2012 EMILIA EARTHQUAKES

The survey and mapping of sand-boil landforms related to the Emilia 2012 earthquakes: preliminary results

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1. Introduction

Sand boils, which are also known as sand blows or sand volcanoes, are among the most common superficial effects induced by high-magnitude earthquakes. These generally occur in or close to alluvial plains when a strong earthquake (M >5) strikes on a lens of saturated and unconsolidated sand deposits that are constrained between silt-clay layers [Ambraseys 1988, Carter and Seed 1988, Galli 2000, Tuttle 2001, Obermeier et al. 2005], where the sediments are converted into a fluid suspension. The liquefaction phenomena requires the presence of saturated and uncompacted sand, and a groundwater table near the ground surface. This geological–geomorphological setting is common and widespread for the Po Plain (Italy) [Castiglioni et al. 1997]. The Po Plain (ca. 46,000 km^2) represents 15% of the Italian territory. It hosts a population of about 20 million people (mean density of 450 people/km^2) and many infrastructures. Thus, the Po Plain is an area of high vulnerability when considering the liquefaction potential in the case of a strong earthquake. Despite the potential, such phenomena are rarely observed in northern Italy [Cavallin et al. 1977, Galli 2000], because strong earthquakes are not frequent in this region; e.g., historical data report soil liquefaction near Ferrara in 1570 (M 5.3) and in Argenta 1624 (M 5.5) [Prestininzi and Romeo 2000, Galli 2000]. In the Emilia quakes of May 20 and 29, 2012, the most widespread coseismic effects were soil liquefaction and ground cracks, which occurred over wide areas in the Provinces of Modena, Ferrara, Bologna, Reggio Emilia and Mantova (Figure 1). These were the causes of considerable damage to buildings and the infrastructure. The soil liquefaction and ground cracks were accompanied by sand boils, which are described in this report. The spatial distribution and geomorphological setting of sand boils and ground cracks are also described here. A detailed three-dimensional (3D) reconstruction of these features is also presented, which was carried out using terrestrial photogrammetry.

Since archeological times, fluvial ridges, and in general sandy deposits on low plains have been the preferred sites for human infrastructure, colonial houses, roads, etc. Therefore, it is very important to understand how the local topography/morphology interacts in the liquefaction processes. Numerous distinctive seismic landforms were generated by the May 2012 strong earthquakes (seven with M >5), and in particular, sand boils and ground fractures. The sand-boil landforms, also known as sand craters or sand volcanoes, are formed by low mounds of sand that have been extruded from fractures [Tuttle 2001]. The cone is a generally short-lived structure that naturally collapses, starting from the center holes that mark the water retreat back into the fracture. Sand boils also occurred along larger cracks (with decimetric lateral and vertical displacements). Here, the upper scarps block the formation of craters and allow the deposition of a sandy layer several centimeters thick (e.g. ca. 4 cm in the San Carlo crack), on the lower side of the steep slope. These landforms are highly vulnerable to erosion. After a few weeks, they are washed out by rain, destroyed by human activity, or masked by growing crops. Thus, ground surveys that investigate these events have to be carried out as soon as possible [Panizza et al. 1981]. In this report, we present preliminary results using methods to map the detailed micro-morphology of some representative liquefaction features (Figure 2) that normally disappear for the aforementioned reasons, or that are recorded only in qualitative terms.

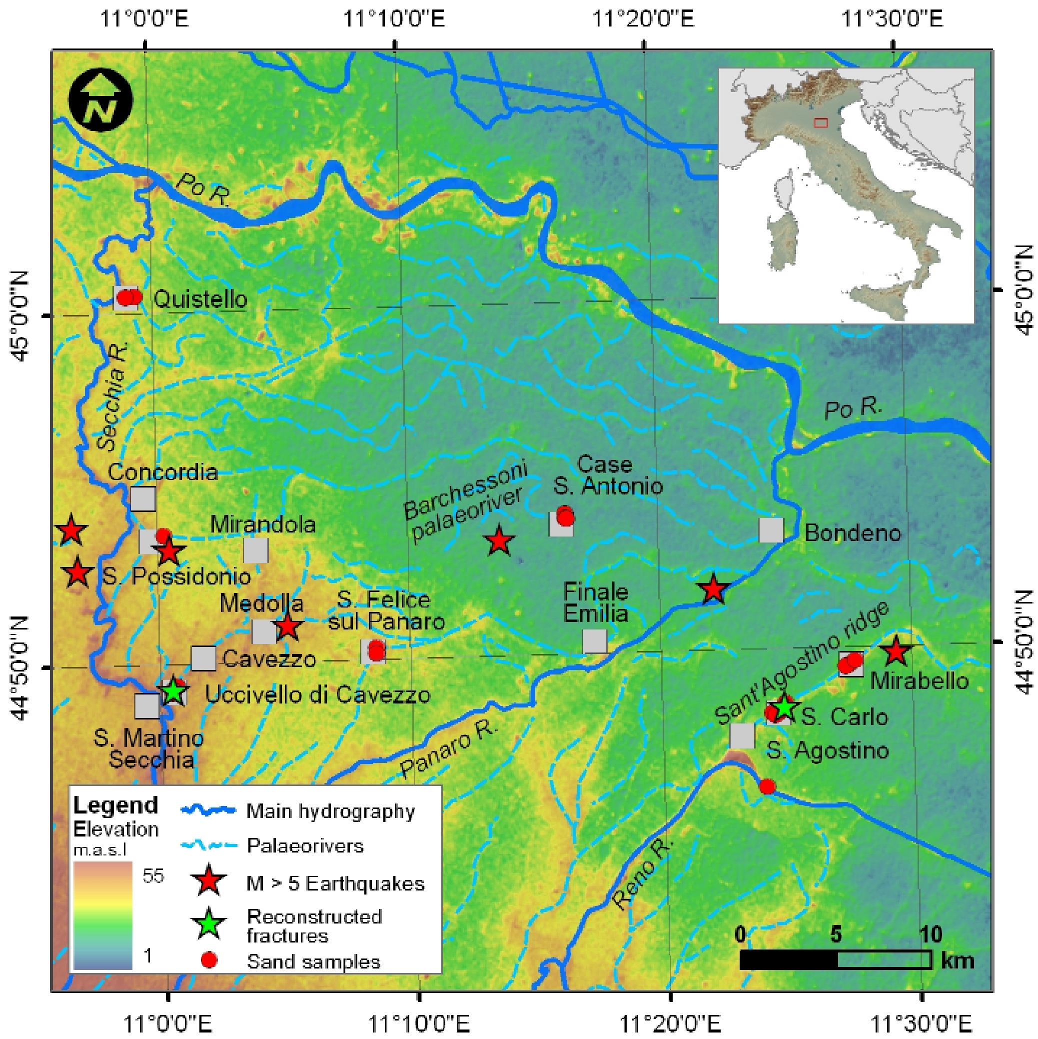

Figure 1. Shuttle Radar Topography Mission (SRTM; cell size, ca. 90 m), red dots represent the location of sand samples. It should be noted that most of the samples came from areas located on high fluvial ridges.

2. Methods

Field surveys and activities were conducted a few days after the May 20 and 29, 2012, mainshocks (M 5.9, M 5.8, respectively). The surveys were carried out using global position system (GPS) and reflex digital cameras. GPS acquisition (tracklog) was used to record the topographic positions of the features and to automatically geolocate / geotag the numerous digital photos acquired. The field data, geomorphological features, and sand-boil location were loaded into a geodatabase and mapped using geographic information systems (GIS).

Photogrammetric surveys were carried out on several sand boils using digital reflex cameras with calibrated 20-mm fixed lenses. To build high resolution digital elevation models (DEMs), images were taken from multiple angles to cover the entire areas of the features of interest (Figure 2). The first step of the model construction, called the alignment, was carried out using the structure-from-motion algorithm [Ullman 1979]. The result was a dataset that was composed of a sparse number of 3D points and camera positions. After that, a stereo matching algorithm was used to correlate each pixel of the photograph, to reconstruct the dense point cloud that is essential to get accurate 3D models [Szeliski 2011, Verhoeven 2011]. Finally, the points were interpolated and the detailed DEMs were created. Different targets of known size were distributed around each scene to build a local reference system that was usable in a GIS environment; one master target was north-oriented and leveled using a micro bubble level. All of the models were rotated, translated and projected on a plane with the Z axis in the correct vertical position. The pictures taken in the zenithal position were used for orthophotograph production. Using this methodology, we were able to develop DEMs with resolutions ranging from one millimeter for the smaller forms, to some centimeters for the large ones (Figure 2).

3. Geomorphological setting of the study area

The Po Plain surface is characterized by a complicated paleohydrographic network that is made up of fluvial ridges, paleochannels, crevasse splays, etc. [Castiglioni et al. 1997, Castiglioni and Pellegrini 2001, Burrato et al. 2003, Toscani et al. 2009]. The area affected by the Emilia 2012 earthquakes lies in the southern central sector of the Po Plain, which is formed by the activities of the Po, Secchia, Panaro and Reno rivers [Castiglioni et al. 1997, Castiglioni and Pellegrini 2001]. In the

Site	**Fluvial domain**	**D50** (mm)	**FC** (%)	**Sand** (%)
Case Sant'Antonio	Po paleoriver	0.1-0.25	5-32	68-88
Uccivello di Cavezzo	Secchia paleoriver	0.15-0.3	11-25	68-88
San Possidonio	Secchia paleoriver	0.22	4	96
Quistello	Po paleoriver	0.18-0.2	8-19	81-92
San Felice sul Panaro	Panaro paleoriver	0.15-0.18	22	78
Mirabello	Reno paleoriver	0.18	16	84
San Carlo	Reno paleoriver	0.04-0.15	17-63	60-83

Table 1. Granulometric characteristics of the liquefied soils. FC, materials that pass through a number 200 sieve ASTM; D50, mean grain size.

lower part of the Plain, the Po River palaeochannels show a constant W-E trend. In the upper sector of the Po Plain, the paleohydrography shows a change in flow direction, from SSW-NNE. Closer to the Apennine margin, the direction is W-E on the sector of the plain closer to the Po River. Since the Bronze Age, the Po River has moved northwards, and its Apennine tributaries have shifted to the east, except for River Secchia, which was diverted westwards [Castaldini 1989a]. In particular, from the first millennium B.C., the evolution of the Po, Secchia, Panaro and Reno rivers has shown wide meanderings and even shifts in the river beds, and they have been conditioned by the subsidence of the Po Plain, as well as by the tectonic activity of the buried Appenine geological structures [Castaldini 1989a, Burrato et al. 2003]. In the last century, they have also been subjected to human activities. The ground-water table level has shown large oscillations during seismic events; e.g., according to many testimonies of the citizens, some 3 m to 9 m of rising occurred in draw wells during the May 20, 2012, earthquake. We describe the local geomorphological settings of the surveyed location, where sand volcanoes were recorded and samples were collected (Figure 1, Table 1).

3.1. Case Sant'Antonio (Bondeno municipality)

This site is located in the municipality of Bondeno (Ferrara Province) at the boundary with the Finale Emilia municipality (Modena Province), which was the epicenter of the May 20, 2012, earthquake (M 5.9). By the middle of July, the coseismic effects (sand boils) were no longer visible in the field, as they were hidden by crops (mainly maize). From a geomorphological point of view, the site is located between

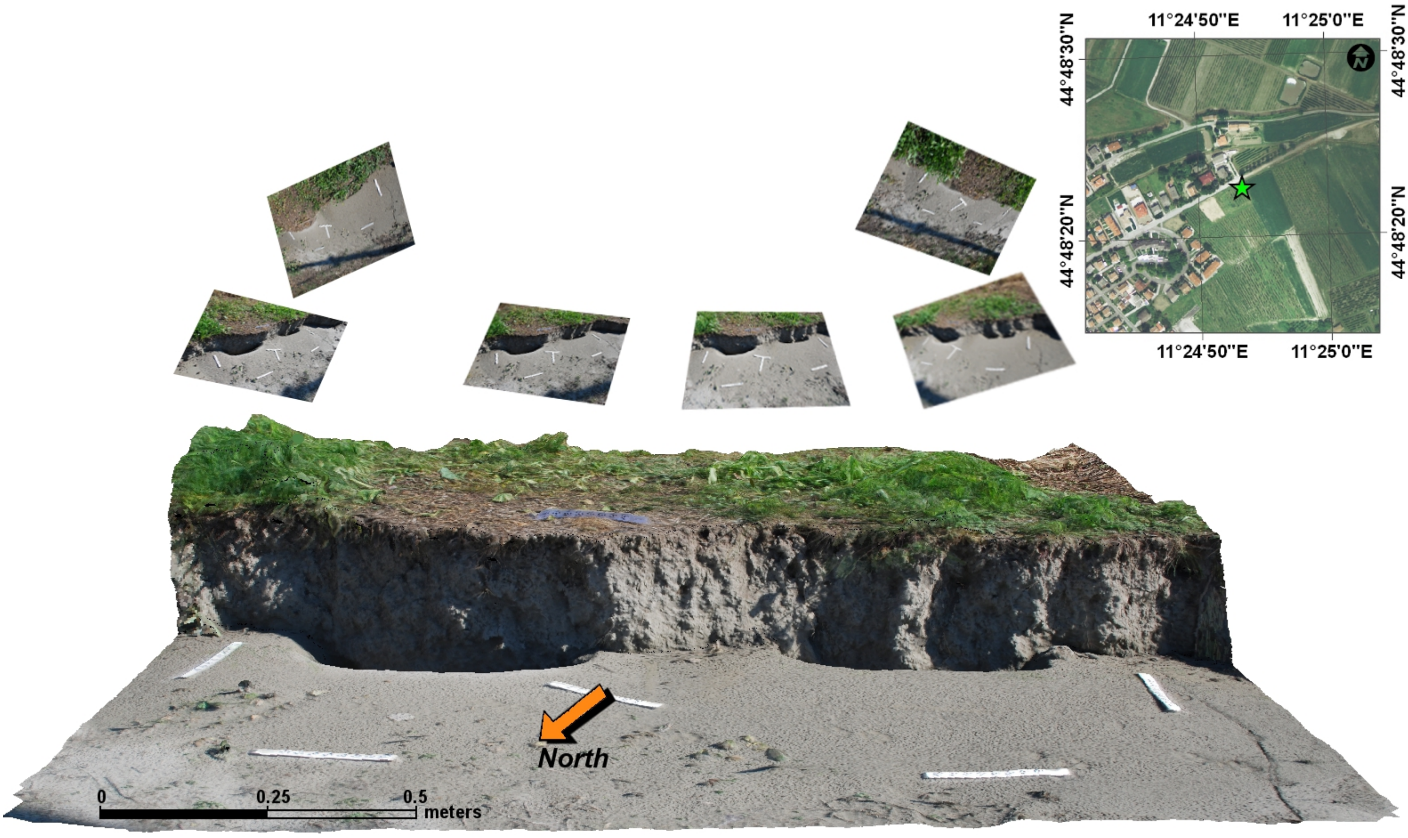

Figure 2. Textured point cloud obtained by dense stereo-matching algorithms and camera position reconstruction. These fractures were in San Carlo.

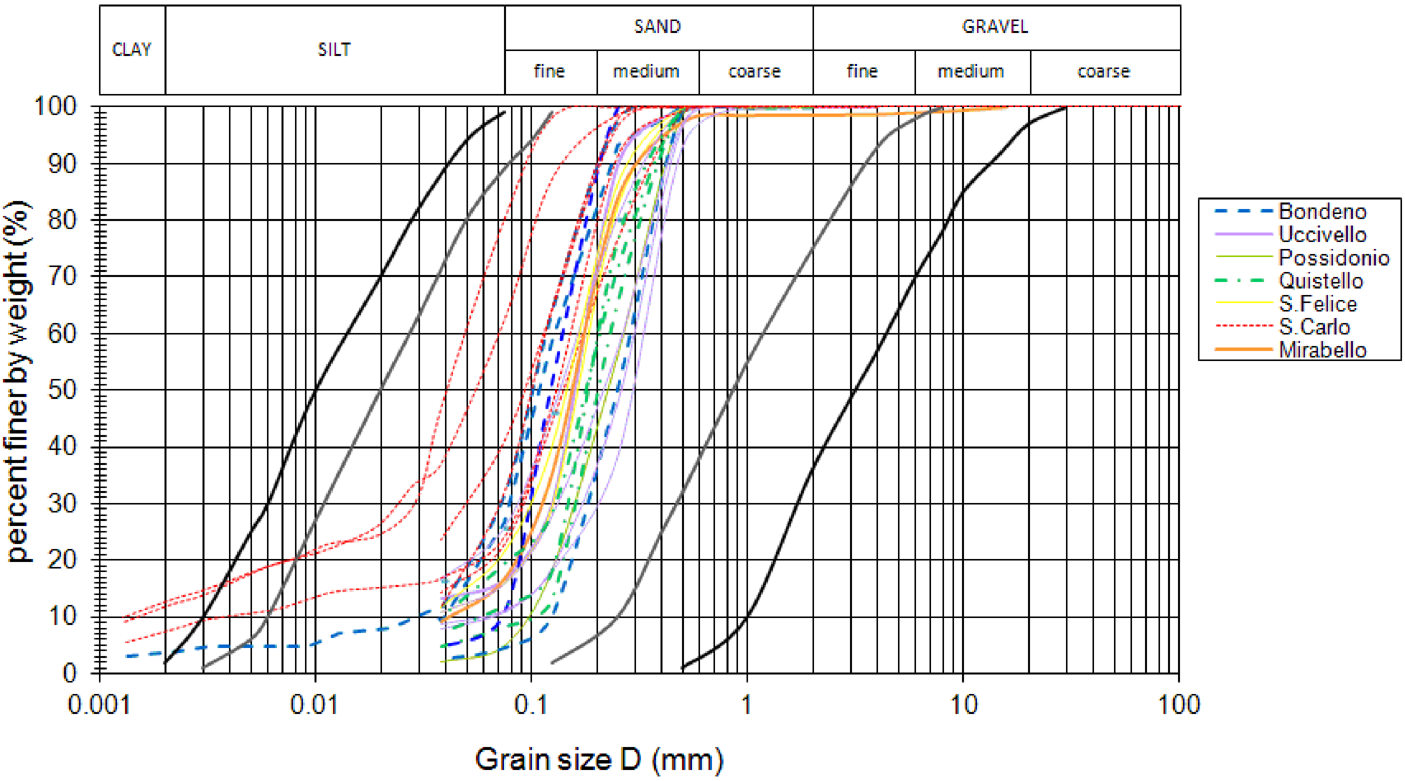

Figure 3. Grain size distribution of liquefied soils. Black lines, boundaries for potentially liquefiable soils [Obermeier 1996]; gray lines, interval with high potentially liquefiable soils (uniformity coefficient >3.5).

the Po, Panaro and Secchia rivers, in the lowest sector of the Modena plain (8 m to 9 m a.s.l.). This area has been flooded many times by the Po River, and the clayey sediments have buried older fluvial sandy deposits and archeological settlements. The collected sand samples belong to the sediments of a paleoriver known in the literature as 'Barchessoni paleoriver'. The geochemical analyses of the sediments and the meandering geometry of the Barchessoni paleoriver are more similar to the present-day Po River than the Secchia or Panaro rivers [Castaldini et al. 1992]. Archeological settlements found here have revealed that this Po paleoriver was already active in the Bronze Age [Balista et al. 2003]. In the Iron Age and in Roman times, it was a small watercourse; the period in which the complete extinction of the channel took place remains unknown [Castaldini et al. 2009].

3.2. Uccivello di Cavezzo, San Possidonio and Quistello

The liquefaction phenomena at Uccivello di Cavezzo, San Possidonio (Modena Province) and Quistello (Mantova Province) were triggered by the earthquake of May 29, 2012 (M 5.8). Uccivello di Cavezzo and San Possidonio are located on an ancient course of the Secchia River [Castaldini 1989a, b]. Uccivello di Cavezzo (23 m a.s.l.) is on the Secchia fluvial ridge, which is orientated NW-SE and crosses San Martino Secchia–Cavezzo–Medolla. It was active during Roman and Medieval times, until XII-XIII A.D. Just one week after the earthquake, the sand boils were removed by agricultural work in the fields. The San Possidonio (20 m a.s.l.) site is also on a sandy fluvial ridge (NW-SE trending), which corresponds to a Secchia paleoriver that was abandoned in modern times. In Quistello (15 m a.s.l.), samples were collected in the urban area of the village, which is located near the right bank of the Secchia River, although it lies on sandy deposits linked to the Po paleorivers that were active in the Bronze Age and in Roman and Medieval times [Castaldini 1984, Castaldini 1989a, Castiglioni et al. 1997].

3.3. San Felice sul Panaro

San Felice sul Panaro (17 m a.s.l.) is located in a sector where silt and clay deposits crop out [Castaldini et al. 1989b, Castiglioni et al. 1997]. The San Felice sul Panaro liquefaction features were produced by the May 20, 2012, earthquake, and were reactivated by the May 29, 2012, earthquake. Samples were collected in the urban areas (in the stadium and in a school yard) that lie at the confluence of a S-N Panaro paleochannel and a Secchia system paleoriver that flows W-E. These were active in Roman and Medieval times [Castaldini et al. 1989b]. Nowadays, the sand sediments have been removed by human activities.

3.4. San Carlo and Mirabello

The San Carlo and Mirabello villages are located on a fluvial ridge that corresponds to a Reno River paleochannel known as 'Sant'Agostino ridge' [Castaldini and Raimondi 1985]. This paleochannel has a SW-NE river trend and is a very evident morphological feature that is 3 m to 4 m higher than the surrounding plain. There are numerous buildings on this sandy ridge. The liquefaction phenomena and ground

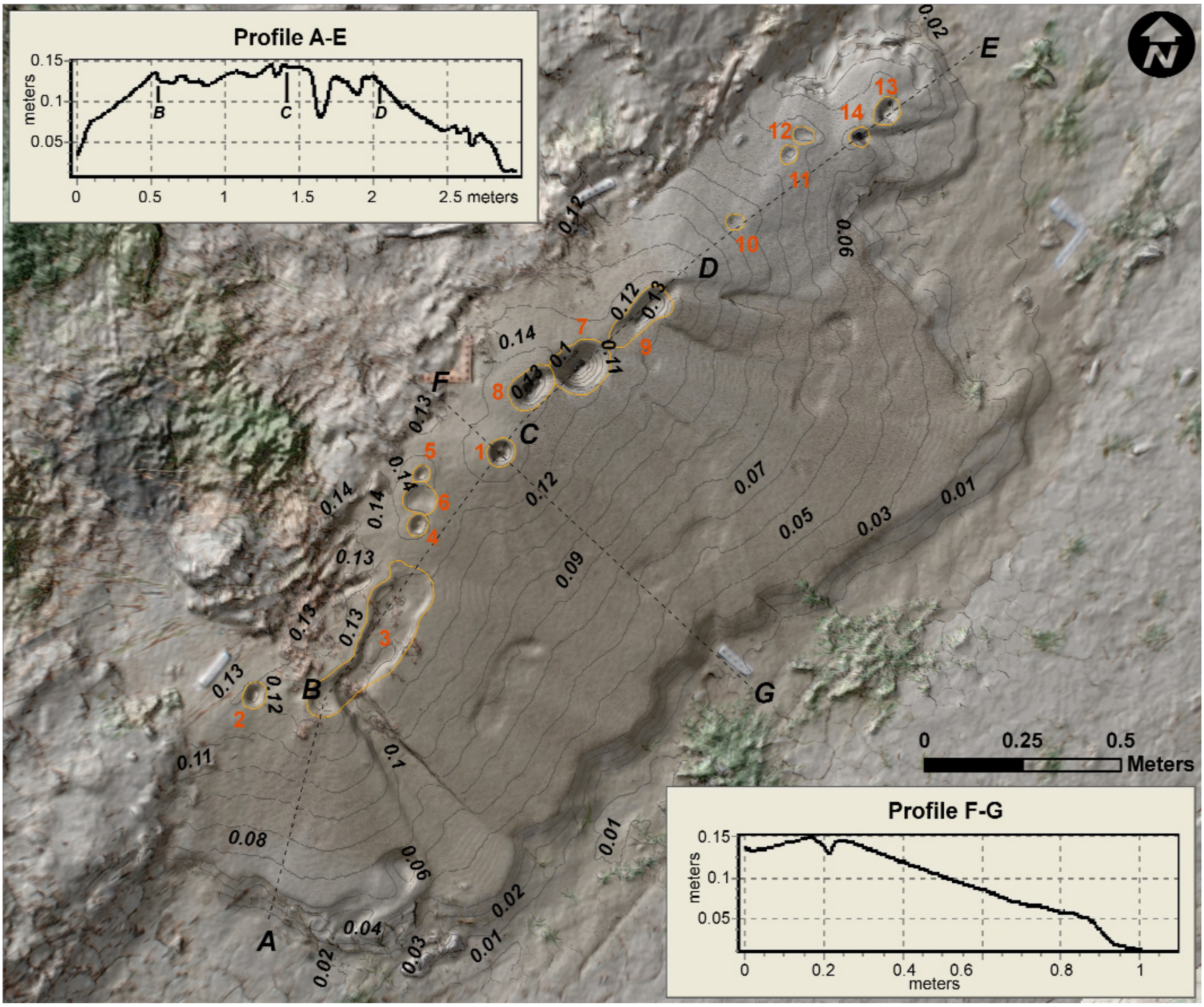

Figure 4. Orthophotograph draped over a shaded relief derived from the sand volcano DEM (cell size, 1 mm) that was reconstructed using a dataset of about 560 million pixels. Black dashed lines, profiles (A-E and F-G); gray lines, contour lines with 1-cm spacing. The limits of the individual emission points are highlighted in orange and numbered. The full dataset is north oriented and projected using a plane projection in a local metric coordinate system.

fractures were triggered by the May 20, 2012, event. At this site, a large quantity of sand was extruded from the subsoil, which caused major instability problems in San Carlo village. This paleoriver of the Reno River was active between Medieval times and the end of the XVIII century, when it was subjected to an artificial diversion near Sant'Agostino village [Castaldini and Raimondi 1985, Castaldini 1989a].

4. Preliminary results from the field activities

Samples of the material that formed the sand volcanoes were collected at the sites described above, to determine the grain-size distribution (Figure 3, Table 1). The arrangement or packing of sand grains has a profound effect on the stability of a sediment and its liquefaction susceptibility [Obermeier 1996]. Sands that are moderately dense or looser liquefy in many field situations, and the distribution of the grain size of the sands strongly influences how susceptible the material is to seismic liquefaction [Obermeier 1996]. The particle size distribution curves of the soils investigated fall into the range of a high possibility of liquefaction.

The grain size distribution in the samples was generally heterogeneous. The uniformity coefficient (Uc) was between 2 and 9, with a fine fraction ranging from 4% to 60%. The samples with the highest uniformity coefficient were from Uccivello di Cavezzo (Uc >5), San Felice sul Panaro and San Carlo where the fines content (FC; materials that pass through a number 200 sieve of the American Society for Testing and Materials [ASTM]) was generally up to 12%. These are classified as silty sands or sandy silts. In the area of Case Sant'Antonio and Quistello, the samples collected were more heterogeneous, and their grain sizes ranged from sand (FC <5%) to silty sand (FC >12%).

Figure 4 shows an example of one of the 3D models constructed. It is a sand boil that was found in an orchard

ID	Length (cm)	Width (cm)	Azimuth (°)	Area (cm^2)	Perimeter (cm)	L/W ratio	Elongation ratio	Circularity ratio
1	7.8	6.9	52	42.4	23.3	1.118	0.945	0.977
2	7.1	5.9	24	33.0	20.8	1.205	0.912	0.959
3	46.1	15.7	32.	502.5	111.7	2.938	0.548	0.506
4	6.1	5.3	28	25.0	18.0	1.153	0.930	0.971
5	4.6	4.3	358	15.8	14.8	1.061	0.985	0.907
6	8.7	8.4	25	57.4	27.5	1.039	0.982	0.955
7	16.0	13.5	67	164.5	47.8	1.189	0.902	0.904
8	13.4	9.1	55	97.6	36.7	1.467	0.834	0.912
9	19.3	8.7	49	126.1	48.5	2.213	0.656	0.674
10	4.9	4.1	84	15.7	14.3	1.203	0.916	0.963
11	5.0	4.3	16	17.4	15.1	1.168	0.939	0.955
12	5.4	4.5	1	20.0	16.2	1.201	0.942	0.953
13	8.2	6.4	34	39.7	23.2	1.278	0.869	0.923
14	5.5	5.0	60	20.8	16.5	1.074	0.945	0.955

Table 2. Dimension and morphometric parameters of the craters (Figure 4, orange) derived from the DEM analysis. Azimuth, semi-major axis of the 'ellipse'. Circularity ratio, calculated according to Miller [1953]; elongation ratio, calculated according to Schumm [1956].

near Uccivello di Cavezzo. The body was around 3 m long and 1 m wide, with 14 craters aligned N 42°. Most of the craters were particularly circular, except 3 and 9, with a mean circularity ratio [Miller 1953] of 0.945. The average slope of the flanks was about 20%, increasing up to 40% at the foot of the cone slope. These sand volcanoes reached a maximum elevation of 15 cm, and were made up of ca. 0.23 m^3 of ejected material over an area equal to 3.13 m^2 (3D area value, 3.23 m^2). The parameters given in Table 2 were obtained automatically by processing the slope map of the sand boil and by applying a series of routines of image enhancement and thresholding.

5. Conclusions and perspectives

After a large earthquake, a lot of coseismic phenomena can occur in the field, and the spatial distribution is very important to understand the fault geometry. In this framework, the application of terrestrial photogrammetry is a less expensive and more rapid method to map the micro-morphology of sand volcanoes, compared to (terrestrial/aerial) laser scanning. The centimetric DEMs obtained can be processed and correlated with other datasets later, to create a complete geodatabase of coseismic features. The 3D reconstruction of sand boils and cracks can be of great interest for geomorphological research, as well as for the documentation of coseismic features. A detailed 3D database of landforms that are so ephemeral can also provide a more useful comparison with paleo-forms that are now buried by sediments [Landuzzi et. al. 1995, Montenat et al. 2007].

These 3D data will also be used to investigate the relationships between the morphometry of the cones, and the magnitude of the pressure associated with the sand boils and the local geomorphological setting (granulometry/stratigraphy).

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