Article accepted for publication in Earthquake Spectra on 12th July 2019 and published in 2020, volume 36, issue no. 1, pp. 455-457

RESPONSE TO

Discussion of "What is the Smallest Earthquake Magnitude that Needs to be Considered in Assessing Liquefaction Hazard?" by Roger M.W. Musson

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The objective of our paper (Green and Bommer 2019) is to determine the smallest earthquake magnitude for which liquefaction could be triggered, in order to define the lower limit of magnitude to be considered in liquefaction hazard assessments. Our findings, supported by extensive field evidence and by analyses, indicated a clear and consistent picture: the lower limit is magnitude 4.5, if one considers all ground types, and 5.0 if one excludes river banks, marshes and beach deposits and limits the consideration to ground of sufficient competence to support engineered building structures.

The 1865 Barrow-in-Furness earthquake case history in the UK is therefore of great importance to the study by Green and Bommer (2019), since it would indicate that the lower limit of magnitude 4.5—we interpret the tidal sands in which Musson (1998) reports liquefaction to fall into the category of susceptible ground that would not be suitable for building foundations—should be lowered by one or two magnitude units, depending on which estimate for the size of the 1865 event is adopted. In other words, if the story narrated by Musson (1998) were credible, we would have to conclude that the answer to the question addressed in our paper is magnitude 2.5, rather than 4.5 for all ground types.

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Musson (2019), unsurprisingly, has responded to our paper (Green and Bommer 2019) to defend his interpretation (Musson 1998) of the 1865 Barrow-in-Furness earthquake and the potential for it to have caused localized, severe liquefaction. However, the comment by Musson (2019) does nothing more than re-state the case made in that original paper and it entirely ignores the context of our paper that frames our conclusion that there are good reasons to doubt the interpretation presented by Musson (1998).

The majority of the case histories on which Green and Bommer (2019) based their conclusion regarding the lower limits of magnitude 4.5 and 5.0 are characterized by two important features: instrumentally-determined earthquake magnitudes and liquefaction features observed in the field by seismologists, geologists, or geotechnical engineers familiar with liquefaction phenomena. For the Barrow-in-Furness case history, both of these characteristics are absent (i.e., little was understood about liquefaction at the time, so no one had familiarity with the phenomenon, and the event predates development of modern recording instruments). Bolton (1869) does provide insightful and scientific/objective post-event observations. This includes the observations of the potential occurrence of liquefaction by two eye witnesses, relayed by Musson (1998): "*a great mass of sand, water and stone thrown up into the air higher than a man's head*." The two witnesses were about a half mile away from the town of Rampside (the town most severely damaged by the earthquake) when they observed "*at a distance*" the water, sand, and stones being ejected from the tidal flats located somewhere between them and Rampside. However, they noted that they "*did not feel the least shock, or know anything of an earthquake until we got to Rampside*" (Bolton 1869). Accordingly, whatever caused the ejecta to be projected more than 2 m into the air and resulted in "*two or three holes in the sand, large enough to bury a horse and cart*" was clearly localized (e.g., the escape of a large body of gas, maybe due to the earthquake, as proposed by Principia (1982) and occurring at a location where shaking was not perceptible to the observers.

The remark by Musson (2019) that the earthquake to which he assigns a magnitude in the range 2.5 to 3.5 causing liquefaction "*raises problems in coming up with a mechanical explanation*" somewhat understates the lack of internal consistency in this story when one considers the nature of the observed 'liquefaction.' We would consider a defensible physical explanation a basic requirement if this case history were to counter all the other evidence—and our simple parametric analysis—and establish the lower limit of magnitude for liquefaction triggering. Musson (2019) asserts that "*facts are facts and should not be dismissed no matter* *how rare or anomalous an occurrence*" but the facts in this case are only that there were reports of felt shaking due to an earthquake and there are written accounts of geotechnical phenomena observed on a beach nearby; everything else in interpretation. Musson (2019) does not address the points made by Green and Bommer (2019) regarding just how rare and anomalous the Barrow-in-Furness case history would be if his interpretation were accurate in all regards. The fact is that nothing remotely comparable has been observed in the century-and-a-half since the Barrow-in-Furness event and no plausible physical explanation has been given to how such a small earthquake could have caused such strong liquefaction effects.

In summary, we appreciate Dr. Musson's attachment to his narrative of an extreme English exception to the patterns observed in a growing—and increasingly reliable—global database, but we would consider it entirely inappropriate to recommend earthquakes smaller than magnitude 5 should be considered in liquefaction hazard assessments conducted for engineered building structures on the basis of such incoherent evidence.

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