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Short Note

Rotational Earthquake Effects in the United Kingdom

by Susanne L. Sargeant and Roger M. W. Musson

Abstract The United Kingdom is an area of low to moderate seismicity, and damaging earthquakes are uncommon. However, even in the limited record of damage from historical British earthquakes, a number of instances can be found of rotational effects on parts of structures, primarily chimneys or the tops of spires. We have assembled all the instances we know of from the United Kingdom record and present them here with illustrations and extracts from the original reports. It is not possible to determine whether these are the effects of true rotational motion or the effects of translatory shaking. Interestingly, this problem was considered in some detail by field investigators as long ago as the 1880s.

Introduction

This short note is a compendium of observations of rotational earthquake effects from British earthquakes extending from the early nineteenth century to the present day. We present several examples of the damage from different earthquakes mainly to chimneys and spires that may be due to rotational movement (yaw) using the notation put forward by Evans *et al.* (2009). Whether these effects directly result from rotational ground motions or rotational motions induced by the structure is unknown, and we do not attempt to determine a cause. We do, however, present some of the explanations put forward by past British workers for these effects, most notably in connection with the 1884 Colchester earthquake.

The United Kingdom is an area of relatively low seismicity (Fig. 1a). The main centers of activity are western Scotland, northwestern England, Wales, the Midlands, and southwestern England. Damaging earthquakes occur infrequently. The most recent damaging earthquakes occurred on 27 February 2008 (Market Rasen, 5.2 M_L) and 28 April 2007 (Folkestone, 4.3 M_L).

Rotational Effects

We use the term rotational effects because the origin of the damage described here is unknown and is by no means unequivocal.

Inverness, 13 August 1816

There have been several damaging earthquakes in the Inverness region of northeastern Scotland. The largest and most severe of these is the 1816 event (5.1 M_L). This earthquake caused considerable damage in Inverness, where there was significant structural damage, and its epicenter was probably southwest of the city (Musson, 1994) as shown in Figure 1b. One report notes that chimney tops were damaged throughout the city. Hugh Miller (Miller, 1905) wrote this account of the damage to the spire of the city jail (Fig. 2): “The neat, well proportioned, very uninteresting jail spire of the burgh, about which, in its integrity, no one cares anything, had been shaken by an earthquake … by a strange vorticose motion, twisted round the spire, so that, at the transverse line of displacement, the panes and corners of the octagonal broach which its top formed overshot their proper positions fully seven inches. The corners were carried into nearly the middle of the panes, as if some gigantic hand, in attempting to twirl round the building by the spire, as one twirls round a spinning top by the stalk or bole, had, from some failure in the coherency of the masonry, succeeded in turning round only the part of which it had laid hold.”

Miller (1905) goes on to observe the similarities between the damage to the Inverness spire and the rotation of two obelisks at a Calabrian convent described by Vivenzio in 1783 and later by Sir Charles Lyell (1830–1833). Miller (1905) also refers to observations of rotational effects made by Darwin and Mallet. A letter to Provost Grant of Inverness dated 26 August 1816 indicates that the spire appeared to be standing perpendicular and was reckoned to be equally secure as when first erected. The writer of the letter suggested that in view of this, the spire should be allowed to remain in its new position and would be “the subject of conversation and the wonder of ages to come,” but it was restored 12 yr later.

Comrie, 23 October 1839

The Comrie district has experienced repeated swarm activity (Fig. 1c). The earthquake of 23 October 1839 (4.8 M_L)

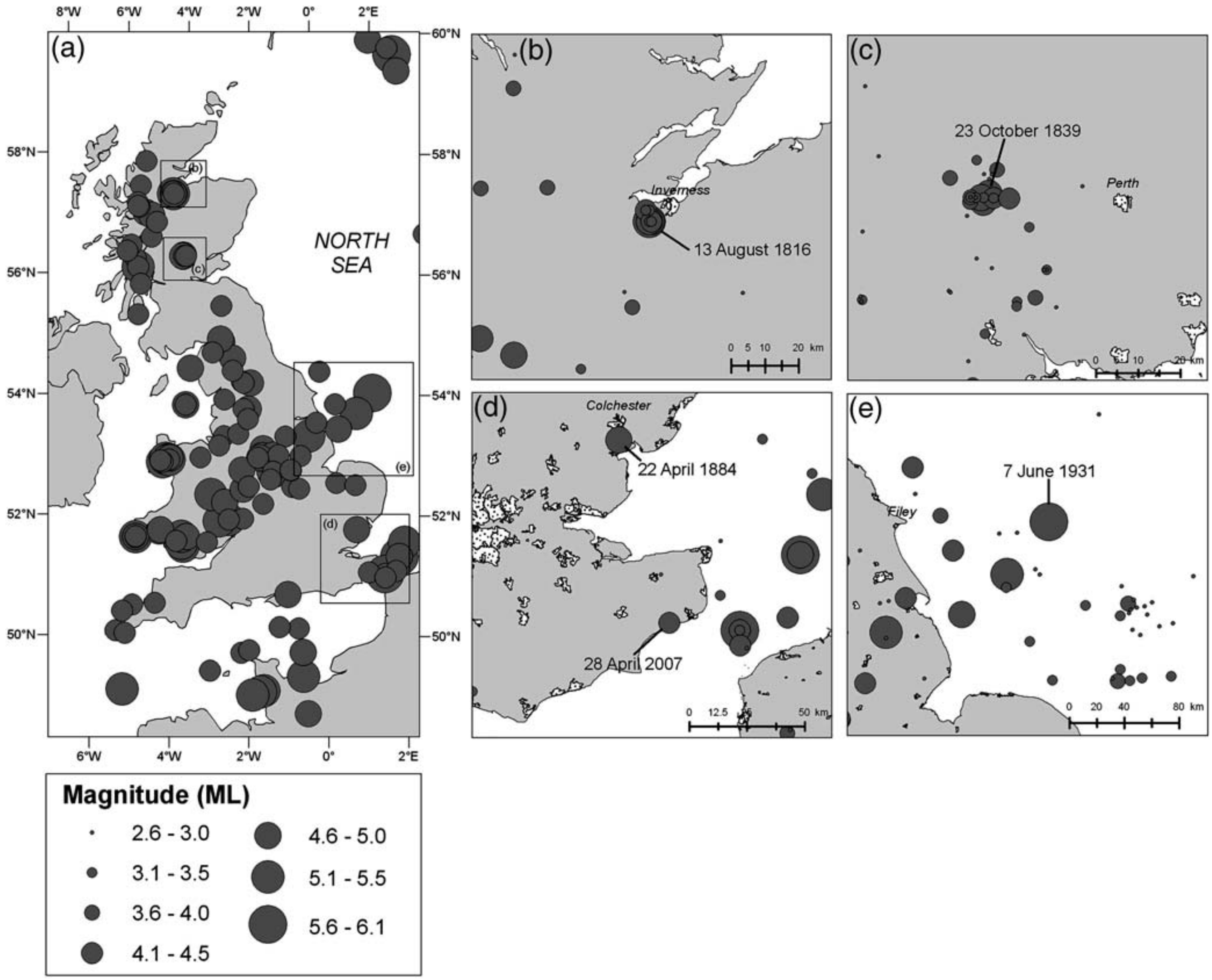

Figure 1. (a) Seismicity map for the United Kingdom ($M_L \geq 4$); (b)–(e) regional seismicity maps ($M_L > 2.5$). Stippled areas denote urban areas.

is the largest of the known Comrie earthquakes at least since the eighteenth century (Musson, 1994). It caused significant damage at Comrie and in the vicinity, mainly to the tops of chimneys (Milne, 1842). Rotational damage to three tall chimneys on a local estate is described by Milne (1842): "The chimney-tops here referred to by Mr. Walker were pointed out to the author by Sir D. Dundas, on whose estate the house is situated. The chimney-stalks were about four feet high, and were built of polished freestone. They were a few inches apart from each other, and had their angles exactly opposite, in the way represented by the adjoining woodcut A B. The effect of the shock is stated to have been to turn each chimney inwards, in the direction of the arrow, so that their faces came nearly opposite to each other."

The woodcut referred to in this extract is reproduced in Figure 3. This particular example may be satisfactorily explained by the impact of translational ground motion on an asymmetric structure.

Colchester, 22 April 1884

The 1884 Colchester earthquake (4.6 M_L) occurred in an area of very low seismicity (see Fig. 1d) in southeastern England. It is one of the most damaging earthquakes to occur in the United Kingdom since the medieval period. The epicenter was south of Colchester, near the village of Peldon in Essex, and the depth was very shallow (3 km; Musson, 1994). Many examples of rotated chimneys and columns were noted, including one at the Rose Inn in Peldon (Fig. 4).

Meldola and White (1885), who produced a comprehensive report on the earthquake, noted: "The twists observed in broken chimneys, etc. give such a strong impression of the displacement having been caused by actual rotation that many writers, both with reference to the present and to former earthquakes, have ascribed the phenomenon to a vorticose movement of the ground. In view of the complicated character of earthquake motion as revealed by seismograph

Figure 2. The spire of Inverness Jail. This picture was taken after the spire was restored. Arrow indicates approximately where the rotation occurred “within 5 or 6 feet of the top, the angles of the octagon turned nearly to the middle of the flat sides of the octagons underneath it” (Anonymous, 1816). This photograph is available as part of the Highland Photographic Archive (see Data and Resources section). Sense of rotation unknown.

tracings, it seems not improbable that the rotation may in some cases be caused by such a twisting motion.”

Although Meldola and White (1885) acknowledge that translational motion would be able to produce these effects, the authors suggest that the fact that the majority of chimneys were twisted in the same direction is evidence for translational movement having played a subordinate role only. They were keen to deduce the direction of wave propagation from these observations, but they concede that the direction of propagation of whatever motion caused the chimneys to twist is impossible to deduce from the direction of rotation.

It is useful to quote Meldola and White (1885) at length on this issue: “But although a twisting motion of the ground may be some cases by admitted, it has been shown by Mallet (Proc. Roy. Irish Acad., vol xxxi, part 1, 1846) that a simple rectilinear movement would be quite competent to produce the effects observed. Were this straight line motion the cause of the twists observed by us, it might have been expected as

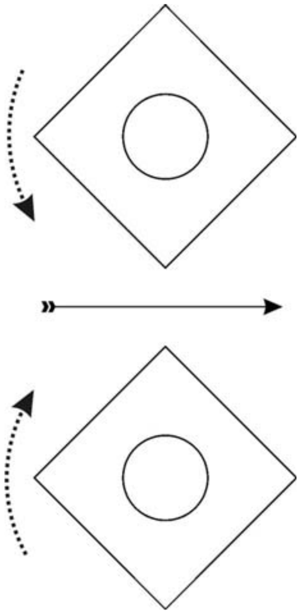

Figure 3. Reproduction of the woodcut presented by Milne (1842): “The effect of the shock is stated to have been to turn each chimney inwards, in the direction of the arrow (and illustrated by the dotted arrows), so that their faces came nearly opposite to each other.” (Milne, 1842)

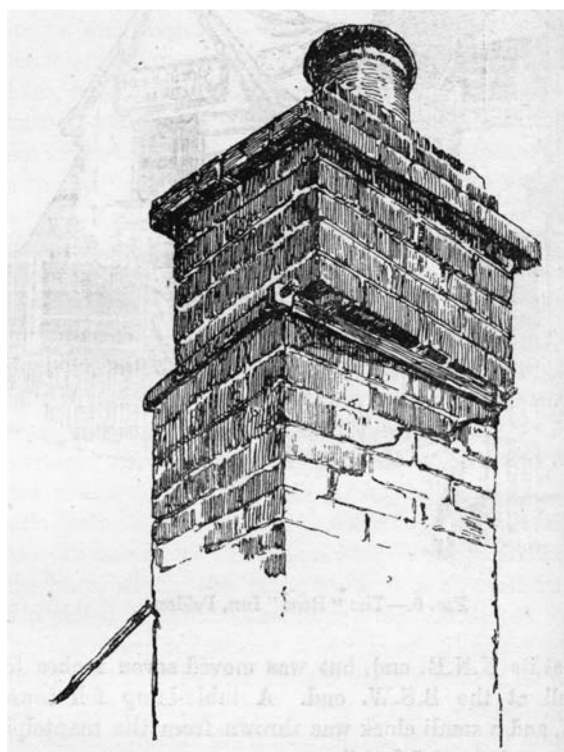

Figure 4. Rotational chimney damage from the 1884 Colchester earthquake (from Meldola and White, 1885). The sense of rotation is counterclockwise in this case, but note that this is only one example of many instances of chimneys rotated in both clockwise and counterclockwise directions.

pointed out by Milne, that the rotation in the same locality would have been very frequently in opposite directions, as it is certain that the centre of friction could not be expected to bear the same relation to the centre of gravity in all the chimneys. As we have already stated, the effect of this opposite rotation was only occasionally observed during our visit of inspection, the majority of the chimneys in each district having been twisted in the same direction. It is probable, therefore, that a simple rectilinear movement played but a subordinate part in producing the twists observed after the present earthquake."

Meldola and White (1885) present the model of Thomas Gray produced by Milne (1880, not seen) in a rather obscure publication, which we think is useful to describe here. The model assumes that ground motion is purely translational and is shown in Figure 5. Gray proposes that a shock passing through any of the shaded octants in the figure would cause rotation from right to left, whereas if the shock passed through any of the unshaded octants, rotation from left to right would occur. Using this model Meldola and White (1885) are not able to constrain the propagation direction.

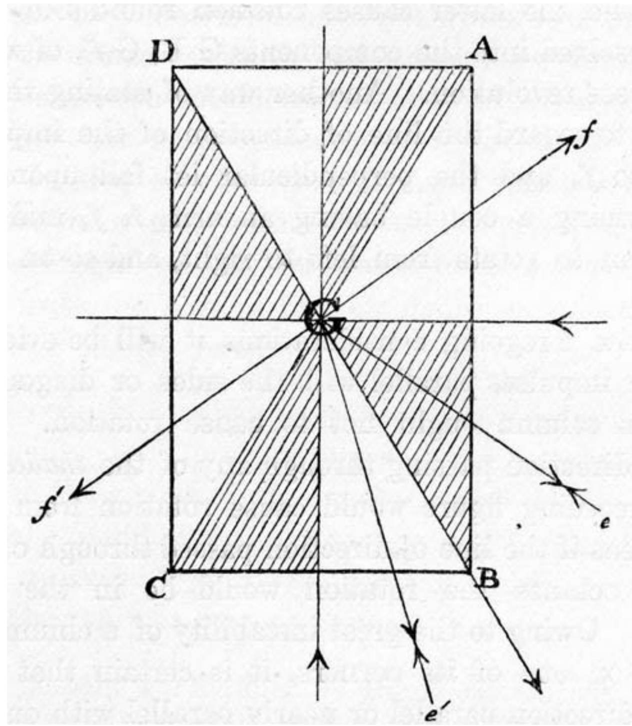

Figure 5. Gray's model showing translational motion impinging (denoted by the inward pointing arrows) on a column in plane view (from Meldola and White, 1885). *G* is the center of gravity. "If the shock has some intermediate direction, such as *e G*, and its effect would be to cause the body to bear heavily on *B* and at the same time to rotate around *B* as an axis in the direction of the hands of a watch, i.e. from right to left" (Meldola and White, 1885).

Dogger Bank, 7 June 1931

The 1931 Dogger Bank earthquake (6.1 M_L, Fig. 1e) is the largest United Kingdom event for which a magnitude can be reliably estimated (Musson, 1994). It was felt across Britain and the low countries. The strongest effects were observed in Yorkshire at Filey, Bridlington, Beverley, and Hull. In Filey, the spire of the Wesleyan Chapel was partially rotated by about two inches. Despite its poor quality, the photograph in Figure 6 shows this damage. One might imagine that the effects at Inverness Jail were similar.

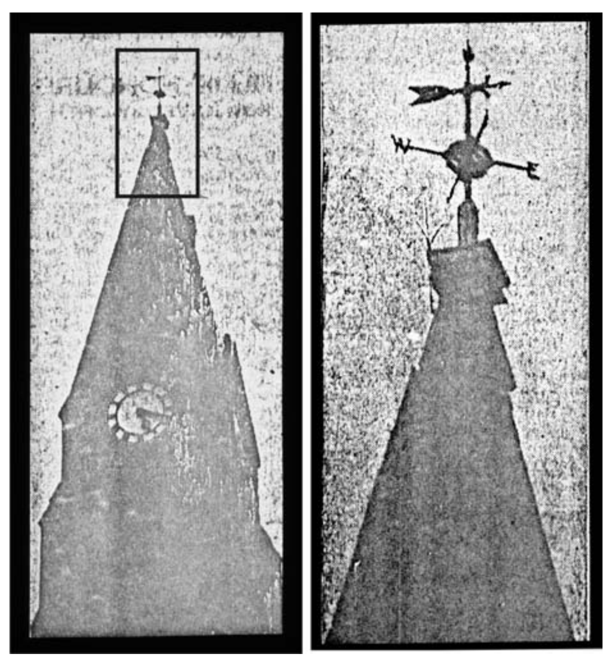

Figure 6. Damage to the chapel steeple at Filey caused by the 1931 Dogger Bank earthquake (counterclockwise rotation). This photograph was taken from The Northern Echo (1931).

Folkestone, 28 April 2007

This is the most recent example of rotational damage from a British earthquake although it is by no means unequivocal. The 2007 earthquake (4.3 M_L, Fig. 1d) caused significant, albeit localized damage in the Foord district of Folkestone, a few kilometers northwest of the epicenter. Most of the damage here was to chimneys although there were some instances of structural damage (Sargeant *et al.*, 2008). In this area at least one of the balustrade supports at the Grace Chapel appears to have been rotated out of position (Fig. 7).

Discussion and Conclusions

The United Kingdom is an area of low to moderate seismicity, and significant earthquake damage is rare. On average, an event of 4.5 M_L or larger is expected somewhere in the United Kingdom once per decade (Musson, 2007). Furthermore, when they do occur, the larger United Kingdom earthquakes tend to be relatively deep within the crust (around 15 km); thus intensities seldom exceed 6 on the Eu-

Figure 7. Balustrade support at Grace Chapel, Folkestone, rotated counterclockwise out of position (Sargeant, NERC, 2007).

ropean Macroseismic Scale, and damage is often confined to a few toppled chimneys and damage to plaster.

It is interesting to note, therefore, that even in this case where earthquake damage is essentially rare, one can still cite instances from the literature where rotational effects have been observed; it is a demonstration of how pervasive this phenomenon can be. From these historical observations, of course, it is not possible to determine whether the observations are due to true rotational shaking or are rotational effects caused by translation, particularly given the asymmetry of these structures. As a matter of historical record, we wish to draw attention to the fact that this very problem was recognized and was being discussed in relation to British earthquakes as long ago as the 1880s when some of the effects described in this article were being investigated in the field.

Data and Resources

This information is available from the National Seismological Archive at the British Geological Survey (Edinburgh). The photograph in Figure 2 is used with the permission of the Highland Photographic Archive, Highland Council (United Kingdom). The United Kingdom earthquake catalogue data are also available from BGS. Please contact the authors. Some plots were made using the Generic Mapping Tools version 3.4.1 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998; last accessed May 2008).

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References

Anonymous (1816). Earthquake in Scotland, *Philos. Mag.* **48,** 150.

Anonymous (1931). photo in 8 July 1931 Ed. *The Northern Echo*, York, United Kingdom.

Evans, J. R., and International Working Group on Rotational Seismology (2009). Suggested notation conventions for rotational seismology, *Bull. Seismol. Soc. Am.* **99,** no. 2B, 1073–1075.

Meldola, R., and W. White (1885). *The East Anglian Earthquake of 1884*, MacMillan. London, United Kingdom.

Miller, H. (1905). *My Schools and Schoolmasters or the Story of My Education*, George A. Morton Edinburgh, United Kingdom.

Milne, D. (1842). Notices of earthquake-shocks felt in Great Britain, especially in Scotland, and inferences suggested by these notices as to the causes of the shocks, *Edinburgh New Philos. J.* **XXXII**.

Musson, R. M. W. (1994). A Catalogue of British Earthquakes, *British Geol. Surv. Technical Rept. WL/94/04*.

Musson, R. M. W. (2007). British earthquakes, *Proc. Geol. Assoc.* **118,** 305–337.

Sargeant, S. L., P. J. Stafford, R. Lawley, G. Weatherill, A.-J. S. Weston, J. J. Bommer, P. W. Burton, M. Free, R. M. W. Musson, T. Kuuyuor, and T. Rossetto (2008). Observations from the Folkestone, United Kingdom, earthquake of 28 April 2007, *Seism. Res. Lett.* **79,** no. 5, 672–687.

Wessel, P., and W. H. F. Smith (1998). New, improved version of the Generic Mapping Tools released, *EOS* **79,** 579.

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