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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Liquefaction susceptibility assessment in fluvial plains using high-resolution airborne LiDAR data: the case of the 2012 Emilia earthquake sequence area (Italy)" *by* R. Civico et al.

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We thank the Reviewer for the comments and suggestions. In the following, we present a description of how and where we have addressed the Reviewer's concerns.

1. RC: However, I am not convinced that the methodology that they suggest is an alternative to the traditional geotechnical approach to susceptibility maps (more on this below), as they suggest (or at least they sound like that).

1.1. AC: We followed the reviewer's suggestion and we modified the text accordingly in the introduction and discussion paragraphs. DEMs derived from LiDAR are going to greatly improve our ability to better identify and map landforms that are prone to liquefaction. We may need to use high-resolution geomorphic mapping as a first/preliminary approach to estimate liquefaction susceptibility over large areas. This is particularly effective in: a) filling the gap of punctual information in areas with poor or no geotechnical data, and/or b) in refining maps that are based on geotechnical-derived indexes. Integrating high-resolution geomorphic mapping with geotechnical analysis can also help reducing the cost of liquefaction susceptibility assessment over very large areas. Notably, our study area is dominated by agricultural fields, and thus the majority of the geotechnical data are present only in small towns and villages, preventing a comprehensive estimate of liquefaction potential over the entire 2012 coseismic area.

2. RC: Page 4533, lines 8-15: This paragraph is confusing. The authors say that liquefaction only occurred during the main events 20 and 29 May but then they say that on certain locations there were 5 liquefaction events "for both 20 and 29 May". I do not quite understand what they mean by 5 liquefaction events.

2.1. AC: We rephrase this section and clarified that based on repeated field and aerial surveys, reports from local people and Web-based surveys, we have evidence for only 5 sites where sand blows reactivated following the 2nd mainshock (29 May). Liquefaction reactivations occurred only in the San Felice sul Panaro municipality (see Fig. 4 in EMERGEO Working Group, 2013), that is located less than 10 km from both mainshocks.

3. RC: Page 4535, Line 20: what do you mean by alluvial ridges? Are they not the same as levee ridges?

3.1. AC: For our mapping purposes we adopted the morphogenetic and morphometric landform classification criteria presented in the work of Castiglioni et al. (1999), where they differentiate among levee ridges (height > 2m, longitudinal slope < 1‰ and alluvial

ridges (less well-defined, or with higher longitudinal slope).

4. RC: Page 4536, Line 13: it will be good for the reader to understand what the authors mean by "liquefaction effects". I understand it is explained in the EMERGEO Working Group report but authors can add brief descriptions here. By looking at the photos (e.g. Fig. 2), the type of liquefaction ejecta is very similar to what we found in Christchurch (see examples in: Villamor et al 2014 at nhttp://www.eqc.govt.nz/research/researchpapers/3787-Exploring-methods-paleoliquefaction-Canterbury; Quigley et al 2013, Geology; Bastin et al 2015 GSA). There we saw, often along inner part of meanders, that sand blows coalesce along a few –meter- long fissures and those fissures aligned along longer fissures (tens of meters). Any of these three can be regarded as a liquefaction effect. Are the points in Figure 6 individual sand blows, or fissures with coalescing sand-blows? This can give the reader a better idea of the correlation that authors are trying to make and a qualitative understanding of the amount/severity of liquefaction (more sand was ejected along fissures than along isolated sand blows).

4.1. AC: We followed the reviewer's suggestion and we modified the text accordingly in section 2.2, where we added: "On the basis of their morphologic and structural characteristics, the observed coseismic effects at the surface can be grouped into three main class: a) individual sand blows, scattered vents and coalescent flat cones; b) elongated/aligned multiple sand volcanoes, fissures with coalescing sand-blows and sand flows from coseismic open fractures occurring both on natural and paved ground surface and c) newly formed open fractures and cracks without evident sand extrusion at the surface, which may be associated to subsidence, bulging or lateral spreading related to sediments liquefaction. The surveyed features appear independent from the type of environment, as they occur on roads, buildings, backyards, parks, agricultural fields, etc. Some manmade underground structures such as wells, foundations, sewers, etc. forming artificial boundaries represent a simpler escape for the overpressured water and sediments." Points in figure 6 represent the three categories of liquefaction

phenomena observed in the field or by aerial survey. For details please refer to figure 4 in EMERGEO Working Group (2013).

5. RC: Page 4536, lines 20-24: do you mean that of the 53%, 63% are on alluvial ridges and... and 20% on...? Please note that you only have 53% of correlation – I will come back to this point latter with respect to final conclusion.

5.1. AC: We rephrase this section. The modified text is as follows: "The analysis of the spatial distribution of the liquefaction effects shows that 699 out of a total of 1306 observed liquefaction phenomena (53%) are located exactly in coincidence with mapped fluvial landforms, which notably represent only the $\sim$15% of the whole study area. Among the liquefactions observed on mapped fluvial landforms, alluvial ridges and levee ridges hosted the 63% of observed liquefaction effects, while crevasse splays account for the 20% and abandoned river beds for the 17% (figure 7). As for the liquefaction effects observed outside mapped fluvial landforms, most of them (about 500) appear randomly distributed over the floodplain. Conversely, less than 100 liquefaction effects show a spatial distribution (e.g. meander-like alignments, etc.) that can potentially be related to concealed/undiscovered fluvial features."

6. RC: Page 4537, Line 3: again, to better understand the liquefaction density parameter, this manuscript needs to include a brief description of what the authors mean by "liquefaction effects". While I think it is a simple good approach to define an index/parameter like this I am not sure if is represents severity of liquefaction (or how can it be used as a proxy for severity). It probably does but it will be easier to understand it if reader knows what are the points of Fig 6. Is it possible to associate the points mapped with a rough volume of ejected sand? I do not mean for each point but if you can do this analysis is a small part of the study you may be able to assign the mean value to all the points. Not sure if this comment is correct without understanding what is each point.

6.1. AC: As suggested by the reviewer, we better described the characteristics of the

observed “liquefaction effects” in the “The 2012 Emilia seismic sequence and observed liquefaction phenomena” section (see also response to point 4.1). Unfortunately, structural and morphological characteristics (thickness of the sand volcanoes and area of sand draping, morphology and diameter of the sand outlets) of the observed geological surface effects have not been systematically collected, so it is not possible to evaluate a rough volume of ejected sand.

7. RC: Page 4537, Lines 8-10: In Figure 6, it is clear that the “liquefaction effects” are concentrated on a few on the fluvial landforms mapped, but there are numerous landforms that do not show much liquefaction. I am missing here an analysis of why is this the case (density of liquefaction seems to vary greatly within the fluvial landforms mapped). For example, is there ground water table data that can also be overlain with the other datasets? Are the fluvial landforms with higher liquefaction density index close to current river course? Also in the area represented in Fig 6, is there substantial difference of PGA across it? (perhaps you can add the epicentres to this figure). There seems to be very high density of liquefaction along the Reno River (your Fig. 8) than other rivers closer to the epicentre, why? I think it is as important to address the lack of correlation as it is to address positive correlation.

7.1. AC: We do not discuss the variability of the density of liquefaction within single fluvial feature because we do not have enough accurate data on the stratigraphy and water table. In general, it is possible to identify two overlying aquifer systems in the study area. The shallower one is a semi-confined and locally phreatic aquifer consisting of interconnected silty sand lenses with a variable thickness up to 6-8 m. It is underlain by an aquiclude composed of silts, clays, and peats, which confine the second, deeper aquifer, located at a mean depth of 16-18 m b.g.l. (Papathanassiou et al. 2012). Moreover, the few coseismic PGA data available do not allow for a classification of the observed coseismic effects based on this parameter. Liquefaction phenomena were particularly abundant and severe in the Sant’Agostino area, being this channel a very young reclamation area (beginning of XIX century). We added this latter point and a

brief description of the underground water in the text.

8. RC: Page 4540 Line 7-8: the way this statement is worded suggests that author are proposing and alternative approach to geotechnical studies. I do agree with the authors that DEMs derived from LIdar are going to greatly improve our ability to better map liquefaction susceptibility. We are working towards the same goal (see preliminary results in Villamor et al 2014 at \http://www.eqc.govt.nz/research/research-papers/3787-Exploring- methods-paleoliquefaction-Canterbury). However, at this stage until we have a better understanding of why those landforms are more prone to liquefaction and why some- times they are not, we may need to use geomorphic mapping as either a first approach (perhaps for areas with not geotech data) or as a way to refine maps that are based on geotechnical data. The danger of only using landforms for liquefaction susceptibility mapping is that certain landforms may be given large probabilities (which is not bad as a conservative measure) but alluvial plains may be given too low probability. When dealing with susceptibility based on landform mapping, it is also important to understand where the liquefaction is coming from. For example, in the SE of Christchurch mentioned above we are finding that one of our sites is on a crevasse splay but the liquefied sands come from deeper levels that the crevasse splay (crevasse splay sediments are neither liquefiable based on their particle size analysis nor water-saturated). We still do not understand the role of the crevasse splay; there is substantial liquefaction associated with it but hard to tell why at this stage (PhD student working on it). So perhaps in some of your sites, it is the landforms covered by the crevasse splay that are important.

8.1. AC: We followed the reviewer’s suggestion and we modified the text accordingly in the introduction and discussion paragraphs. DEMs derived from LiDAR are going to greatly improve our ability to better identify and map landforms that are prone to liquefaction. We may need to use high-resolution geomorphic mapping as a first/preliminary approach to better estimate liquefaction susceptibility over large areas. This is effective in: a) filling the lack of punctual information in areas with poor or no geotechnical data,

and/or b) in refining maps that are based on geotechnical-derived indexes. Integrating high-resolution geomorphic mapping with geotechnical analysis can thus help reducing the cost of liquefaction susceptibility assessment over very large areas. Notably, our study area is dominated by agricultural fields, and thus the majority of the geotechnical data are present only in small towns and villages, preventing a comprehensive estimate of liquefaction potential over the entire 2012 coseismic area. In our case, we have evidence that soils prone to liquefaction are confined in the uppermost 10 meters and many punctual data show that the source of the liquefied sediments is around 5-6 meters, which is also the mean water-table level before the earthquake. This layer may belong to a covered landform right below the actual crevasse for which we do not know the lateral extent, and this the reason why we insert the buffer zones in our analysis.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 3, 4527, 2015.