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Tutorial on Earthquake Rotational Effects: Historical Examples

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Abstract Earthquake rotational effects have been observed for centuries. The first class of rotational seismic models includes two models defined by Mallet (1862) in the mid-nineteenth century based on the rotation of bodies to their underlying structures. These rotational effects satisfactorily explain observed surface rotations. In this short tutorial (based mostly on western literature), we will briefly discuss the historical aspects of earthquake rotational effects.

Introduction

There are two classes of rotational seismic models. The first class includes two models defined by Mallet (1862) in the mid-nineteenth century based on the rotation of bodies to their underlying structures. These two models are named Rot1 and Rot2 by Kozák (2006). These rotational effects satisfactorily explain observed surface rotations.

The second class is derived from recent advances in theoretical studies in micromorfic and asymmetric theories of continuum mechanics, and progress in nonlinear physics, and contributions based on modern highly sensitive seismic registration techniques to reveal three other types of rotational models, Rot3, Rot4, and Rot5 (Kozák, 2006). These are derived and seismically verified by detailed analyses of the inner focal zone and wave propagation in structured medium.

In this short tutorial (based mostly on Western literature), we will briefly discuss the historical aspects of the first class of rotational seismic models. Teisseyre *et al.* (2006) presented in a monograph the second class of models. This tutorial is a condensed version of the one presented at the First International Workshop on Rotational Seismology and Engineering Applications (Lee *et al.*, 2007).

Prior to the 1755 Great Lisbon earthquake very little was written on the nature of the observational phenomenon of rotational seismological effects. Numerous remarks on rotational effects resulting from earthquake occurrences had the character of chronicle records in encyclopedic books by Schedel (1493), Münster (1544), Lycosthenes (Wolffardt) (1557), and Zahn (1696). Detailed bibliographic citations of the pertinent works are listed in Charles Davison's Founders of Seismology (Davison, 1927, 1978).

The eighteenth century, according to Davison (1927), ushered in the birth of seismology. It was closely linked with the occurrence of two strong earthquakes in southwestern and southern Europe on 1 November 1755 (Lisbon) and on 5 February 1783 (Calabria). Many pertinent articles on the Lisbon event may also be found in the "Proceedings of the Symposium on the 250th Anniversary of the 1755 Lisbon Earthquake" edited by Victor Mendes (2005).

The 1783 Calabria Earthquake

The 5 February 1783, intensity I_0 XI–XII Mercalli–Cancani–Sieberg Macroseismic Scale (MCS) earthquake occurred near the tip of the Italian boot, in Calabria, and was followed by a series of aftershocks of comparable intensity (IX, X, and XI MCS), which repeatedly shook Calabria and northwest Sicily for the next 10 yr. Estimated casualties of this earthquake ranged from 30,000 to 35,000 people.

Soon after the mainshock, a scientific commission was appointed by the Royal Academy of Sciences and Belle Letters under the leadership of the secretary of the Academy, Michele Sarconi. The participants visited the damaged area, reporting in detail the earthquake damage and other effects. Three artists, Pompeo Schiantarelli, Ignazio Stile, and Bernardo Ruli, accompanied the expedition making detailed pictorial records of the earthquake effects in the localities visited (Vivenzio, 1783, 1788).

These artists were architects by profession and therefore paid attention to details such as the seismic displacements of stone blocks. In the monastery of San Bruno a decorative obelisk, composed of four vertically arranged stony blocks, is portrayed in the lower left of Figure 1. This drawing shows mutual rotation or twisting of the four monument blocks around a vertical axis, caused by seismic movements.

The distortion of the San Bruno obelisk soon became famous as a symbol of seismic rotational effects. In the nineteenth century and even later, the obelisk drawing by Schiantarelli of 1783 appeared in many pamphlets and textbooks on earthquakes and appeared in encyclopedias to illustrate horizontal rotational effects. It was not until the mid-nineteenth century that Robert Mallet provided a mechanical explanation for the rotation.

For the first time Schiantarelli's drawings illustrated the rotational effects of an earthquake; however, the process of deciphering the physical nature of this phenomenon was still in its infancy. To nineteenth century observers the common meaning of speculative character was that there must be an independent vortical movement under the rotated objects responsible for the observed rotations.

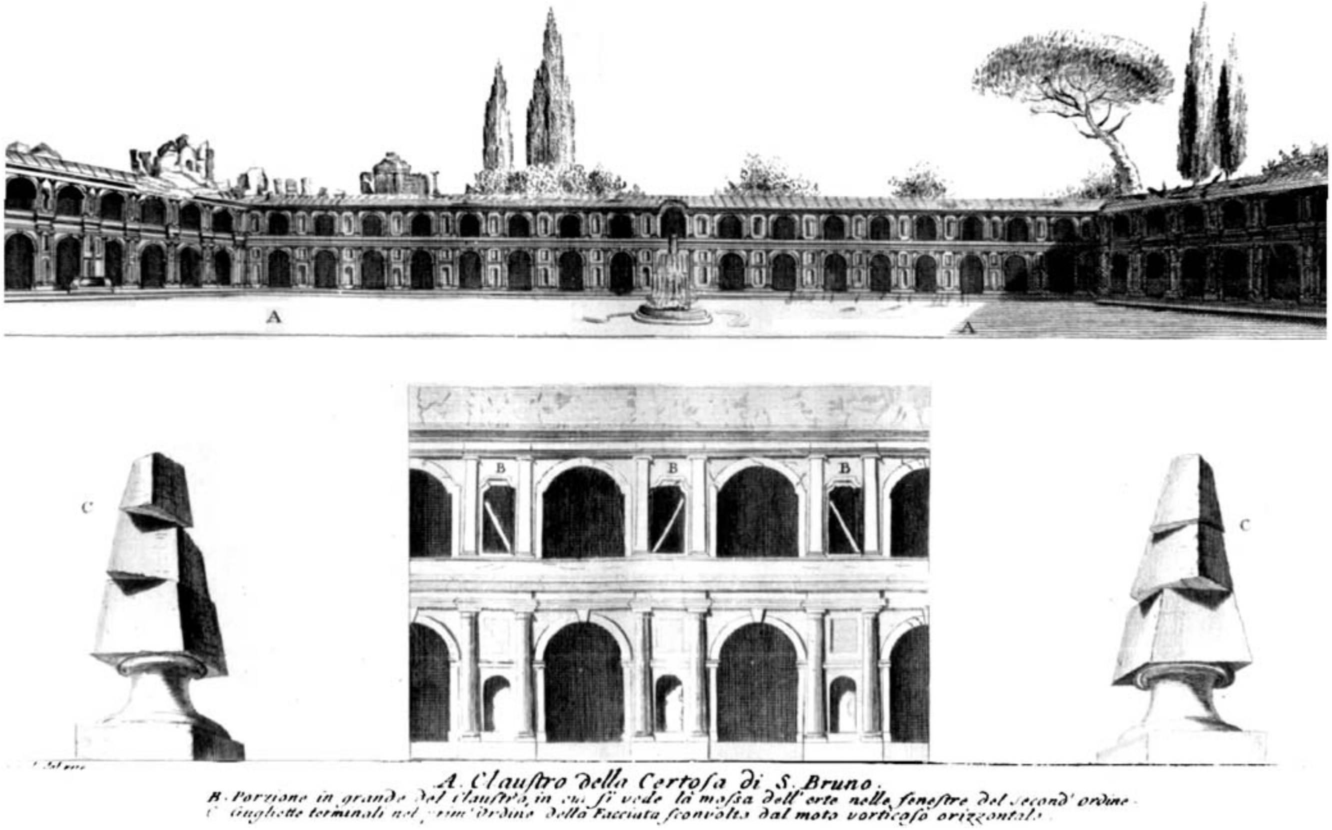

Figure 1. Rotated obelisk of the 1783 Calabria earthquake.

Charles Lyell's *Principals of Geology* (1830) mentioned the rotation of the San Bruno obelisk in the chapter on the 1783 Calabrian earthquakes. Lyell reproduced seven older illustrations of this earthquake's effects drawn by Schiantarelli including this one portraying the rotated San Bruno obelisk. He stated "… it appears that the wavelike motions and those which are called vorticose or whirling in a vortex, often produced effects of the most capricious kind."

To commemorate the 200 yr anniversary of the 1783 Calabria earthquake, a reprint of Placanica's (1885) book gave a detailed and erudite look into late eighteenth century earthquake study scene and contains the most complete list of contemporary bibliography of the works on the 1783 event (118 publications). The monograph by Barbano *et al.* (1980) presents a modern seismic analysis of this earthquake.

Lacking specific knowledge of seismic waves, the famous pictorial inventory of the 1783 earthquake brought speculation to the minds of the educated on fundamentals of the earthquake. They struggled with such terms as earthquake focus, seismic waves, their types and propagation velocities, and even with simple mechanics of a solid body subjected to dynamical load. These limitations prevented them from submitting even simple mechanical explanations of the observed rotational effects. It follows that the reports on the occasionally detected rotational effects remained in the level of notes, remarks, or curiosities. This had been true up to the 1840s when Robert Mallet presented his mechanical explanation of the subject in question (Mallet, 1848, 1849–1850).

Robert Mallet's Contributions

The San Bruno illustrations may have provoked and initiated interest in the Irish engineer Robert Mallet to turn his attention at the age of 35 yr to earthquakes for the first time. Robert Mallet disagreed with the common explanation of earthquake rotational effects by means of so called vortical movements and decided to engage in earthquake studies. He, allegedly after reading Lyell's Principles of Geology, made a try to clear out this question utilizing his rich practical engineer knowledge in physics and mechanics. He laid the underlying theoretical basis of a physical/mechanical explanation of horizontal earthquake rotational effects in his articles of 1846–50 (Mallet, 1848, 1849–1850).

" … It must be remarked, however, that these torsional strains—'Vorticosi' of the Italians and Mexicans—must not be supposed capable of producing those twistings of objects upon their bases, such as vases, chimneys, obelisks, etc., of which we shall record many examples, but which are due to other circumstances first explained by myself several years since.

"A continuous jarring movement, consisting of rapidly arriving series of waves moving in a horizontal plane, especially in lofty buildings, such as churches and towers, when the time of torsion vibration of the building itself (once set in motion), happens to be isochronous with that of the wave vibration, twisting strains of enormous violence result."

Mallet's early, but already very well-formulated prospect of seismic rotations was clearly formulated in his voluminous work on the 1857 Basilicata earthquake, in which he demonstrated his theoretical physical and mechanical ideas on the subject. H. F. Reid mentioned (Lawson *et al.*, 1908) that it was F. Hoffmann who first submitted a coherent theory of rotational seismic effects 8 yr before Mallet (Hoffmann, 1838).

Mallet, in his 1862 analysis of the 1857 Basilicata event, reproduced numerous images of observed rotational effects and complemented them with his mechanical explanations. Some of his illustrations are displayed in Figure 2. He summarized his observations and analysis in chapter XII, which is reproduced in full in Appendix A. Mallet's precise analysis and his effort to take into account all the parameters ruling the rotational process made his analytical arguing a bit complex. In modern formulation we may try to generalize his ideas using a simple model in the following way.

If a solid body lying face-to-face on a horizontal underlying plane is subjected to translational wave impact coming in the horizontal direction, it may rotate if the point of vertical projection of its center of gravity into the contact plane is not identical with the point of strongest adhesion (or mechanical fixing) of the body to its underlay. For vertical variant of such a rotation we have a simple illustration: if you push linearly a framed picture hanging on the wall out of its center of gravity, it could vertically rotate (this situation corresponds to the Rot1 model mentioned previously).

Mallet admits another mechanism of rotation. Subsequent incident seismic phases may gradually alter the body's horizontal position especially when the latter wave phases are coming to the considered point under another angle; in result, a physical body on the surface may gradually be turned in the horizontal plane through the period of individual wave arrivals. This explanation of the rotational effects was often presented by seismologists at the turn of the nineteenth century when detection of seismic rotations was most popular (this situation corresponds to the Rot2 model mentioned previously).

Interpretation of Mechanical Rotational Effects

Table 1 contains a list of a group of historical earthquakes documented by naturalists (and later by geophysicists and seismologists). The table describes and illustrates the rotational or twisting character of these earthquakes. These descriptions can be divided in two time periods that correspond to the gradual gain in seismological knowledge. The first period is dated approximately from the San Bruno obelisk ef-

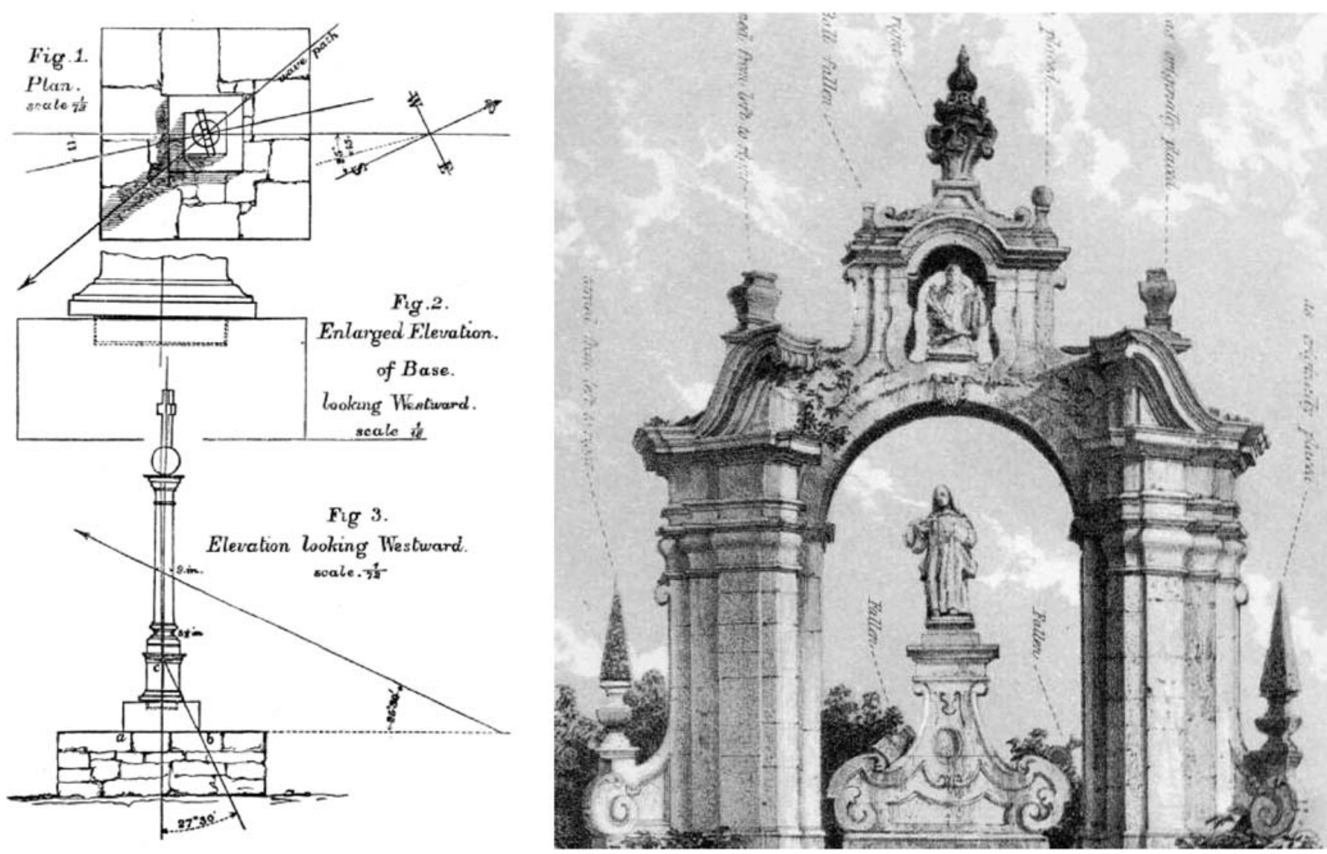

Figure 2. Rotational effects of the 1857 Basilicata earthquake, illustrated by Mallet (1862).

Table 1
A List of Historical Earthquakes with Observed Rotation Effects

Number	Date	Location	Intensity	Depth (km)	Rotational Effect	Reference Sources
1	5 February 1783	Calabria	XI	13	Rotated San Bruno obelisk	Vivenzio (1783, 1788); Postpischl (1985a)
2	26 July 1805	Baranello	X–XI	10	Visual description plus image	Postpischl (1985a); Poli (1806)
3	20 February 1818	Catanes	X	5	Visual description	Postpischl (1985a); Ferrara (1818), Longo (1818)
4	23 October 1839	Comrie	VII	9	Rotated chimneys	Milne (1842), Musson (1991)
5	1846	general	—	—	Visual description	Mallet (1848, 1849–1850, 1880, 1882; Davison, 1927, p. 67)
6	16 December 1857	Basilicata	XI	2	Rotated columns, etc.	Mallet (1862), Postpischl (1985a)
7	16 December 1857	Gera	VIII	9	Rotated wooden structure	Seebach (1873); Grünthal (1992)
8	29 June 1873	Belluno	X	25	Rotated tomb pyramid	Sieberg (1904); Postpischl (1985a)
9	22 October 1894	Shonai	$M = 7\frac{1}{4}$	1	Rotated bell tower	Omori (1894 or 1895), Sieberg (1904)
10	12 June 1897	Assam	IX–X	1	Rotated obelisk	Oldham (1899)
11	18 April 1906	SF (Cal.)	XI	20	Rotated tombstones	Jeništa (1906–1907) [after unidentified article by Larkin, cited by Jeništa, published allegedly in 1906]
12	8 May 1914	Linera	IX	2	Visual description	Platania (1915); Postpischl (1985a,b); Sabatini (1914)

fects to the advent of the twentieth century and is denoted as the classical mechanical period. The second period reopened this question of rotational movements in the last few decades. After geophysicists were armed with the advancements in the mechanics of structured media and in asymmetric theory of continuum, with the achievements in the field of nonlinear physics, with the recent progress in the knowledge of the inner parts of the Earth and seismic waves and their behavior, and with the advancements in seismic recording and computational techniques, they entered the second period of rotational effects studies sometimes called the modern period. This second period is discussed in the monograph by Teisseyre *et al.*, 2006.

Naturalists at the time of the 1783 Calabria earthquakes and during the aftershocks in the region in the following 16 yr were not prepared to submit reasonable explanation of the observed effects and simply attributed them to the "misty vorticose movements" discussed by Mallet. This is true also for the disastrous Baranello earthquake of 1805, which had its epicenter some 80 km north-northeast from Naples. According to Postpischl (1985a) who cites Poli (1806), "… in towns situated in the Boiano Valley … statues and crucifixes twirled, the latter being bent and twisted."

Only one description of rotational motion exists for the 1818 Catanese earthquake that occurred north of Catania on the southern slope of Mount Etna. Postpischl (1985a) cites Ferrara (1818) and Longo (1818) as follows: "The shock was also strongly felt in Catania, and descriptions of falling objects and rotation of monuments and crosses were often reported." The 1818 event was a strong shock with a shallow seismic source and Catania, where the rotational effects were observed, was located near to the epicenter, at a distance of 4–6 km.

In 1839 a series of relatively strong earthquakes appeared in central Scotland on the southern slopes of Grampian Mountains near Comrie. Among slight damage to buildings, rotation of chimneys were observed and recorded by Scottish naturalist David Milne. In 1840 he was named secretary of the commission appointed to study the Comrie earthquakes and issued four reports published between 1841 and 1844 on this topic (Milne, 1841, 1842, 1843, 1844). In Milne (1842) there is a vague sketch of two chimneys rotated by the 1839 earthquake. Milne's image, Figure 3, was presented by Musson (1991) at a symposium on historical earthquakes without any physical/mechanical explanations.

As mentioned in the previous section, Robert Mallet took issue with the common explanation of earthquake rotational effects by means of unclear so-called vorticose movements and presented fundamental physical/mechanical explanations of horizontal earthquake rotational effects. He

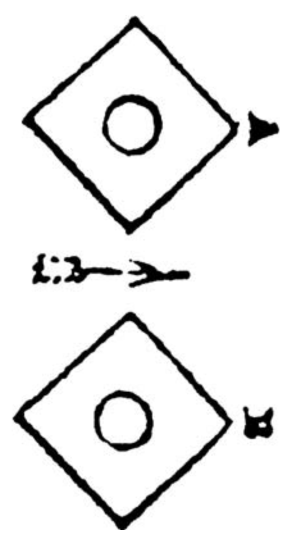

Figure 3. Rotation of chimneys in Comrie from the 1839 Comrie earthquake.

expounded on his explanation in reports on both the 1783 and the 1857 Italian earthquakes.

The 6 March 1872 central German earthquake located by Gera, Saxony, surprised inhabitants of this relatively seismically quiet region. A voluminous report of this event was composed by Karl von Seebach who published his work in the following year (Seebach, 1873). The author, when collecting microseismic data for his report, visited a metallurgic laboratory near the Czech town Chomutov (Kommotau) on the south slopes of the Ore Mountains, some 100–110 km south of the earthquake epicenter, and detected an interesting earthquake rotational effect there (see Fig. 4).

Quoting the author: "In the enterprise laboratory handling table there were two pyramids of polished wooden laboratory mats for handling chemical glass—see their vertical and horizontal projection given in sketches Nos 1 and 2 [in Figure 4 of the current article]. After the passage of seismic impact from the earthquake the position of the upper two mats were dislocated and/or rotated [as Figure 4 shows]. Immediately afterwards the angle declinations were determined by means of compass and pertinent sketched made. It was found that the upper mats were shifted and/or rotated in the direction SW to NE; it follows that according that the direction of the Earth shock propagation would be from NW to SE."

In this case the rotational effects were explained by classical mechanics: it is the configuration of direction of seismic-wave propagation, position of the center of rotated body gravity and pivot location, which may possibly result in nonzero rotational moment causing the observed rotational and twisting effects (Grünthal, 1992).

The 1883 Belluno earthquake effects were discussed by Sieberg (1904), who stated that "… here, as in the epicenter regions of many earthquakes 'Drehung' (which is twisting or torsion) was observed." This displacement consisted of both rotational and rectilinear movements as shown in Figure 5.

The depiction in Figure 6 is a sketch of a wooden bell tower rotated during the Japanese Shonai earthquake on 22 October 1894. It is taken from Sieberg (1904), who cites F. Omori as the author of the original sketch. The strong (M $7\frac{1}{4}$) 1894 Shonai earthquake caused remarkable surface effects on the Shonai plains that indicated a shallow depth earthquake source. Rotation of the whole bell tower around its one corner pillar–column is easily explained mechanically. The first onset of seismic waves broke the anchoring of three corner pillar–columns of the cabin, and the last pillar worked as an axis of rotation of the tower being later subjected to rectilinear wave impact.

George Inglis of Chatack, India, showed the mechanical twisting of the stony blocks of a large, approximately 20 m high obelisk, shown in Figure 7, as a result of the strong Assam (Shillong) earthquake of 12 June 1897. The depth of focus of the earthquake was moderate, between 10 and 40 km. Extremely strong surface effects indicate that fault movement for this earthquake reached the Earth's surface. The epicenter intensity value reached X on the modified Mercalli scale, and a magnitude of 8.0–8.1 has been determined by modern analysis.

Numerous reports on the 18 April 1906 San Francisco earthquake contain interesting evidence of rotational effects. Remarkable strong displacement along the central part of the densely inhabited San Andreas fault occurred in San Francisco and throughout the coastal regions. The city and the many coastal settlements located along the fault might be considered a macroseismic array. Many written reports and many recordings describe the macroseismic effects of this earthquake. The California state government appointed a commission to investigate the 1906 earthquake under the supervision of Andrew C. Lawson (Lawson *et al.*, 1908–1910). In the report, rotational effects are repeatedly mentioned, especially from the localities near to the San Andreas fault surface trace. The following three paragraphs contain excerpts from the report.

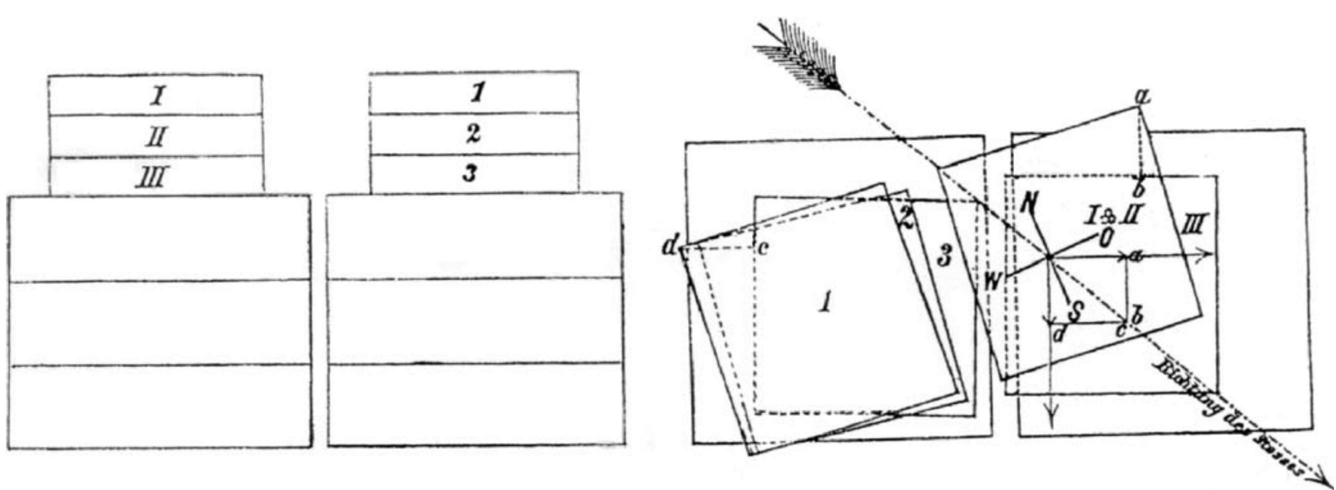

Figure 4. Rotation of laboratory mats from the 1872 Gera earthquake.

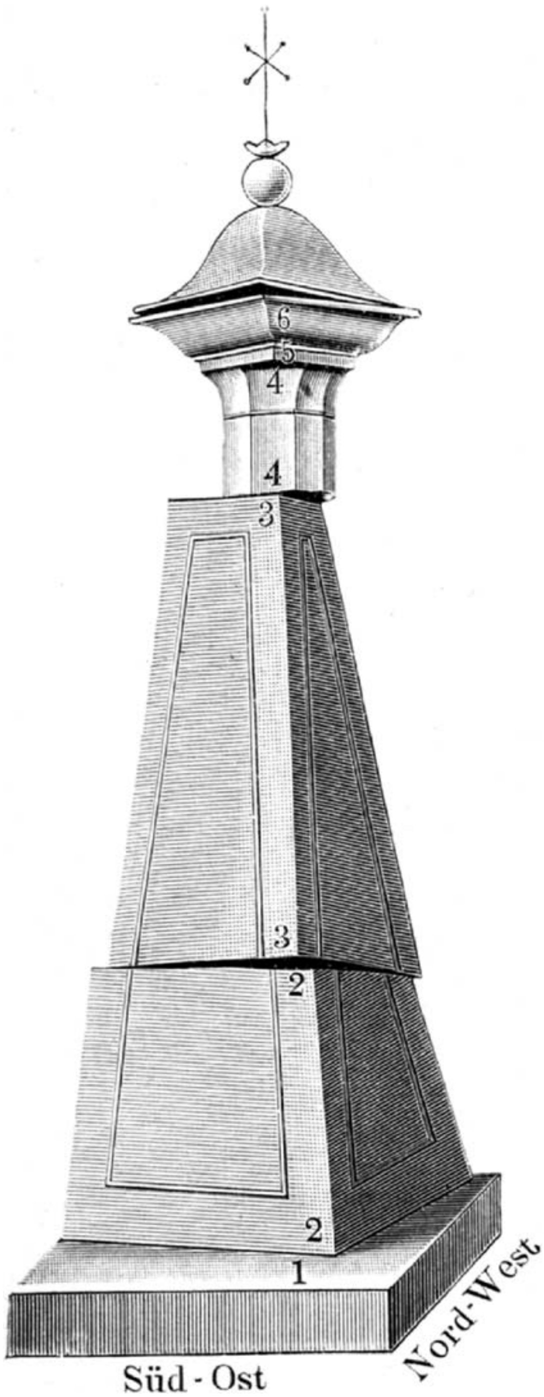

Figure 5. Rotation of obelisk segments from the 1873 Belluno earthquake.

L. H. Snyder wrote that in Los Gatos "… chimneys fell in many different directions and nearly half of the damaged chimneys left standing were twisted" (p. 245) and "In the catholic cemetery, … $\frac{1}{4}$ mile nearer Santa Clara, three monuments were turned on their bases, two clockwise and one counter-clockwise" (p. 275).

W. C. Prosser wrote "… The only clear cases of rotary motion seen by me were two cases near my home [in San Jose], two miles northwest of the center of town. One tank house turned exactly half way round as well as upside down, and one chimney turned about 4 inches clockwise. Both rotary and vertical motions were felt by many, however" (p. 285).

Figure 6. Rotated bell tower from the 1894 Shonai earthquake.

R. Newcomb wrote "… in Oakland cemetery of St. Mary … many monuments were moved or twisted … near the top of the cemetery ridge many monuments were overturned, and nearly all of them showed twisting and shifting … fifteen were rotated counter[-clock]wise, 4 of these thru 1°–2°, 6 thru 5°, 1 thru 15°, … 3 thru from 5°

Figure 7. Rotation of obelisk segments from the 1897 Assam earthquake.

to 8°, with a lateral shift of 1 inch to the east; and 1 thru 8° with a lateral shift to the south … and in Alameda … Pond and McFarland … counted 61 dislocated and twisted chimneys and of these 51 were rotated counter-clockwise and 3 clockwise" (p 302).

Harry Fielding Reid wrote an important section in the Lawson report discussing and analyzing the seismic rotational effects. Professor Reid first corrected some weak points of Mallet's analysis and afterward presented the spectrum of possible configurations of earthquake foci-parameters such as double consequently working sources in one point, two simultaneously active influence of sources in nonidentical points, and the influence of special geometry of undersurface reflecting planes and medium parameters. Reid's explanation of rotational effects from earthquakes represents the most coherent mechanical analysis of these phenomena; it is reproduced in Appendix B.

The 1906 San Francisco earthquake met with a lively response abroad. Omori (1906) statistically evaluated macroseismic data on damaged chimneys noting only directions of displacement. The Czech seismologist of the time, Jeništa (1906–1907), reproduced a sketch showing displacement of tombstones in a San Francisco cemetery due to the earthquake. Jeništa disclosed a seismographic function of San Francisco cemeteries, that is, the way and directions of grave tombstones displacement, if properly deciphered, may supply much information on seismic-wave propagation and on the seismogenic process itself. In Figure 8, please note that the dislocation of the upper tombstones (numbers 1–5 and 9–12) had a horizontal rotational component.

The last example of Table 1 is the Linera (Sicily) earthquake of 8 May 1914 on the eastern slopes of the Etna volcano. This event, similar to the 1818 Catanese shock, was characterized by high intensity ($I_o = \mathrm{XI}$) and a shallow seismic source ($h = 2$ km) resulting in a small epicenter zone not exceeding a region 4×8 km. Postpischl's atlas of isoseismal maps and his catalog of earthquakes (Postpischl, 1985a,b) recorded some of the effects in the localities where major damages occurred, referencing original sources by Platania (1915) and Sabatini (1914), who observed that in Roca d'Api, "… moreover, various phenomena of rotation of headstones and columns were noticed in both clockwise

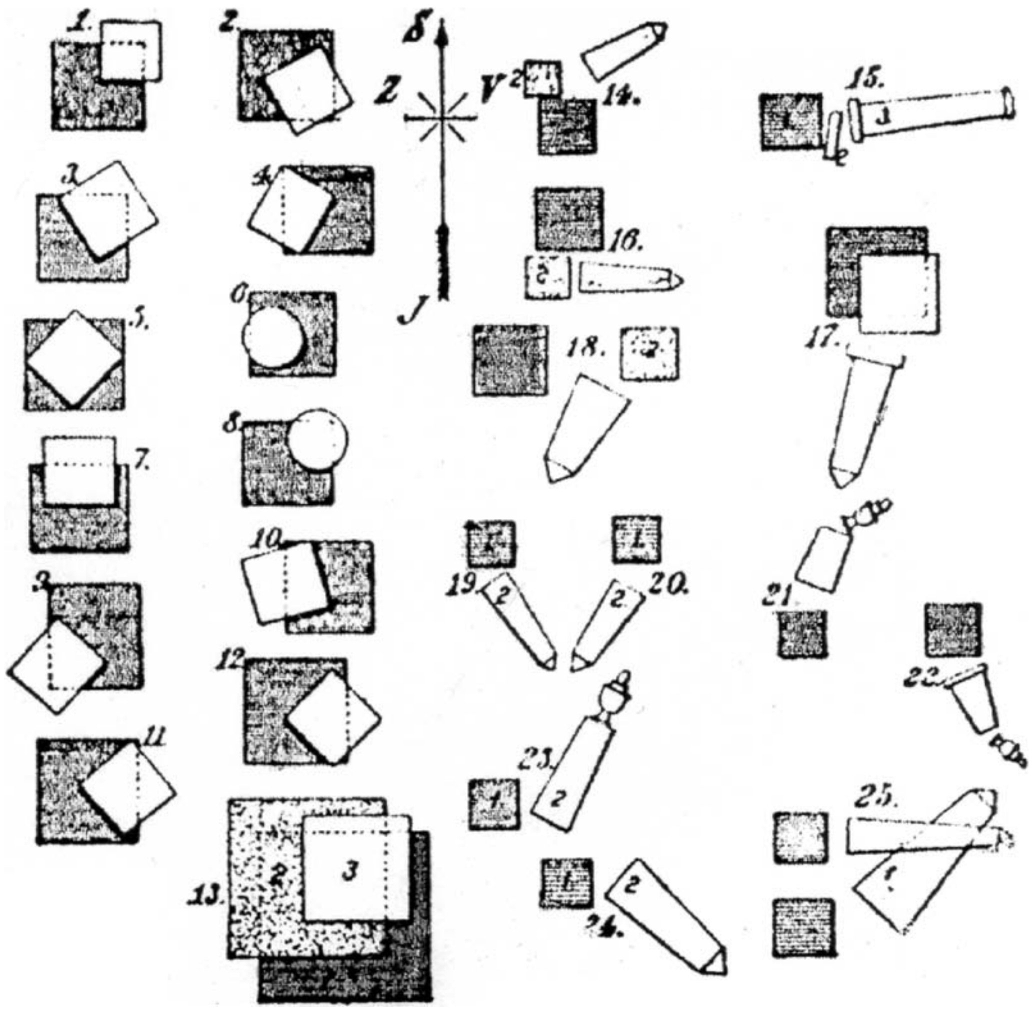

Figure 8. Rotated tombstones from the 1906 San Francisco earthquake.

and counter-clockwise directions." In fact Platania and Sabatini carefully described the phenomena of rotation and projection observed for numerous tombstones in order to obtain indications regarding the acceleration and the direction of the movement of the soil.

Summary

The following list summarizes the previous comments on the rotational effects related to the selected earthquakes from Table 1:

1. The absolute majority of the discussed effects (all except the 1872 Gera event) were observed in the epicenter zone.
2. Seven of the twelve earthquakes discussed were shallow events having focal depths between 2 and 13 km, and only 3 were deeper (14–40 km), so that the observations were in most cases made in the near field.
3. In most cases the effects were observed on vertically organized objects, such as chimneys, obelisks, and grave tombstones, composed of blocks or layers separated by horizontal planes allowing frictional displacement including rotations.
4. The explanation for the observed effects in most cases relates to classical mechanics principles presented by Robert Mallet between 1846 and 1882 (Mallet, 1848, 1849–1850, 1862, 1880, 1882) and to Harry Fielding Reid through his coherent advanced mechanical analysis published in 1908–1910 (Lawson *et al.*, 1908–1910). (At the time of Mallet and Reid an advanced theory about seismic waves was yet to be developed, and there were no instruments capable of detecting rotational motions in either near field or far field. Therefore, Mallet and Reid explained the visually observed rotational effects by using classical mechanics.)

Data and Resources

All data used are included in the References.

Acknowledgments

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Appendix A

Excerpt from Mallet (1862, Vol. 1, pp. 375–381)

Chapter XII: First Deductions from Facts of the Certosa Doubleshooks

I now pass to the deductions to be obtained from the observed facts here.

There is evidence everywhere, of a double if not a triple shock, confirmatory of the statements made at the town of Padula, of oscillation in various directions. The main shock was in the primary wave-path, right along the Vallone 15° W. of north towards the south, and arrived, through the deep clays and loose material of the plain. This was *preceded* at a very brief interval by a secondary shock, transverse in path to this by a certain angle, and derived from the lateral vibration of the mass of limestone mountain on the range to the north-east. Lastly, the primary shock appears to have been reflected, from the abrupt neighbouring mountain further south, and to have returned again, as an *earthquake echo*, through the clays, with very diminished force, arriving last upon the scene.

Referring to the Photog. No. 225 [Fig. 2 in this article], of the monument of St. Bruno, it will be seen that many of the obelisks and finials are twisted, and some are overthrown. We have universal evidence of the shock, in the path 15° W. of north to south. Here the finials which are *overthrown* are thrown directly westward. All those that are twisted are turned from left to right.

Now there are two distinct trains of earthquake causation, by either of which bodies may be twisted on their bases. 1st. By the action of a *single* shock, when the centre of adherence of the base of the object, lies to one side or other of the vertical plane passing through the centre of gravity, and the line of the wave-path. 2nd. By the conjoint action of *two closely successive* shocks. By the first shock, the body is tilted up from its base, but not overthrown, so that for a time greater or less, it rests wholly upon one edge of its base; while thus poised, if another shock bear upon it, in any direction transverse to the first, it acts as usual at the centre of gravity of the body, to displace it by inertia, in the contrary direction to the wave transit; but the body is held more or less, by friction *at the edge momentarily in contact* with its support, and there only; but this edge must always lie to one side of the vertical plane passing through the centre of gravity, in the direction of the wave-path: hence the tilted body, *while relapsing upon its base also rotates*, round some point situated in the edge of its base upon which it had been tilted, and thus it comes to rest in a new position, having twisted more or less round a vertical axis.

If the observer look due south at a square pyramid, for example, whose sides stood cardinal, and it be tilted by the *first semiphase* of *a* shock from east to west, the pyramid will tilt or rise upon the eastern edge of its base; and if, before it has had time-to fall back, it be acted on by another shock from north to south, the pyramid will rotate, upon the bisection or on some other point, of the edge on which it momentarily rested, and will hence come to repose, after having twisted from left to right, or *with* the hands of a watch.

If the tilting up, had been produced by the *second semiphase*, of the same shock from east to west, then the pyramid would have risen upon the western edge of its base, and the *same* direction (north to south) of second shock, would have produced rotation upon that edge, but in a *contrary* direction to the preceding, or from right to left, or *against* the hands of a watch.

Again, if, on the first supposition, the first *semiphase* of the east to west shock, had tilted the pyramid upon its *eastern* edge of base, but the second shock had been from south to north, in place of the reverse as before, then the rotation would have been from right to left; and if tilted by the *second semiphase* on the *western* edge, the second shock, south to north, would produce rotation left to right.

It would therefore appear at first impossible, to determine the *direction* of motion in transit, of either shock, from such an observation: we can, however, generally discover upon which edge of the base any heavy body of stone or masonry has tilted, by the abrasion or splintering of the arris, and the rotation must have taken place round some point in that edge. If, therefore, we know the direction of either one of the two shocks, we can always discover that of the other, by the rotation observed; and if the time of oscillation of the body be ascertainable, we are enabled to calculate a major limit, for the interval of time that must have elapsed, between the arrival at the twisted body, of the first and of the second shock, when both the wave-paths are known.

With a single instance of such twisting, it may be impossible to decide, whether the twist has been due to one shock, (1st case) or to two shocks in succession, (2nd case); but when several bodies alike or dissimilar, at the same locality, are *all found twisted in one direction*, it is certain to have been *the work of two distinct shocks*, for it is beyond the reach of probability, that several bodies, should *all* happen to have their respective centres of adherence, at the *same side* of their respective centres of gravity, and unless they have, some will rotate in one, some in the other direction by any single shock; rotation thus produced, being always by the centre of gravity, moving contrary to the first or second semiphase of the wave, and carried round the centre of adherence, by the line joining them as a radius vector; the inertia of motion at the centre of gravity, and the resistance of the point of rotation in the edge of the base, or of the centre of adherence, forming in every case, the extremities of the dynamic couple.

All the effects of the double shock will be understood by examination of the Figures Nos. 235 and 236, in which Fig. 235 shows the action of any double shock; Fig. 236 the variations of result produced, first, by rotation in the first semiphase A, and second semiphase B, by the same double shock; secondly, the like by rotation, in the first semiphase (C), the first shock being as before, but the second, contrary in direction to that of the previous cases (A and B), and the like for the second semiphase (D), the two shocks being the same (C and D).

Applying this to the facts at the monument of St. Bruno. *All* the finials, &c., are twisted from left to right; we know that the main shock was from 15° W. of north to the south, it therefore follows, that the shock which first moved them, arrived in a path somewhere between that, and from east to west: by this they were tilted; by the immediately following

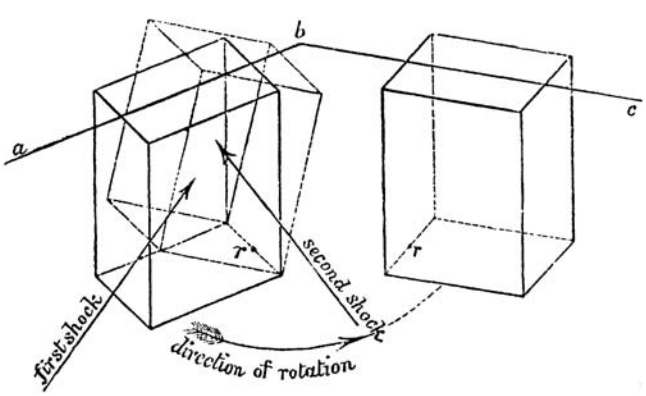

Figure 235.

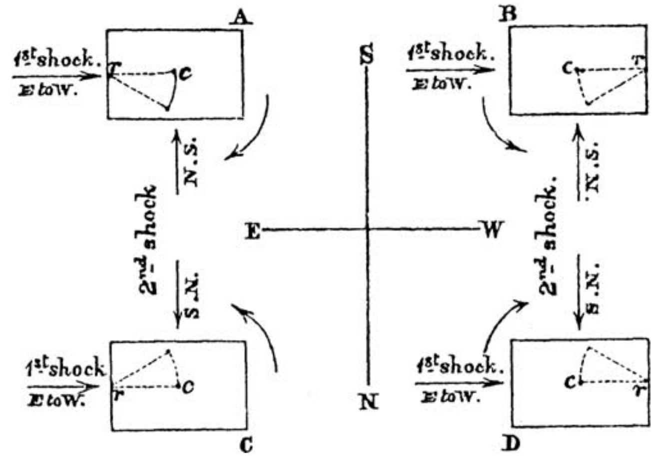

Figure 236.

shock, 15° W. of north to south they were *twisted*. Neither shock was sufficient, in velocity or range, completely to overthrow any of them, except those which were top-heavy, by having had balls at their summits, which have, except in one instance, been all dislodged.

A great many pyramids and finials on the top of the fountain in the entrance square B, Fig. 1, Diagram No. 240, and Photog. (Coll. Roy. Soc.), presented precisely similar phenomena, as did those on the parapet of the great facade Photog. (Coll. Roy. Soc.), and in divers other places.

The complex forms of these objects, which rendered the ascertainment of the positions of their centres of oscillation on the edges of their bases, difficult and uncertain, unless by experiment, prevents any calculation of a precise character, from their movements, as to the velocity of either shock, nor do we require it.

They give us other valuable information, however. In the case of the parallelopipedal chimney, (F, Fig. 1, Diagram Nos. 238–240, and Fig. 4, same diagram), twisted upon its base, it had rotated upon a point in the western edge of its base at *b*, Fig. 237. We know already that the direction (generally) of the first shock, was from some points east or N.E. towards the west or S.W., the second being from 15′ W. of north to south. The chimney stalk had therefore made, *one semi*-oscillation, and *one complete* oscillation; that is, it was

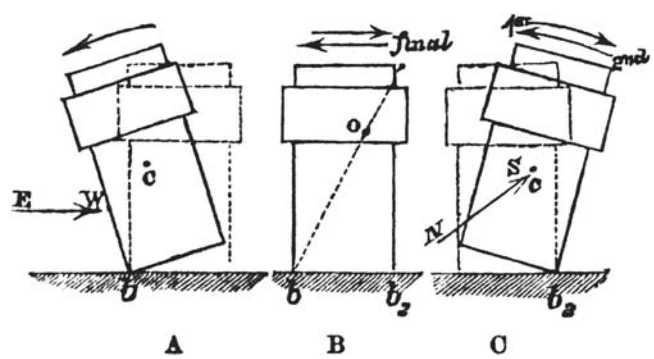

Figure 237.

being acted on by the *second* semiphase of the wave of the *first* shock, at the moment when the second shock arrived at it, as in Fig. 237.

The centre of oscillation of the chimney above b thus tilted was, as nearly as could be ascertained, 4·33 feet distant from the edges of the base upon which it tilted b and b_2 The first shock, east to west, fractured the chimney from its base, and produced in the detached chimney, one semi-oscillation eastward (A, Fig. 237). The chimney then relapsed upon its base (B), Fig. 237, and rising again upon the edge b_2 leaned over westward (C), Fig. 237, having thus made one complete oscillation in that direction, with the moment of repose (B), when it had fallen back plumb upon its base. Between that moment of repose, and the completion of the oscillation, or *almost instantly after it had commenced to fall back (C)* from west to east, to reassume its original position of repose, the second shock from the north to south reached it, and twisted it round horizontally, in the manner that has been already explained.

[Note: Three figures, namely Figures 235, 236, and 237, are used as illustrations in Chapter XII of Mallet (1862), and they are reproduced here.]

Appendix B

Excerpt from Reid (1910, pp. 43–47)

Rotatory Movements and the Rotation of Objects on Their Supports

It has been a matter of frequent observation that during the shocks of large earthquakes a twisting motion is felt, and after the shock, chimneys which were not thrown down, monuments in cemeteries, ornaments, etc., are found to have been rotated on their supports. This has given rise to the belief that there is a rotary motion of the various parts of the ground like that of wheels about their axes. It should be pointed out that this kind of motion can not exist, for it could not be propagated as an elastic disturbance, but would break up into waves of compression and distortion, which would be propagated at different speeds and would soon be separated from each other. Moreover such a motion would produce rents in the ground, which have not been found; nor has any such motion of the ground itself ever actually been observed. Waves of elastic distortion do, however, produce very small rotations, whose maximum amount, we shall see (page 146), is given by the expression $2\pi A/\lambda$, where A is the amplitude and λ the wave-length; with a wave as short as 10,000 feet (3 km.) and an amplitude as large as 0.2 of a foot (6 cm.), the maximum rotation would only be about 0.25 of a minute of arc, a quantity far too small to be noticeable; even if the rotation were 100 times as great as this, it would probably not be noticed.

But there is another kind of rotation, which undoubtedly does occur, and which would, if strong enough, give rise to the sensation of twisting and would cause objects to rotate on their supports. If a swinging pendulum, as it passes its lowest point, should receive a blow at right angles to the direction of its motion, it would simply change its direction and continue to swing back and forth in a different plane; but if the blow should be received at any other part of its motion, it would swing in an ellipse; if the blow were of the right intensity and were received at the end of the swing, the pendulum would swing in a circle.

Two vibrations making an angle with each other would produce just such an elliptical or circular motion, unless they were so adjusted that they would combine to make a simple linear vibration in a direction between the two; but this would rarely occur. If the two groups of combining vibrations had different periods, the resulting movement would be very complex; and we might have rotations first in one direction and then in the other. The kind of rotatory motion thus set up is not like that of a wheel about its axis, but is like that of a book which is carried around in a circle keeping the edge always parallel to its original position. We must look upon the rotatory motion of the earth reported during earthquakes as such that every point describes an ellipse, each point with a different center, but all with parallel axes; and the lines connecting near-by points remain parallel to their original directions, and do not, as in the case of a wheel, also rotate. For the sake of clearness let us speak of this kind of motion as *parallel rotation*, to distinguish it from rotations where the various points rotate around the same center.

We have conclusive evidence that the motion of the earth during the Californian earthquake was not merely a to-and-fro motion in one direction, but that the direction of the motion changed markedly. This is shown by the sensations of observers and by the fact that objects in the same place were thrown in various directions; statements that the earthquake was a "twister" were not uncommon, and some observers reported that the motion was first in one direction and then at right angles to it; and lastly the seismographs themselves indicate a combination of simple vibratory motions; this is well shown in the seismogram made by the simple pendulum at Yountville and in all made by Ewing duplex pendulums. (See Seismograms, sheet No. 3.)

We can picture to ourselves many ways in which movements in different directions could be produced at the same time. Suppose, for instance, that there were two shocks originating at the same place with some seconds interval between them; each in general would give rise to compressional and distortional waves; the first kind travels faster and hence outraces the second. The compressional waves of the second shock would overtake the distortional waves of the first shock in a circular zone surrounding the origin, and as their motions are at right angles to each other, we should find parallel rotations in this zone. Again, suppose two shocks originated at different centers, their waves, in general, would cross each other at an angle, and we might have circular or elliptical motion as a result of the combination of the two sets of compressional waves, of the two sets of distortional waves, or of each set of compressional with the other set of distortional waves. Modifications of the waves on passing from one kind of rockto another would occur and give rise to still other combinations which would cause parallel rotations.

With the hope of throwing light on the progress of the rupture along the fault-plane by determining the distribution of rotatory effects in the surrounding regions a special list of questions was sent out and many answers were received. They may be summarized as follows: at a distance, where the shock was but slightly felt, rotations were rarely noticed; but where the shock was strong, even tho many miles from the fault, they were almost universal; a number of observers stated that the disturbance was first a simple vibration, and that the rotatory motion only appeared later; no one put the rotatory motion in the early part of the shock. Some, who did not notice rotations, stated that the direction of the motion changed during the disturbance. At a distance from the fault, where the movement was slow and gentle, the rotatory effect would not be very noticeable, but that it still existed is shown by the seismogram made at Carson City, where the intensity of the shock was greatly reduced. This general distribution of parallel rotations does not show how the rupture took place on the fault, but merely confirms the idea that the disturbance at any point was due to vibrations originating in many parts of the fault-plane; and the combinations of these vibrations would cause the variations in intensity and the rotations observed. The writhing motion of the steel smokestack at Mare Island (vol. I, p. 212) must have been the result of a double vibratory motion of the ground combined into a parallel rotation; the elastic bending of the stack would cause a much greater vibration of the top than of the bottom; this explains the whole motion without the assumption of a tilting of the ground.

In the first volume numerous examples are given of statues, monuments in cemeteries, chimneys, etc., which were rotated on their supports by the earthquake; many were turned thru an angle of 90° and some as much as 180° (vol. I, p. 359), the in the majority of cases the rotation was less than 20°. In the cemetery near San Rafael all except one of the rotated monuments were turned with the hands of a watch thru angles of 16° or less. Similarly, at Lakeport all the rotated chimneys were turned in the same direction (vol. I, p. 188). This phenomenon has long been observed and occurs at the times of all violent earthquakes; it naturally suggests a rotation of the support; but, as has been seen, a more careful examination of this idea shows that it is entirely untenable; indeed, Charles Darwin long ago pointed out that if objects were turned on their supports by true rotations, the axis of each rotated object must be an axis of the rotation, which is a practical impossibility. The effort, therefore, was made to explain the rotation merely as the result of a to-and-fro vibration. What is necessary is to produce a moment around the vertical axis thru the center of gravity.

Three suggestions have been made. First, Mallet [Mallet, 1848] suggested that the object may not bear uniformly on its support, but may only press on it in a few points, and as the pressure will in general be different at these points a moment around the center of gravity due to the frictional forces would be produced during a vibratory movement, resulting in a rotation. Altho it may be possible for small rotations to be brought about in this way, they are probably very small and unimportant; for it can easily be shown that if the frictional forces at the points of contact follow the ordinary laws of solid friction, namely, that the tangential forces are proportional to the normal pressures, then no moment around a vertical axis thro the center of gravity will be set up by the vibrations, and it is only in so far as the ordinary laws of friction are departed from that moments can be produced. For the normal pressures must be such as to produce no moment around any straight line in the plane of the points of contact and immediately under the center of gravity; otherwise, the object, when undisturbed, could not remain stationary. If now we take the straight line parallel with the direction of vibration, the moments of each frictional force about the vertical, thru the center of gravity, will be proportional to the moment of the corresponding normal force about the straight line, and therefore their sum will be zero. Houses, however, are not rigid bodies resting on rigid foundations, like a statue on its base; and the ground itself, on account of slight variations in texture or firmness, would not behave like a rigid body during the earthquake, but would have somewhat different movements at different places under the house; in this way it is quite possible for a house to be slightly rotated by the frictional forces between it and its foundation. Examples of such rotations are given in vol. I, pp. 170, 176.

Second: Professor Thomas Gray [Milne, 1880a,b] has shown that if the vibrations are at right angles to the edge of the rectangular base of a column, or along the line joining opposite corners, no rotating moment is developed; but if the shock lies between these directions, as, for example, in the direction, of, in fig. 24, then the column tends to rock on the corner, and to rotate around it; for the force is applied at the corner and acts in a direction parallel with the vibration and does not pass through the center of gravity. This is in entire accord with the laws of mechanics, and undoubtedly some small rotations are caused in this way; but it *a* is to be noticed that the tendency is only to rotate until the $J\surd$ edge is at right- angles to the direction of vibration; if this direction is nearly at right angles to the edge, the rotation will be small; if the direction is nearly along the diagonal, the moment produced will be small; if the direction of vibration gradually changes, keeping pace with the turning of the column, a larger rotation might accumulate. In the case of columns with circular bases, the method would not apply at all; and it may be well doubted if any large rotations are produced in this way.

Third: The combination of vibrations at right angles offers a simpler explanation for any amount of rotation and for any form of base. If an object, as a result of the vibration, is rocking on its edge and is then subjected to a second vibration at right angles to the first, a strong moment will be set up

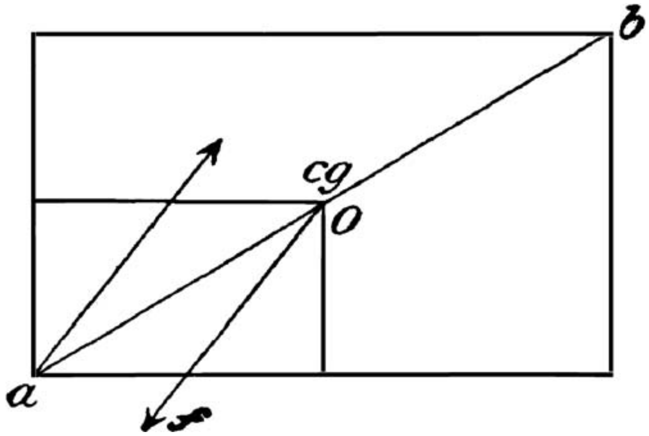

Figure 24.

and the object will rotate; if these vibrations are so timed as to produce parallel rotation of the support, the body will continue to rotate as long as the vibrations are sufficiently strong. One can easily realize this experimentally by means of a chair. Raise the front legs slightly from the floor by pressing against the back; then press against the side of the chair, and it will swing around about 90° on one leg; or, place a box or bottle on a book, and then rotate the book, keeping it parallel with itself; if the movement be strong enough and the friction sufficient to prevent slipping, the object will rock and rotate. The principle of crost vibrations seems to be the true explanation of the rotation in most cases and in all cases where the rotation is large. Crost vibrations will not be produced by a single shock from a single center; but a protracted shock, or successive shocks from the same center, or shocks from different centers, will produce them; that is, they will practically occur at the time of all large and important earthquakes, for then the vibrations usually originate at many points and at slightly different times.

The explanation of rotations by means of crost vibrations seems first to have been given by F. Hoffmann [Hoffmann, 1838, p. 310] and later repeated independently by Mallet [Mallet, 1862, vol. I, pp. 375–381] and others, but it does not seem to have received the consideration it deserves. I think it is clear from this chapter that crost vibrations are not only capable of explaining rotations wherever the disturbance is sufficiently strong, but that no other theory, so far proposed, can explain satisfactorily the very large rotations which statues and monuments experience.

[Notes: Figure 24 of Reid (1910) is reproduced in this article. The footnote notations in the original section from Reid (1910) have been modified in this article.]

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