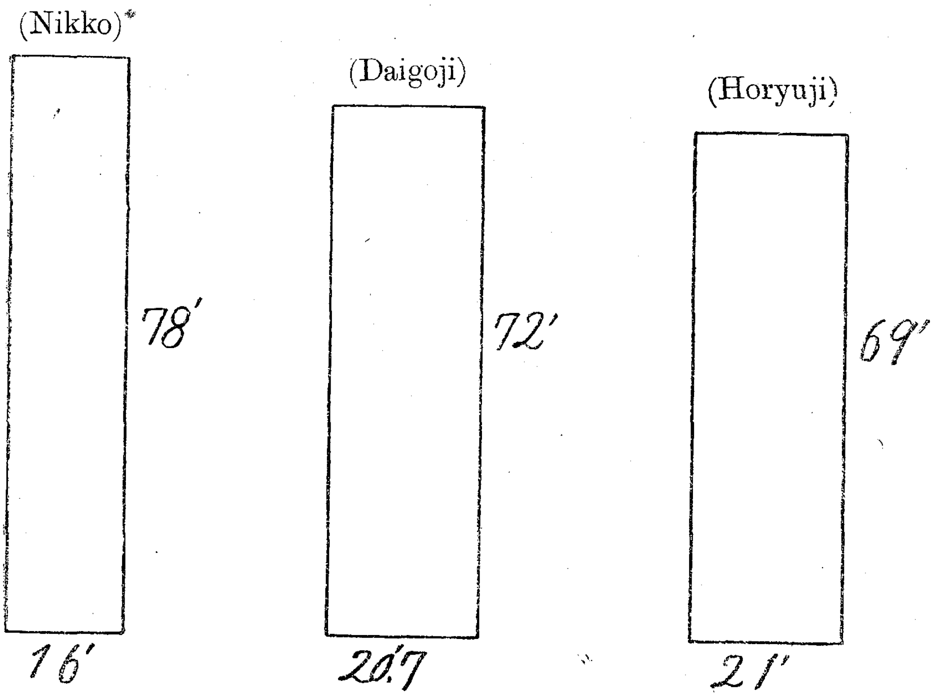



Fig. 15. Nikko, Daigoji, and Horyuji Gojunotos represented as columns.

The ratio in question for the Ueno, Hommonji, and Asaksa gojunotos will be somewhat larger than that for the Nikko one.

**14. Stability of gojunotos against overturning.** The gojunotos, though tall and apparently unstable, are in reality very stable and can resist overturning by earthquake shocks, however violent. Even supposing these structures to come under the category of "small body"* the approximate acceleration ($=\alpha$) of the earthquake motion necessary for the overturning* would be, for the three gojunotos considered in the preceding §, fairly high and vary from 2,000 mm./sec.$^2$ to 3,000 mm./sec.,$^2$ as follows:—

Nikko ... ... ... ... ... $\alpha = \frac{16}{78} \times g = 2{,}000$ mm./sec.$^2$

Horyuji ... ... ... ... $\alpha = \frac{20.7}{72} \times g = 2{,}800$ „

Daigoji... ... ... ... ... $\alpha = \frac{21}{69} \times g = 3{,}000$ „

* See the Publications of the Earthquake Investigation Committee, No. 12.

where g represents the acceleration due to the gravity. These structures are, however, to be regarded as large bodies, since the period of their natural bodily rocking must be sufficiently longer than that of the destructive earthquake motion. Thus, for the Nikko gojunoto, the rough range of horizontal seismic motion necessary for overturning the tower as a whole would be

$$2a=\frac{8h}{y_0}=\frac{8\times 52}{39}=10.6 \text{ shaku}=3.2 \text{ metres},$$

$y_0$ being the height of the centre of gravity, and h the height of the point corresponding to the centre of percussion with respect to the ground surface. The motion 2a of 10 feet or so can never occur even in greatest seismic shocks. In other words, the Nikko and other gojunotos are subject to no risk of overturning from earthquakes.

Toji Gojunoto. It may not be entirely wrong to suppose that the principle of the non-overturning of large bodies was known to the architect who built the Toji gojunoto, whose construction indicates a bold confidence in the immunity from seismic shocks of the huge shinbashira, or central post, which is nowhere in contact with the tower body. The range of horizontal earthquake motion necessary to overturn the vertical column composed of the shinbashira and the kurin would be some 2.5 feet, which is beyond the limit of possible destructive seismic vibration. The free shinbashira of the smaller but much similar gojunoto of Daigoji has also a very stable proportion, the diameter at the base being 2.6 shaku. The large size of shinbashira seems to be a distinct feature of this class of gojunotos.

The shinbashiras of the Horyuji and Ueno gojunotos, whose erection is to a certain degree similar to that for the Toji tower, are also fairly large, their base diameters being respectively 3.3 and 2.0 shaku.

Nikko and Asaksa Gojunotos. The principle of construction of these two towers is very interesting, being really a sort of duplex pendulum, formed by the combination of the suspended system of the shinbashira and the kurin, which constitute an ordinary pendulum, and of the tall frame construction of the tower body, which may be regarded as a sort of inverted pendulum. Now an ordinary pendulum, which is in stable equilibrium, returns to its original position even when displaced from the condition of rest, but, in doing so, is often thrown into large proper oscillations. On the other hand, an inverted pendulum, whose equilibrium is unstable, tends to topple over, if displaced from its position of rest. Speaking in a general way, a gojunoto of the Nikko or Asaksa type may be said, so far as the overturning tendency is concerned, to have its unstability compensated in a measure by the introduction of the stable pendulum, so as to give the combined system some approach to a neutral equilibrium, thereby minimizing the seismic effect on the structure. The Hommonji gojunoto, in which the free shinbashira is erected from the floor of the 2nd story may be regarded as a modification, or rather as a first step toward the introduction, of the pendulum method of suspension. A characteristic relating to the stupas of this sort is the comparatively small size of the central post.

**15. Stability against fracture.** In each of the three pendulum or semi-pendulum type gojunotos of Nikko, Asaksa, and Hommonji, the period of oscillation of the structure caused by artificially shaking the shinbashira was 1.35 to 1.39 sec. and identical with that of the natural free motion. The period of the latter will also characterize the large oscillations of these structures to be produced in the case of a destructive earthquake. In the Ueno gojunoto, the forced vibration period, =0.95 sec., was found to be the same as that of the shinbashira, whose great mass and lack of sufficient rigidity give evidently a preponderating effect on the motion of the whole structure. A strong seismic motion, which must set in considerable movement the central post in question, would cause the tower to assume oscillations with the period equal to that of the latter. Thus for the first three and the last one of the stupas here considered, the period of the tower vibration on the occasion of a great earthquake would be respectively about 1.4 sec. and 1.0 sec., which are of the same order of length as the period of the destructive seismic motion for the localities concerned, namely, one of 1 to 1½ sec. Hence each of the gojunotos of Nikko, Asaksa, Hommonji, and Ueno is to be regarded, in the discussion of the stability against the fracturing by earthquake shocks, as a "short column,"* whose weakest section is at the base. This conclusion may be extended to the majority of the other gojunotos of height not exceeding some 110 shaku.

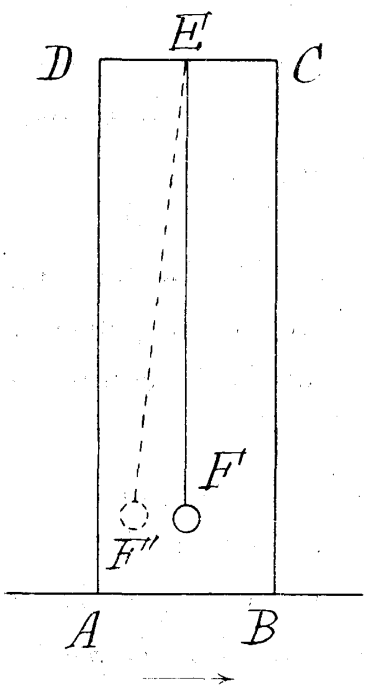


Fig. 16.

The reduction by the pendulum central post of the seismic effect of the gojunoto may diagrammatically be seen from fig. 16. The tower moves together with the ground in the direction of the earthquake displacement indicated by the arrow, but the shinbashira EF, kept by inertia in its place, is displaced to some position EF' relative to the point of

* See the Publications of the Imperial Earthquake Investigation Committee, No. 4, (1899).

suspension, thereby counterbalancing to some extent the forward motion of the rest of the structure.

The period of movement of Horyuji gojunoto in a strong earthquake is probably the same as that of the large forced oscillation, namely, 1.64 sec. The stupa may be regarded as belonging to the category of "short column."

The behaviour of the great tower of Toji in a violent earthquake may be different from that of the smaller gojunotos. When the shaking of the building becomes sufficiently large, the heavy shinbashira will come in contact with and materially influence the motion of the tower body. The latter is then likely to move with the period of about $3\frac{1}{4}$ sec. proper to the former, which is much longer than the period of the destructive earthquake motion. The tower is therefore to be regarded as a "tall column," which is weakest seismically at about the two-third height. In other words, the gojunoto in question will be moved, when strongly shaken, as if it were fixed in space at the section corresponding to the latter height.

**16. Rate of damping of motion.** The Asaksa gojunoto, whose shinbashira and kurin form a most perfect pendulum, is subject to least damping effect; 30 to 35 complete oscillations being required to reduce the motion from some 3.0 mm. to about 0.1 mm., as follows:—

| | | | | | | |
|---|---|---|---|---|---|---|
| 2a reduced from | 2.1 mm. | to 0.07 mm. | after 35 | oscillations. | (N. S.) |
| ,, | 2.7 | ,, 0.17 | ,, 27 | ,, | (N. S.) |
| ,, | 3.0 | ,, 0.43 | ,, 28 | ,, | (E.W.) |
| ,, | 2.6 | ,, 0.30 | ,, 28 | ,, | (E.W.) |

The motion of the Nikko gojunoto, the lower end of whose kurin and shinbashira pendulum is at present partly in contact with the inner wall of the receptacle cavity below, is subject to a quicker decrease rate, the 2a being reduced from 1.0 mm. practically to zero after 15 or 16 vibrations.

In the case of the Ueno gojunoto, the heavy shinbashira, which stands on the foundation stone and whose top is supported by the tower body, evidently tends to damp the motion very effectively, reducing the 2a from 2.6 mm. to zero in 16 oscillations, as follows:—

| | | | | | |
|---|---|---|---|---|---|
| 2a reduced from | 2.2 mm. | to | 0.03 mm. | after | 16 oscillations. |
| ,, | 2.6 | ,, | 0.0 | ,, | 16 ,, |
| ,, | 2.2 | ,, | 0.0 | ,, | 16 ,, |

In the Hommonji gojunoto the free shinbashira fixed to the floor of the 2nd story acts as a means of bringing large oscillation of the tower almost immediately to rest, as shown in fig. 23.

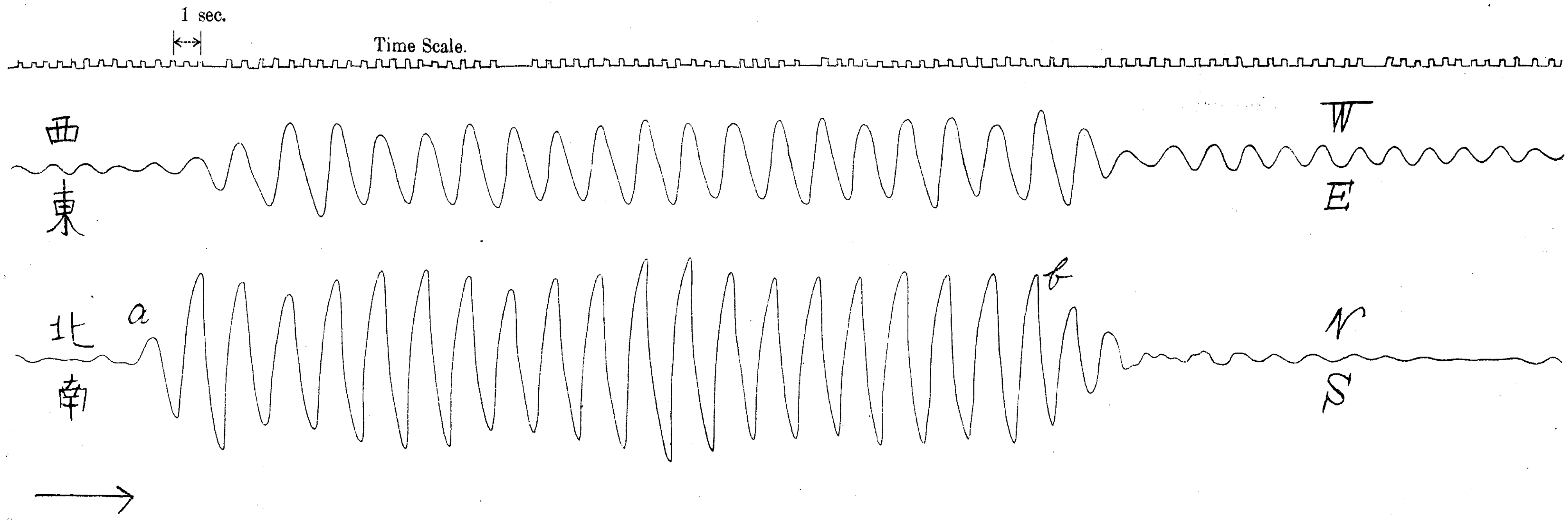
In the Horyuji gojunoto, whose shinbashira stands on the foundation stone and whose middle portion is in contact with the tower body, the damping effect is also very marked, the large motion being almost at once reduced to insignificant size when the disturbing agency is withdrawn.

The use of inverted pendulum type shinbashira in the cases of the Horyuji and Hommonji gojunotos seems to have an advantage of quickly reducing the motion of the tower body when thrown into large displacements.

**Fig. 17. Vibration of the Horyuji Gojunoto Caused by Shaking the Central Post in the N.S. Direction at the Foot of the Kurin.**

July 18th, 1910.

Multiplication=30. (a b)......Interval during which the man power shaking was applied.



# Fig. 18. Vibration of the Ueno Gojunoto Caused by Shaking the Central Post from the E. Side.

June 26th, 1919. (Multiplication = 30.)

(b)......The man power shaking stopped.
(bd)......Natural Motion.

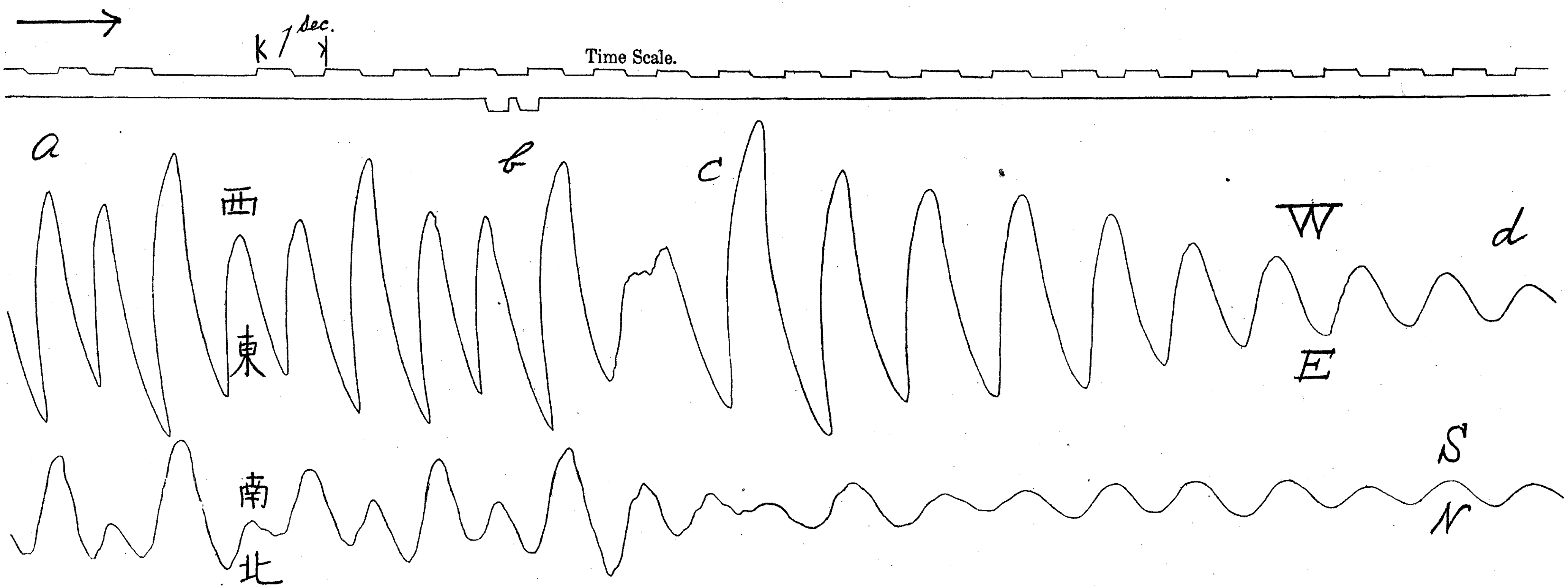


Fig. 19. Vibration of the Nikko Gojunoto Caused by Shaking the Central Post in the E.W. Direction.

March 1st, 1919.

(Multiplication=30.)
(b) ......Man power shaking stopped.
(bc)......Natural Vibration of the Tower.

PL. XXXIX.

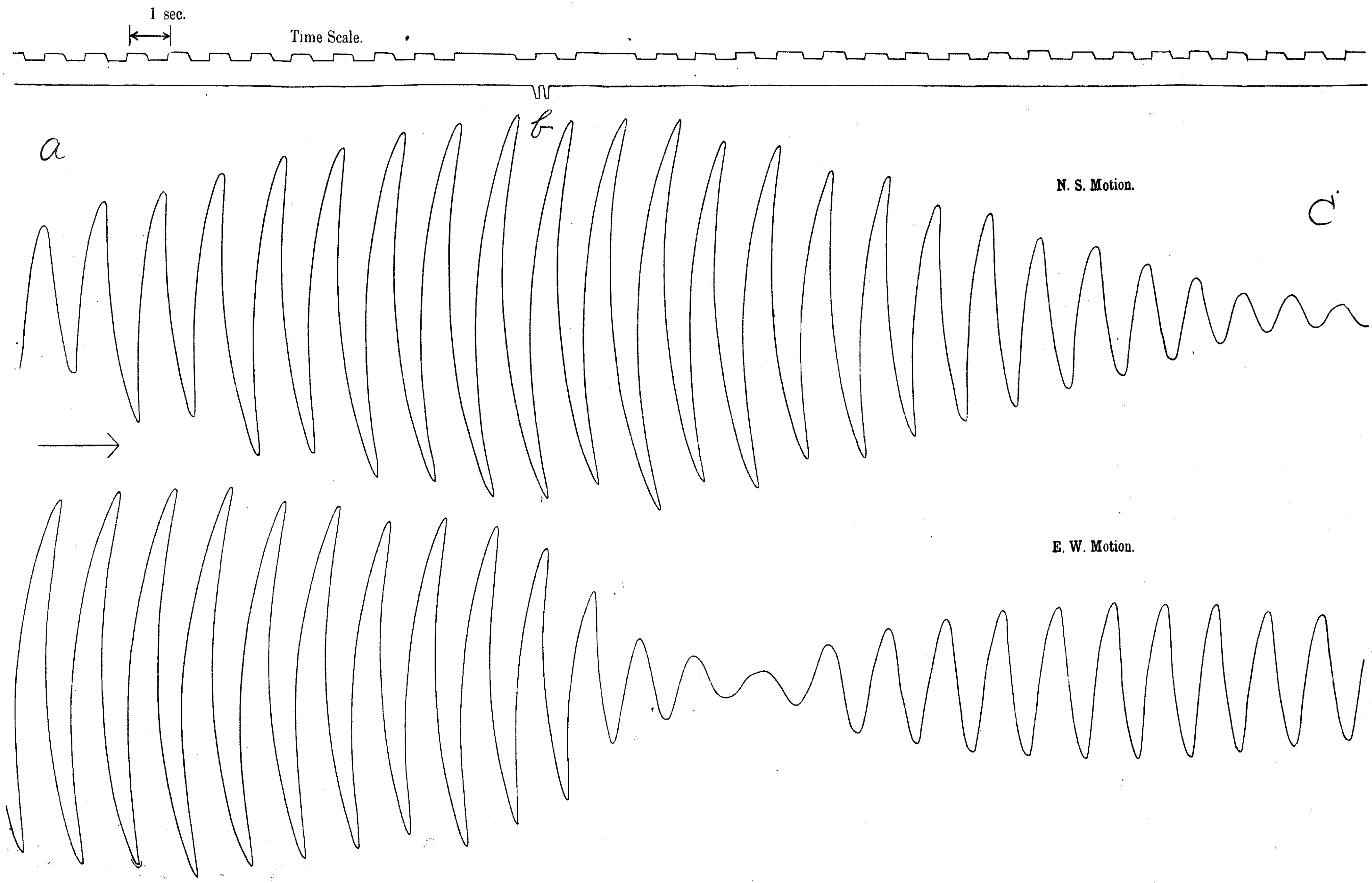
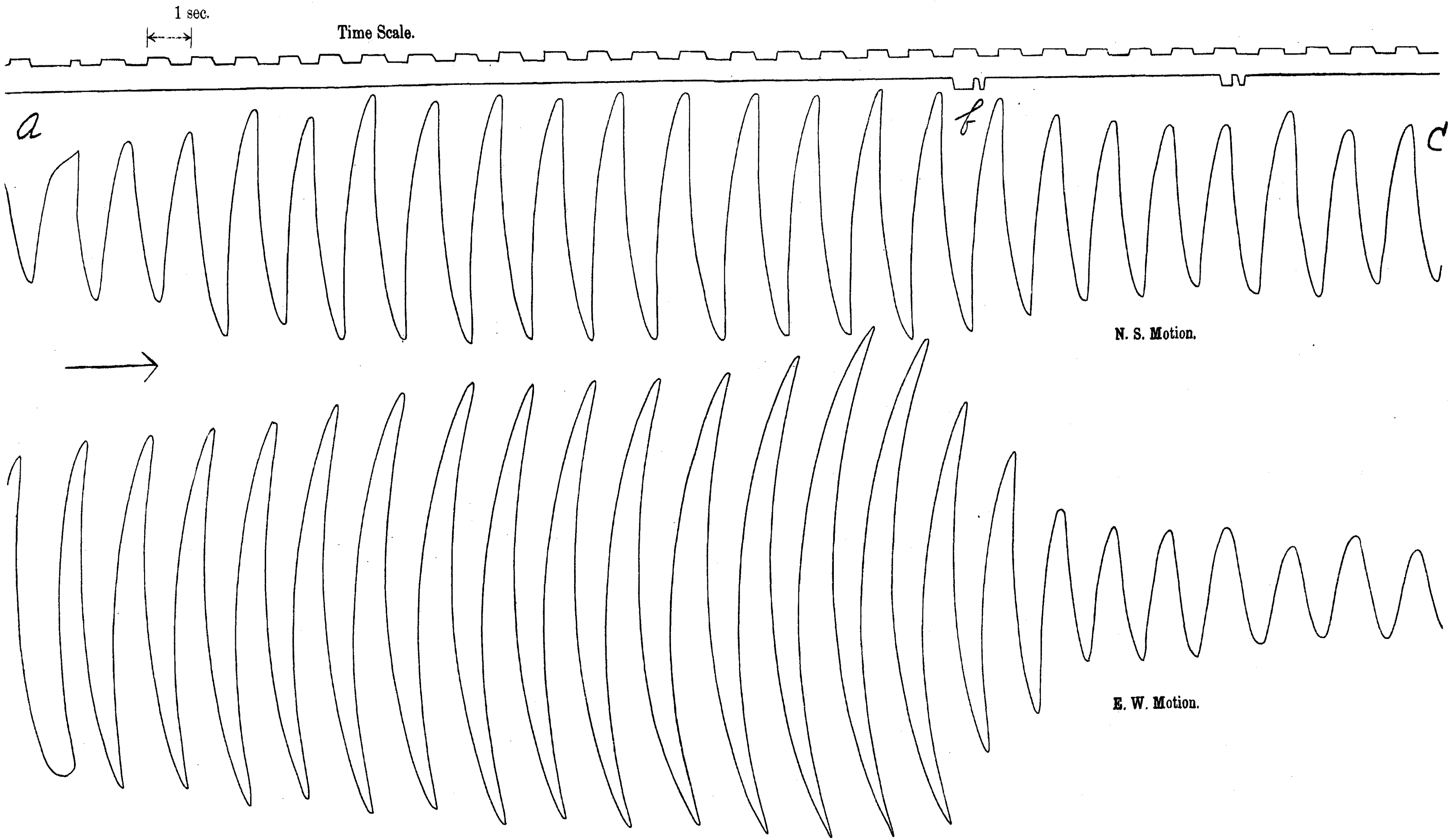


Fig. 20. Vibration of the Nikko Gojunoto Caused by Shaking the Central Post in the E.W. Direction.

March 1st, 1919.

(Multiplication = 30.)
(b) ......Man power shaking stopped.
(bc)......Natural Vibration of the Tower.

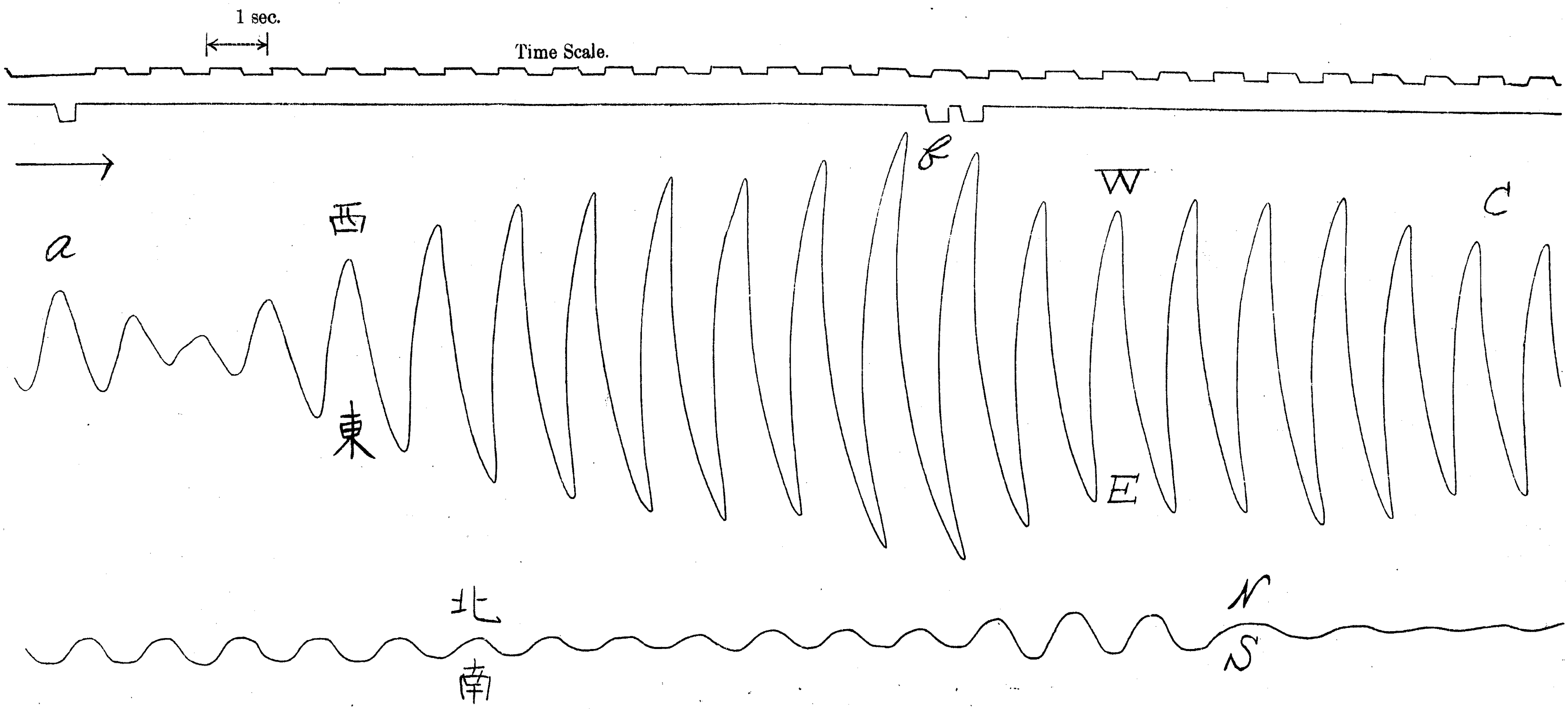


# Fig. 21. Vibration of the Asaksa Gojunoto Caused by Shaking the Central Post from the W. Side.

July 3rd, 1919.

(b) ......Man power shaking stopped.
(bc)......Natural vibration of the Tower.

(Multiplication = 30.)



# Fig. 22. Vibration of the Asaksa Gojunoto Caused by Shaking the Central Post from the E.

July 3rd, 1919.

(b) ......Man power shaking stopped.

(bc)......Natural Vibration of the Tower.

(Multiplication=20.)

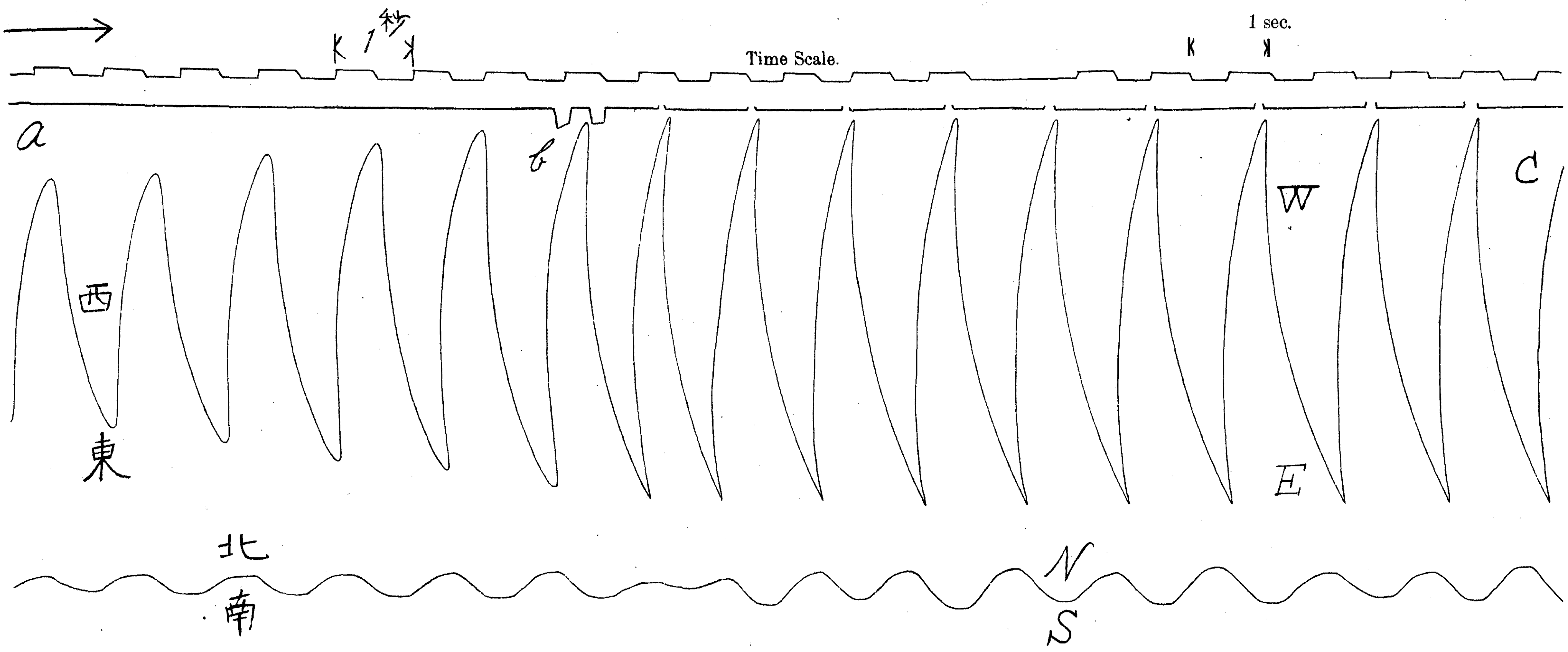
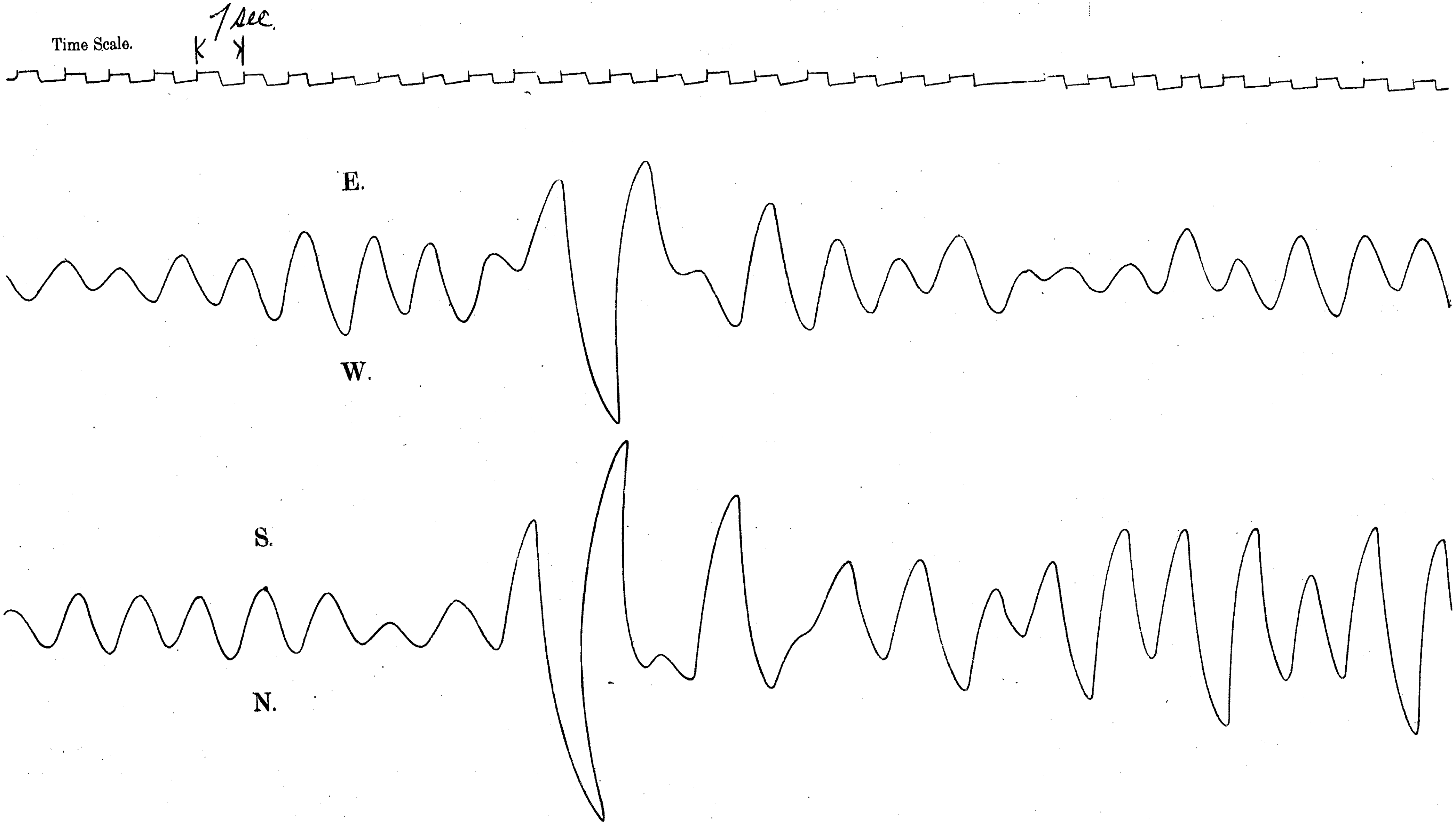


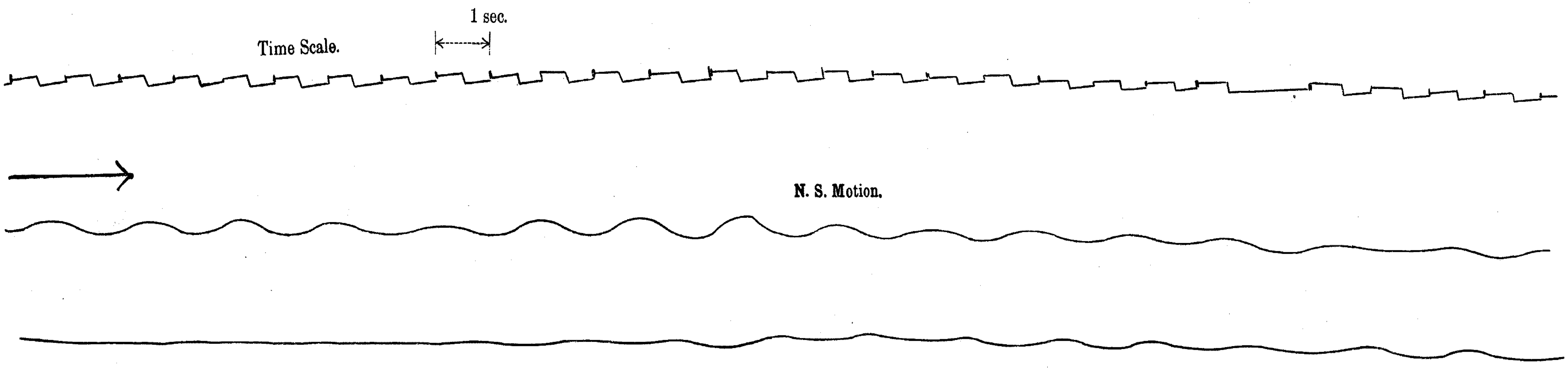
Fig. 23. Vibration of the Hommonji Gojunoto Caused by Wind. June 15th, 1920. (Multiplication = 30.)



# Vibration of the Toji Gojunoto. June 27th, 1920. (Multiplication=30.)



Fig. 24. Natural Motion Caused by Wind.



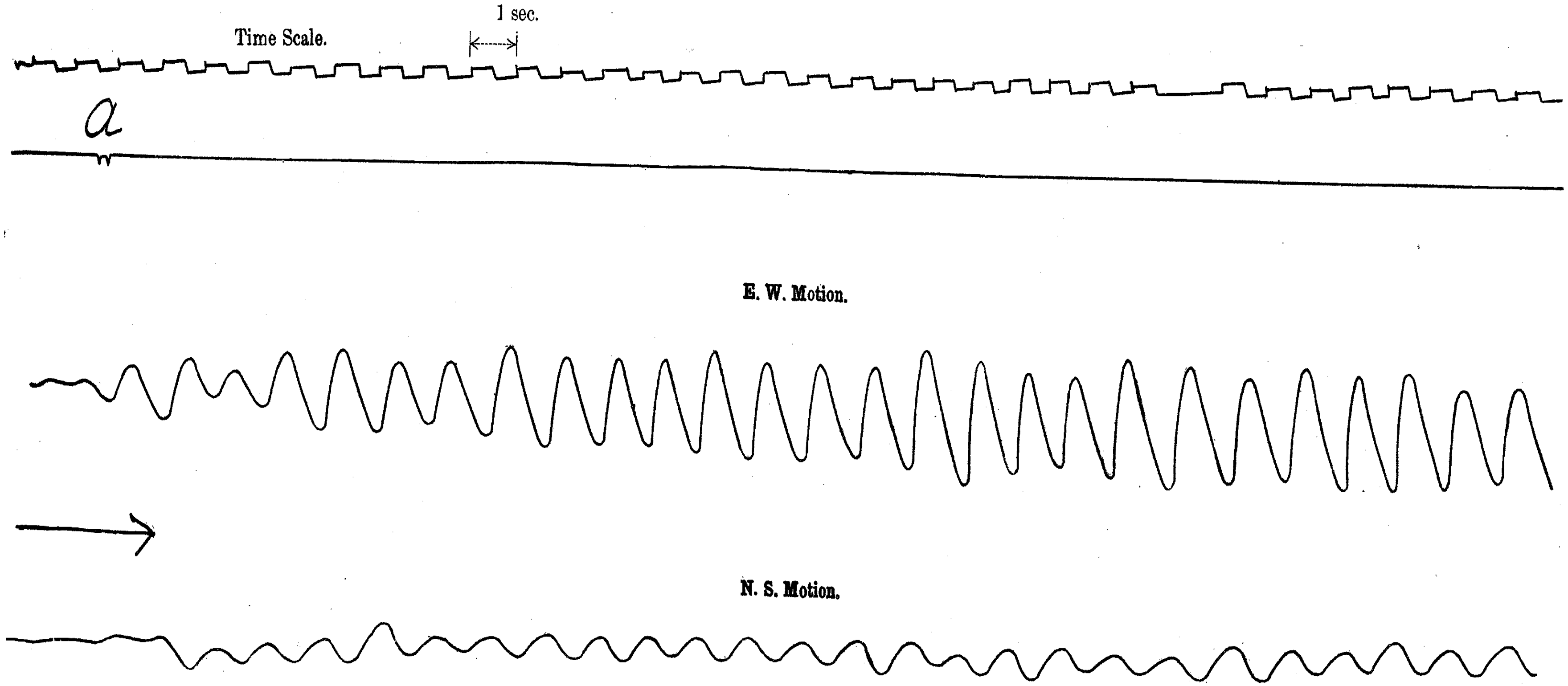




Fig. 25.
Motion Caused by Shaking the Central Post in E. W. Direction.