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2 Sand liquefaction induced by a blast test: new insights on source layer and grain-size segregation

3 mechanisms (Late Quaternary, Emilia, Italy)

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5 Daniela Fontana[1], Sara Amoroso[2], Luca Minarelli[3] and Marco Stefani[4]

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7 *[.1] Department of Chemical and Geological Sciences, University of Modena and Reggio*

8 *Emilia, Modena, Italy*

9 *[2] Istituto Nazionale di Geofisica e Vulcanologia, L'Aquila, Italy*

10 *[3] Geotema s.r.l. Spin-off University of Ferrara, Italy*

11 *[4] Department of Architecture, University of Ferrara, Italy*

12 *e-mail: daniela.fontana@unimore.it*

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ABSTRACT

15

16 The composition and texture of liquefied sands represent an important tool for the recognition of

17 buried source layers and for a better understanding of earthquake-induced liquefaction mechanisms.

18 The earthquake-simulating field experiment (blast test) carried out in 2016 in fluvial sediments of

19 the Emilia plain induced subsurface liquefaction and the surface expulsion of sand as sand blows.

20 The area was widely affected by liquefaction phenomena during the Mw 6.1 Emilia earthquake

21 (2012). The grain size and composition of sand blows ejected during the blast test have been

22 compared with various horizons of buried fluvial sediments as deep as 20 m, and with sands from

23 two trenches in the blast site representative of co-seismic 2012 liquefied sands. The sands from the

24 cores show a clear trend from shallow lithoarenitic to deeper quartz–feldspar-rich compositions.

25 The sands at shallow depth (up to 7.7 m) are the most lithoarenitic, with fine-grained sedimentary

26 rock fragments (shales, siltstones, and limestone) as the dominant lithic type. Lithic fragments

1   derive mostly from erosion of sedimentary terrigenous and carbonate successions of Apenninic

2   affinity. In contrast, deeper sands (at depth > 7.7 m) are enriched in quartz and feldspars and

3   impoverished in lithic fragments, which are similar in character to Po River sands. The composition

4   of ejected sands largely overlap that of the shallow litharenitic Apenninic sands, indicating that

5   liquefaction processes affected mainly sand layers at relatively shallow depth (5.9–7.7 m). Textural

6   parameters show that silty sands and silts characterized by relatively high content of fines can also

7   liquefy. This is in contrast to most of the literature, where fine-grained sediments are considered as

8   incapable of generating the high pore pressures commonly associated with liquefaction. This result

9   should be considered when estimating the liquefaction as a potential hazard. Moreover, we observe

10   that there is a selective loss of fines in the clastic dikes and sand volcanoes relative to the source

11   beds, indicating that the liquefaction process appears to preferentially select the diameters of the

12   grains that reach the ground surface, probably following the generated excess pore-water pressure.

13   This may have caused the segregation and dispersion of the fine silt–clay content, producing highly

14   sorted sand boils. This effect is well observable in both the blast-induced sand boils, and the co-

15   seismic 2012 dikes and sand boils ejected in the same area.

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18   Keywords: silty sand liquefaction, blast test, provenance, fluvial sands, Emilia earthquake

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21   **INTRODUCTION**

22

23   Extensive liquefaction phenomena of fluvial sands buried in the shallow subsurface have

24   occurred in the central-eastern sector of the Po plain, following the two main shocks (M_L 5.8 and

25   5.9) of the 2012 Emilia earthquake. The ejection of liquefied sands through fractures to the

1 surface has generated numerous sand boils, concentrated along buried old channels of Apenninic

2 rivers (Fig. 1).

3 It is well known that the occurrence of sand liquefaction phenomena may cause significant

4 modifications of soil geotechnical properties and reduction of load-bearing capacity, with

5 potential destruction and damages to structures and even human casualties. It is therefore crucial

6 to improve the understanding of the factors that may induce liquefaction (Krinitzsky et al., 1988;

7 Mitchell and Soga, 2005; Chen et al., 2008). Some of these factors, such as earthquake

8 magnitude, depth of the groundwater table, peak ground acceleration, and sediment grain size,

9 are relatively well defined (Youd and Perkings, 1978; Ishihara, 1993; Kramer, 1996; Bray and

10 Sancio, 2006; Chang et al., 2011) although simplified models of soils are used. However, little is

11 known about other relevant geological parameters, in particular sedimentary facies and lateral

12 facies changes, and changes in texture and composition of sediment in liquefiable layers. Recent

13 papers have shown the potential of detailed sedimentological studies for the comprehension of

14 liquefaction processes (Hurst et al., 2011; Owen and Moretti, 2011; Ross et al., 2011, 2013;

15 Quigley et al., 2013; Fontana et al., 2015; Rodriguez Pasqua et al., 2015; Amorosi et al., 2016;

16 Cobain et al., 2017; Giona Bucci et al., 2017). The composition of sand dikes and blows

17 represents an important tool to identify the liquefied source layers in the subsurface, while

18 sedimentary structures and texture may provide information on pulse injection mechanisms of

19 liquefied sands along fractures (Nichols et al., 1994; Hurst et al., 2011; Ross et al., 2014;

20 Fontana et al., 2015).

21   Physical experiments in New Zealand and in the United States have shown that liquefaction

22 can be induced and monitored with field-scale blast tests in order to study the associated effects

23 on soil characteristics (Ashford et al., 2004; Rollins et al., 2004; Wentz et al., 2015; Finno et al.,

24 2016). Following these experiments, in 2016 a research project on blast-induced liquefaction at

25 the field scale was performed at a trial site located in Mirabello (Ferrara, Italy; Amoroso et al.,

26 2017) (Fig. 1), a small town strongly affected by liquefaction phenomena during the 2012 Emilia

1   earthquake (Caputo and Papathanasiou, 2012; Emergeo Working Group, 2013; Fioravante et al.,

2   2013). The stratigraphical, geotechnical, and geophysical properties at the test site were

3   investigated in detail, through several multidisciplinary techniques (Amoroso et al., 2017). Two

4   cores (10 and 20 m deep) and two shallow trenches in the test site allowed to reconstruct the

5   stratigraphy of sediments in the subsurface and the sampling of sands.

6   Here, the composition of sand blows ejected during the blast test, compared with the

7   composition of different horizons of buried fluvial sediments as deep as 20 m, has proved to be

8   an important tool to identify the liquefied layers. Moreover, for the first time the sands involved

9   into the blast-test experiment are characterized by a relatively high fine-grained content

10   compared with previous blast experiences performed in cleaner sands. This has allowed a better

11   understanding of the selective processes undergone by sediments during the ejection.

12

13

14   **GEOLOGICAL SETTING**

15

16   The Po Plain represents the sedimentary filling of the Apennine foredeep, made up of a thick

17   succession of Miocene–Quaternary marine and continental deposits. Beneath the alluvial plain,

18   the fault–fold structures of the external portion of the Apenninic orogenic wedge are buried

19   (Boccaletti et al., 2004; Ghielmi et al., 2013). Buried anticlines formed mainly during the

20   Cenozoic in response to the collision between the European and the Adria plates (Ricci Lucchi,

21   1986; Argnani et al., 2006). The ongoing deformation of the buried fault–fold structures,

22   superimposed on a fast regional subsidence affecting mainly the southern portion of the foredeep

23   basin (Carminati et al, 2005) allowed a thick accumulation of fluvial sediments, primarily due to

24   the Po River and multiple Apenninic tributaries. The thickness of the sedimentary infill is highly

25   variable, from 4 km in depocenter area, close to the Apenninic mountain front, to a few hundred

1   meters in correspondence of the buried anticlines (Mariotti and Doglioni, 2000; Ghielmi et al,

2   2013).

3   The thick Quaternary successions are punctuated by several unconformities controlled by the

4   glacio-eustatic transgressive–regressive fluctuations (Amorosi et al, 2008; Garzanti et al, 2011),

5   supporting the subdivision of the succession into allostratigraphic units. The sediments discussed

6   in this research are ascribed to the last depositional cycle, referable to the upper portion of the

7   Villa Verrucchio Subsynthem (AES7) and the Ravenna Subsynthem (AES8) (Fig. 2). The two

8   units, here consisting entirely of fluvial sediments, are separated by a regional discontinuity

9   surface marked by widespread organic-rich and weakly developed paleosoils (Stefani et al.,

10   2018).

11   In the study area, the upper portion of the Villa Verrucchio Subsynthem (AES7) is dominated

12   by sands accumulated during the Last Glacial Maximum (LGM). The Ravenna Subsynthem

13   (AES8) is made up of silt, silty clay, organic-rich clay, and peats recording wide continental

14   swamps intercalated with sands and silty sands deposited into fluvial channel and levee settings

15   by various rivers. The upper portion of the AES8 is dominated by the large sand body of the

16   Reno River, flanked by its levee and by interfluvial depression deposits (Stefani et al., 2018).

17   The region is affected by significant seismic activity due to the compressional deformation of

18   fault–fold structures of the buried orogenic wedge. In May 2012, a severe seismic sequence

19   induced significant human casualties, diffuse damage of buildings, and widespread liquefaction

20   of fluvial sand and silt bodies, buried in the shallow subsurface (Caputo and Papathanasiou,

21   2012; Emergeo Working Group, 2013; Fioravante et al., 2013). An area severely affected by the

22   liquefaction phenomena has been the southwestern portion of the Ferrara Province, at San Carlo

23   and Mirabello, which is the object of this study (Fig. 1).

24

25

26   **MATERIALS AND METHODS**

1

2   **Blast Test.---**The blast technique is based on a controlled detonation of explosives aimed at

3   generating long-duration cyclic shaking of the ground and testing the *in situ* soil liquefaction

4   potential, as recent experiments in New Zealand and the United States have shown (Wentz et al.,

5   2015; Finno et al., 2016). A blast test produces accelerations whose frequencies are significantly

6   higher than the real earthquakes, but the obtained ground velocity and displacement amplitudes are

7   similar to those generated by a strong earthquake. Sequential blasts can also induce multiple shear

8   strain cycles and generate a build-up of excess pore pressure, inducing liquefaction. *In situ*

9   geotechnical monitoring, laboratory investigations, and geophysical surveys are usually coupled

10   with the detonations to optimize their effectiveness (Gohl et al., 2009; Ashford et al, 2004; Rollins

11   et al, 2004) and to evaluate variations in soil parameters before and after liquefaction. The first

12   Italian blast experiment at the target site of Mirabello (Ferrara, Italy) was performed on May 2016

13   with various purposes, including the evaluation of the source layers of the blast-ejected sands and

14   the interpretation of the blast-induced liquefaction mechanism. The controlled blasting experiment

15   induced liquefaction in the trial field site because sand boils, mixes of sand and water that reach the

16   surface and commonly form sand volcanoes (e.g. Marcuson, 1978), were observed (Amoroso et al.,

17   2017). The blast research activities (Fig. 3) included an intensive geological, geotechnical, and

18   geophysical campaign before and after the implementation of two blast sequences. Pore-pressure

19   transducers and settlement profilometers were installed in order to measure, during and after the

20   blast test, the generation and subsequent dissipation of the pore-water pressure along with the

21   vertical deformations. Based on the subsoil model and liquefaction assessment provided by

22   Amoroso et al. (2017), the blast layout was designed considering two sequences of blast charges to

23   detonate separately. Further details of the blast test are reported in Passeri et al., (2018) and Pesci et

24   al. (2018).

25

1   **Cone-Penetration Test**.---Important stratigraphic information were deduced from the

2   comparative analysis of the cone-penetration tests (CPT) performed in the surroundings of the

3   trial area (Fig. 3) for the seismic microzonation studies of Mirabello municipality (CPTuB11,

4   CPTu019, CPTu13244; Geotema, 2014) and for the blast-test experiment (CPTu1, CPTu2,

5   CPTu3; Amoroso et al., 2017). The vertical variation trends of the penetration logs supported the

6   recognition of various fluvial depositional bodies, paleosols and peat levels.

7

8   **Sampling**.---A total of 35 samples were collected and analyzed for grain size and

9   composition. Samples are representative of blast-induced liquefied sands and of sands in the

10   subsurface (Tables 1 and 2, Figs. 3 and 4). Thirteen samples come from two cores (S1 and S3)

11   located in the test site that allowed to reconstruct the stratigraphy and sand horizons from the

12   surface down to 20 m (Fig. 4, Table 1). Sampling was particularly dense in the interval between

13   5 and 8 m, considered as the most critical liquefiable layer. Two samples come from the helical

14   system that anchored the CPT truck at 2 m depth (ANC1, ANC2). Eight samples are liquefied

15   sand induced by the blast test: three are representative of boils (C1, C2, C5) collected

16   immediately after the first detonation within the 5 m-radius blast ring (Fig. 5A), and five were

17   collected during and after the blast experiment around blast monitoring equipment (instrumented

18   micropile and profilometers). Sample SB2012 is a sand boil from the 2012 Emilia earthquake in

19   the studied area (Fig. 3A). Finally, eleven samples are from dikes that crosscut the shallow

20   subsurface in 2 trenches (2.0–2.5 m deep) dug in the test site named BH15 trench (8 m long) and

21   MPA4 trench (10 m long) (Fig. 3). Table 1 and Figs 5B, C report more detail on dike depth and

22   shape. Samples are from the center of the dikes. Exploratory trenches were excavated by Istituto

23   Nazionale di Geofisica e Vulcanologia (INGV, Rome, Italy) across the 2012 sand blows,

24   approximately 5 to 12 m from the blast center. Dikes are not observed to reach the surface in the

25   trench cross section. They likely represent sands liquefied during the 2012 earthquake and

26   possibly previous events (INGV, work in progress).

1

2   **Grain-Size Analyses.---**32 samples were analyzed using standard techniques: mechanical

3   sieving for the sandy fraction and hydrometer analysis for fine-grained sediments. Sand samples

4   consisting of a few hundreds of grams were washed with dilute H_2O_2 to remove organic matter

5   and were air dried and mechanically sieved for granulometric and compositonal analyses. Grain-

6   size analyses are reported as the granulometric curve in Figure 6. Table 1 reports the fines

7   content (FC) which represents percentage of particles finer than 0.075 mm. D_{60}, $D_{30,}$ and D_{10} are

8   the diameters of the 60th , 30th, and 10th percentile of the granulometric curve. The coefficient

9   of uniformity U is given by the ratio between D_{60} and D_{10}, and the coefficient of curvature C is

10   function of D_{30}, D_{60}, and D_{10}:

11
$$C = \frac{D_{30}^{2}}{D_{10} \cdot D_{60}}$$

12   According to the Unified Soil Classification System (USCS, ASTM D2487-11 2011) the

13   sands characterized by $U > 6$ and $1 < C < 3$ are well-graded (or poorly sorted).

14   **Compositional Analyses**.--- Modal analyses were carried out on 32 samples of sands and on

15   the sandy fraction of sandy silt. Point counting under transmitted-light microscopy was

16   performed on the 0.125–0.250 mm fraction, according to the Gazzi-Dickinson method designed

17   to minimize the dependence of the analysis on the grain size (Zuffa, 1985) and to support a

18   comparison with previous compositional studies of the area (Lugli et al., 2004, 2007). Results of

19   point counting (300 grains for each section) are presented in Table 2. For textural and

20   provenance considerations we refer to studies of Weltje and Von Eynatten,(2004), Arribas and

21   Tortosa (2003), and Garzanti et al. (2011); detrital carbonate lithics were identified according to

22   Fontana (1991). Components not related to the original sand composition, such as authigenic

23   carbonate concretions, were excluded from the final calculations.

24

25   **RESULTS**

1

3

4   The shallow sedimentary succession (0–20 m) involved into the blast test was outlined by two

5   boreholes integrated with CPTu data (Fig. 4) and interpreted within the knowledge framework

6   deriving from a recent study on the geology of the area (Minarelli et al., 2016 and references

7   therein). We recognized different units from the older to the younger:

8   •   unit A, from 20.5 m to 17 m below the surface. This is the deepest unit involved in the

9   blast-test investigation, and is formed by gray, medium- to coarse-grained sands. From the

10   integration of the blast test data with evidence of regional geology, we can assume that the unit

11   represents to the upper portion of the AES7 subsynthem, and accumulated into a braided-river

12   environment mainly during the Last Glacial Maximum (LGM).

13   Sediments above unit A represent the upper portion of AES8 and show a complex

14   sedimentary architecture. They can be subdivided into three superposed units:

15   •   unit B1 (from 17 to 7.7 m). It consists of fine- to medium-grained sand intercalated with

16   poorly sorted silty sand. The lower portion, between 16 and 17 m, is coarser grained. At 13 m a

17   thin silty layer is present. Based on the detailed correlation of the CPTu and stratigraphic core

18   logs, the interval can be interpreted as a meander channel body. An organic-rich layer within the

19   unit in an adjacent area has been dated 4440 ± 40 yr BP by [14]C (Amorosi et al., 2008; Stefani et

20   al., 2018).

21   •   unit B2 (from 7.7 to 5.9 m). It is formed by fine-grained sand and silty sand, with

22   subordinated intercalations of silt and, in the lower portion, argillaceous levels. The interval can

23   be interpreted as a fluvial levee complex, laterally grading into crevasse splays probably

24   accumulated between 4000 to 3000 years ago.

25   •   unit B3 (from 5.9 to 0 m). Interfluvial depression and distal levee deposits made up of:

26   silt and clayey silt with subordinate coarser-grained sandy levels, interpretable as an interfluvial

1   depression (5.9–4.4 m); sandy silt layer with diagenetic carbonate nodules interpretable as a

2   palaeosol (4.4–4.1 m) associated with an emersion phase (Roman surface); dark-colored plastic

3   silt and clay (4.1–2.2 m) with an intercalation of organic-rich clay and peat (3.1–3.5 m) (1080 ±

4   30 yr BP by ^{14}C; Amoroso et al., 2017). Organic-rich levels are common also in the upper

5   portion of the unit, recording widespread interfluvial depression marshes; silty clay and silt (2.2–

6   0.7 m) referable to the distal portion of crevasses splays of the paleo-Reno River (post Medieval,

7   up to the 18th century); reworked materials by agricultural practises (0.7–0.0 m), containing

8   muddy sediments with brick fragments and extruded sands liquefied during the 2012 Emilia

9   earthquake.

10

11   *Grain-Size Distribution*

12

13   The analyzed samples range from almost pure sands to silt with a variable content of sand and

14   clay. Samples from cores (Fig. 6A) show a gradual increase in grain size from shallow to deepest

15   samples. In particular, samples from the upper portion (up to 6.5 m) are the finest, made up of

16   coarse silt and sandy silt with a clay content higher than 10%. Sands from 7 m to 18.5 m are

17   coarser grained and fit in a narrow field predominantly made up of fine- and medium-grained

18   sands; the amount of silt is 20 to 30%, and the percentage of clay is lower than 10%.

19   Induced liquefied sands are almost pure sands (Fig. 6B) with a very narrow range around

20   medium-grained sand. The amount of silt and clay is less than 10% (except LP2: 18%).

21   The dike samples are similar to blast-liquefied sands, but with a slightly higher percentage of

22   silt and clay (up to 24%); clay is less than 10%, except in sample S12NW (Fig.6B). Samples are

23   well sorted. We did not observe significant grain-size variation along dikes at different depths

24   (0.2 to 2.2 m; Table 1).

1   The fines content (FC, Table 1) in cores ranges between 32 and 78 % in samples from 5.9 to

2   7.7 m and is lower (28–39%) in deeper samples. A distinctly lower FC content (< 25%) is

3   recorded in the blast-induced liquefied sands (FC 5–22%) and in trench samples (FC 10–25%).

4   The coefficients of uniformity U and curvature C in samples from the boreholes show that the

5   silty sands are well-graded (i.e., they contain particles with a wide range of sizes). In contrast,

6   the blast-liquefied sands and dikes are well sorted.

7

8   *Composition of Sands*

9

10   Data from modal analyses are reported in Table 2 and in the ternary diagram Q+F

11   (quartz+feldspars), L (siliciclastic fine-grained lithics), C (carbonate lithics) of Figure 7. This

12   diagram, better than the traditional QFL, allows the compositional fields of fluvial sands in the

13   Po plain to be differentiated as discussed by Lugli et al. (2007).

14

15   **Fluvial Sands from Boreholes**.---Fluvial sandy sediments in the subsurface (sands and the

16   sandy fraction in sandy silt), both from cores S1 and S3, show varying compositions from

17   lithoarenitic to quartz-feldspar-rich (Fig. 7A). They are made up of quartz (single crystal and

18   polycrystalline) ranging from 36.6 to 55.6% of the bulk rock; the highest amounts are in the

19   deepest sands at 18.2 m. Feldspars, both plagioclase and K-feldspar, vary from 6.3 to 30.6%.

20   Siliciclastic lithic are fine-grained detrital rocks, siltstones and shales, and subordinate low-grade

21   metamorphic rocks. Lithics range from 8 to 27.7% with minor amounts in deeper sands. Shales

22   are well lithified, with an evident preferred orientation of clay minerals, and for these characters

23   they appear to have a detrital origin, derived from older pelitic successions. Volcanites, spilites,

24   and serpentinites are only minor components. Carbonate lithics range from 6.3 to 15.7% of the

25   bulk sand and are made up of micritic and sparitic limestones; spars of calcite are also included,

1   as they derive from the breakage of sparitic limestones and veins. Micas (muscovite and

2   chlorite), glauconitic grains, and Fe-oxides are minor components. Few diagenetic concretions

3   occur in some samples. Sands do not show any evidence of grain cementation, including the

4   deepest ones.

5   In the Q+F, L, C diagram (Fig. 7A), sands in the subsurface show a well-defined trend from

6   litharenitic to quartz–feldspar-rich compositions. In particular, sands at depth up to 7.7 m are, in

7   different proportion, more litharenitic, rich in fine-grained sedimentary lithics (siltstones and

8   shales) (Fig. 8A), while the deepest sands (samples from 8.5 to 18.5 m) are enriched in quartz

9   and feldspars and fit in a well defined field of arkosic composition (Figs. 8B, C).

10   *Provenance of Fluvial Sands:* based on type and abundance of lithic grains, which are mainly

11   sedimentary, both fine-grained siliciclastic and carbonate derived from the erosion of Apenninic

12   sedimentary units, shallow sands up to 7.7 m indicate a clear Apenninic provenance referable to

13   the paleo-Reno River. Deeper sands, richer in quartz and feldspars, with abundant micas and

14   very low siltstones and shales, show affinities with the Po River sands. The deepest sample of

15   sands at 18.2 m is the richest in quartz (Fig. 8C) and poorest in sedimentary lithics, and is linked

16   to the older unit A, deposited by the Po River during the Last Glacial Maximum.

17

18   **Blast-Induced Liquefied Sands**.---Liquefied sands from sand boils (Fig. 7B, 8D) are quite

19   homogeneous in composition. Total quartz ranges from 40.4 to 52.6%. Feldspars (both

20   plagioclase and K-feldspar) vary from 7 to 15.4%. Fine-grained siliciclastic lithics, made up of

21   siltstones, shales, and low-grade metamorphites, account for 15 to 25.8% of the whole sands.

22   Carbonate lithics, such as micritic and sparitic limestones, vary from 11.3 to 16.7%. Sands from

23   micropile (see Table 1) show similar compositions with more variations in quartz content.

24   Composition of liquefied sands overlap that of the shallow fluvial sands down to the depth of

25   7.7 m and clearly differ from layers deeper than 8 m, higher in quartz–feldspar content.

26

1   **Sand from Dikes in Trenches**.   The sands filling the dikes in the trenches (Fig. 7C) show

2   relatively homogeneous compositions. Total quartz ranges from 33.4 to 48%, and feldspars from

3   10.7 to 20%. Siliciclastic lithics, largely low-grade metamorphics and shales, range from 12.6 to

4   23.8%. Carbonate lithics vary from 13.9 to 19.4%. We did not observe significant variations in

5   sands from single dikes at different depths. In the Q+ F,L,C diagram, sands from dikes plot in the

6   same field as shallow sands (up to 7.7 m).

7

8

9   **DISCUSSION**

10

11   The earthquake-simulation field experiment (blast test) carried out in Quaternary fluvial

12   sediments of the Emilia plain induced subsurface liquefaction and the formation of sand blows.

13   The grain size and composition of ejected sediments were compared with subsurface data from

14   boreholes and trenches. The main findings of the study are discussed with particular concern to

15   the recognition of the source layer and grain-size segregation mechanisms during liquefaction.

16

17   *Stratigraphic Framework*

18

19   Data from two boreholes and several cone-penetration tests supported the reconstruction of a

20   detailed stratigraphic framework of fluvial sediments in which the liquefiable layers are located

21   (Fig. 9). The deepest portion of the section (unit A) consists of Po River sands deposited in the

22   Late Pleistocene into braided channels during Last Glacial Maximum and late Glacial times

23   (LGM in Fig. 9). A thick sand body, interpreted as a Po River channel fill (unit B1) is identified

24   between 8 and 17 m. This is overlain by silty sands and silts from a paleo-Reno River levee body

25   (unit B2, 5.9–7.7 m), which accumulated approximately between 4000 to 3000 years ago. The

1   uppermost portion of the studied successions is largely formed by argillaceous sediments,

2   deposited in interfluvial swamp and distal levee areas of the paleo-Reno River in Medieval and

3   modern times (unit B3).

4

5   *Source Layer Identification*

6

7   The composition of sands liquefied by the blast test poses an important constraint in the

8   recognition of the source layer. Measurements of excess pore pressures and soil deformation

9   during the blast monitoring have detected a wide liquefiable layer that extended at least from 6 to

10   12 m depth (Amoroso et al., 2017). However, only silty sands of unit B2, between 5.9 and 7.7 m

11   deep, were ejected to the surface to form sand boils, as clearly deduced by petrographic analysis

12   (Fig. 7). In fact, the composition of sands from blows shows close similarity with shallow sands

13   of unit B2 at a depth from 5.9 to 7.7 m, while it clearly differs from deeper sands, which are

14   richer in quartz and feldspar and poorer in sedimentary lithic fragments. These data indicate that

15   the ejected layer largely corresponds to the fluvial Apenninic deposits of the paleo-Reno River,

16   while the underlying sands referable to a paleochannel of the Po River (unit B1 and A) were not

17   involved.

18   Our data also show that the composition of blast-induced sand boils overlap that of dikes in

19   trenches of the blast area. As already reported by Amoroso et al. (2017), dikes are fractures

20   infilled by sands injected upward during the 2012 earthquake or older events. This indicates that

21   sand layers liquefied by seismic events are the same as induced by the blast test.

22   Results from the blast test fit well with data obtained from the study of the sands ejected in

23   the nearby area of San Carlo during the M_L 5.9 earthquake (Fontana et al., 2015). Even in this

24   case, sand composition and fabric indicate that liquefaction processes mainly affected sand

25   layers at relatively shallow depth (6.8–7.5 m) characterized by litharenitic composition, and did

26   not affect deeper sands, Holocene to Pleistocene in age, with a quartz–feldspar-rich composition.

1   In all these cases, the liquefied sands share a litharenitic composition, with abundant lithic

2   fragments of micritic limestones, shales, and siltstones, usually rounded in shape, rather than

3   sands rich in quartz and feldspars angular in shape. It is reported in the literature that the

4   presence of rounded grains is one factor that can increase the liquefaction susceptibility (Kramer,

5   1996), but very little data are available on petrography of liquefied sands and injectites (Ross et

6   al., 2014). It could be that specific compositions favor liquefaction rather than others, but further

7   studies are necessary to validate this factor.

8

9   *Grain-Size Characteristics and Liquefaction Susceptibility*

10

11   The grain-size characteristics of the examined sands are compared to data reported in the

12   literature for sands ejected during earthquakes. Several papers (Kishida, 1970; Tokimatsu and

13   Yoshimi, 1983; Figueroa et al., 1995) report that mainly clean sand with a low natural clay

14   content are susceptible to liquefaction, and report a cut-off for liquefaction susceptibility at a

15   clay content of about 10–15%. The liquefaction susceptibility of fine-grained sediments has been

16   debated over the last 20 years (e.g., Andrew and Martin, 2000; Idriss and Boulanger, 2008; Bray

17   et al., 2014; Boncio et al., 2018): fine-grained sediments were considered incapable of generating

18   the high pore pressures commonly associated with liquefaction (Kramer 1996). Only a few

19   papers (Ishihara, 1984; Chang et al, 2011) observed liquefaction of non-plastic silts, indicating

20   that plasticity characteristics rather than grain size alone influence the liquefaction susceptibility

21   of fine-grained soils. Non-plastic and cohesionless coarse silts with bulky particle shape are fully

22   susceptible to liquefaction, while finer silts with flaky or plate-like particles generally exhibit

23   sufficient cohesion to inhibit liquefaction (Ishihara 1993).

24   Since our study takes into consideration not only the characteristics of the sands that reach the

25   surface but also those of the buried source layer, the effects of particle size in the liquefaction

26   processes can be better outlined. Liquefied sands that reached the surface are well-sorted

1 medium-grained sands with silt and clay content less than 10%; they fall within the expected

2 parameters for liquefaction. However, when comparing liquefied sands with their source layer at

3 5.9–7.7 m depth (Fig. 6), we observe that "source" sands have a higher amount of fine-grained

4 particles (silt and clay > 30%; clay < 15%). This has two interesting implications.

5   Firstly, the source beds can contain higher amounts of silt than reported in many previous

6 liquefaction studies, indicating that also coarse silts and silty sands are fully susceptible to

7 liquefaction. This aspect has to be considered while estimating the liquefaction potential hazard.

8 Poorly sorted sands and finer-grained sediments are more susceptible to liquefaction phenomena

9 than previously thought.

10   Secondly, we observe that there is a selective loss of fines in the dikes and sand volcanoes

11 relative to the source beds, indicating that the liquefaction process appears to be able to select the

12 diameters of the grains that reach the ground surface. This effect is well observed in the blast-

13 induced liquefaction and in 2012 sand boil ejected in the same area (sample SB 2012, Fig. 6B)

14 and to a lesser extent in the trench dikes (yellow curves in Fig. 6B).

15

16   *Grain-Size Segregation during Liquefaction*

17

18 Studies and experiments on liquefaction and fluidization of silty sand sediments, as occurs in

19 dikes and sand volcanoes, suggest that sorting may occur within the source bed and dikes, and

20 further separation occurs as the material is extruded (e.g., Diggs, 2007; Ross et al., 2011). As

21 pore pressure builds, finer-grained material may be moved into the surrounding sediment,

22 forming an infiltration horizon and the slightly cleaner sediment can then break through this

23 infiltration horizon and be injected upwards (Ross et al., 2011). Segregation can also occur in the

24 injected dikes, with Ross et al. (2011) showing that fines can line the pipe walls as water flows

25 radially out of the pipe due to the flow velocity gradient between the pipe and the ambient

26 velocity in the surrounding sediment. This pipe-lining phenomenon has been observed elsewhere

1   (Mount, 1993, Diggs, 2007, Kazerouni et al., 2011, Ross et al., 2014). Once the fluidized flow

2   hits the surface then further segregation can occur. Ross et al. (2013) show for subaqueous sand

3   volcanoes that clay and grain size decrease with increasing distance from the vent, which they

4   interpret as a result of settling of the coarsest particles close to the vent, and preferential transport

5   of the clay within the currents. Such processes also occur in subaerial systems: Quigley et al.,

6   (2013) show silt drapes on the top of sand volcanoes between liquefaction-inducing earthquakes,

7   which they interpret as drapes from suspended sediment as ejected ground-water drained

8   following the liquefaction event. The clay, and potentially some of the finer silts, become part of

9   a pseudofluid (Di Felice, 2010; Ross et al., 2014) and travels with the fluid phase whilst the

10   larger particles are deposited from this suspension. Such fine-rich fluids can be seen in videos of

11   earthquake-induced eruptions of sand volcanoes, such as those in Christchurch, New Zealand,

12   described by Quigley et al. (2013). Pulse flows are hypothesized in dikes and sand blows in

13   liquefaction sites due to the 2012 Emilia earthquake described by Fontana et al (2015) and

14   Rodríguez-Pascua et al. (2015). The sedimentary features (inverse and normal grading, vertical

15   and concave lamination) suggest that fractures were rhythmically injected and filled by a slurry

16   of sand and mud during the compression pulses, and emptied by the rushing of the slurry back

17   down deep into the fractures during the extension peak, forming laminated structures in sand

18   volcanoes on the top of the fractures (millimeter- to centimeter-thick alternating graded laminae

19   of sand and mud).

20   In interpreting results from our study (Fig. 10), we cannot exclude differences between

21   shaking generated by the blast test versus earthquake. In fact, a blast test produces accelerations

22   whose frequencies are significantly higher than real earthquakes, but the obtained ground

23   velocity and displacement amplitudes should be similar to those generated by a strong

24   earthquake (Amoroso et al., 2017). Data from this study confirm that some sorting occurs within

25   dikes, and further sorting occurs as the material is extruded (both in blast-liquefied sands and in

26   2012 earthquake sand boil), probably following the generated excess pore-water pressure. This

1   may have caused the segregation and dispersion of the fine silt–clay content, producing highly

2   sorted sand boils. Instead it seems that the selective mechanism due to ejection of liquefied sands

3   has not influenced the sand composition (see also Fontana et al., 2015), and that disintegration or

4   erosion of the most erodible grains due to the abrasive flow of sand grains is almost negligible.

5

6   **CONCLUSIONS**

7

8   •   Study of the sands ejected during the blast test in the Mirabello area (Po plain), and

9   comparison of their texture and composition with those of buried fluvial sediments as deep as 20

10   m supported a reliable source-layers identification.

11   •   Ejected sands show a litharenitic composition that largely overlap that of the shallow

12   Apenninic sands down to the depth of 5.9–7.7 m. These sands clearly differ from deeper sands,

13   enriched in quartz and feldspars, largely referred to paleochannels of the Po River.

14   •   Similarly the sands from the dikes show a composition compatible with that of the

15   shallow sands of Apenninic affinity, suggesting that liquefied layer during the 2012 seismic

16   crisis are the same as that induced by blast test.

17   •   The study indicates that silty sands and silts characterized by relatively high fines content

18   (FC 32–76%) can also liquefy, differently from what reported in most of the literature.

19   •   The liquefaction process appears to be able to select the diameters of the grains which

20   reach the ground surface. Some sorting occurs within injected dikes, probably due to pulse flows,

21   and further segregation occurs as the material is extruded following the generated excess pore-

22   water pressure. This may have caused the dispersion of the fine silt–clay content, producing

23   highly sorted sand boils.

24   •   The study indicates that we have a significant tool for a better understanding of

25   earthquake-induced liquefaction mechanisms, using textural and petrographic parameters to

1   correlate ejected sands with their buried source beds. This is pivotal for the recognition of

2   potential areas prone to hazardous sand liquefaction phenomena.

3

4

5   **ACKNOWLEDGMENTS**

6

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1   **FIGURE CAPTIONS**

2

3   Fig. 1.---Map of the Emilia alluvial plain showing the blast test site of Mirabello. The area

4   was affected by the 2012 earthquakes (two major epicenters are located) that generated

5   numerous sand boils (red dots) (data from Emergeo Working Group, 2013; Caputo and

6   Papathanasiou, 2012). At the end of 18th century the course of the Reno River was artificially

7   forced to reach the Adriatic sea. The studied site is located just northeast of the diversion point,

8   along the buried paleochannel.

9

10   Fig. 2.---Simplified stratigraphic section of the Ferrara alluvial plain (modified from

11   Geotema, 2014). The deepest succession (AES7) is dominated by sands accumulated during the

12   Last Glacial Maximum (LGM) (late Pleistocene). The overlying successions (AES8) is made up

13   of Holocene fluvial channel and levee sands and silts alternating with silt and clay recording

14   wide continental swamps. The upper portion of the AES8 is dominated by the large sand body of

15   the Reno River flanked by its levee and interfluvial deposits

16

17   Fig. 3.---A) Location map of the trial Mirabello blast test site showing the CPTu tests and 2012

18   sand boils (modified from Amoroso et al., 2017). B) Detail of blast investigations with location

19   of blast-induced sand boils and trenches.

20

21   Fig. 4.---Stratigraphy of the two cores S1 and S2, coupled with cone-tip resistance profile. Four

22   units are distinguished: A, B1, B2, and B3. Samples examined in this work are reported along

23   the sections.

24

25   Fig 5.---A) Blast-induced sand boils (C1) after the first detonation. Sample C1 is 15 cm distant from

26   the center; the sand sheet is 7 cm thick. B) Sketch of sand dikes in the BH15 trench and location of

1   sample S2 NW (1.4 m of depth from the topographic surface). C) Detail of sand dikes (see sample

2   S2 for comparison). The width of dikes is around 5 cm

3   Fig 6.---Cumulative grain-size distributions of examined samples. A) Curves of samples from

4   cores S1 and S2 plus anchor of CPTu2 piezocone test. B) Granulometric curves of induced

5   liquefied sands (C1, C2, C3, LP1, LP2, LPS, and MPA1), of the SB2012 sand boil and of dikes.

6

7   Fig 7.--- Q+F, L, C diagram showing the composition of examined sands. A) Sands from cores.

8   B) liquefied sands from the blast test. C) Sands from dikes in trenches. Q, total quartz; F, total

9   feldspars; L, siliciclastic lithic fragments; C, carbonate lithic fragments. Numbers in core

10   samples refer to depth.

11

12   Fig. 8.---Photomicrographs of the examined sands. A) Sand from core S1 at depth of 6.2 m, with

13   abundant sedimentary lithic fragments indicating an Apenninic provenance (Reno River). B) Sand

14   from core S1 at depth of 9.4 m rich in quartz and feldspars referable to the paleo Po River. C) Sands

15   from the deepest horizon (S1 18.2) referable to the older Po River sands accumulated during the

16   Last Glacial Maximum. D) Liquefied sands from sand boil C5. Transmitted light, crossed polars. Q,

17   quartz; Qpx, polycrystalline quartz; F, feldspar; Sh, shale; St, siltstone; C, limestone; Cs, calcite

18   spar, M, micas.

19

20   Fig. 9.--- Stratigraphic scheme of the successions involved in the blast test. Source layer for

21   the ejected liquefied sands is the unit B2 at 5.7–7.7 m depth, represented by levee silty sands and

22   silts of the paleo-Reno River. Underlying sands of unit B1 were not involved in the ejection.

23

24   Fig. 10---Sketch of the stratigrahy and various potential source layers in fluvial sediments of

25   the Emilia alluvial plain, with compositional and grain-size characteristics. Selective

1 mechanisms during liquefaction, that might have caused grain-size segregation within dikes and

2 as the material is extruded, are shown. Symbols refer to Fig. 9.

3

4   Table 1.--- Granulometric properties of the analyzed samples: FC is the fines content; D_{60}, $D_{30,}$

5 and D_{10} are the diameters of the 60th, 30th, and 10th percentile of the granulometric curve; U is the

6 coefficient of uniformity; C is the coefficient of curvature.

7

8   Table 2.--- Compositional modal analyses of examined sands (r.f.: rock fragment). Composition

9 is determined based on transmitted-light spectroscopy of the 125-250 micrometer fraction.
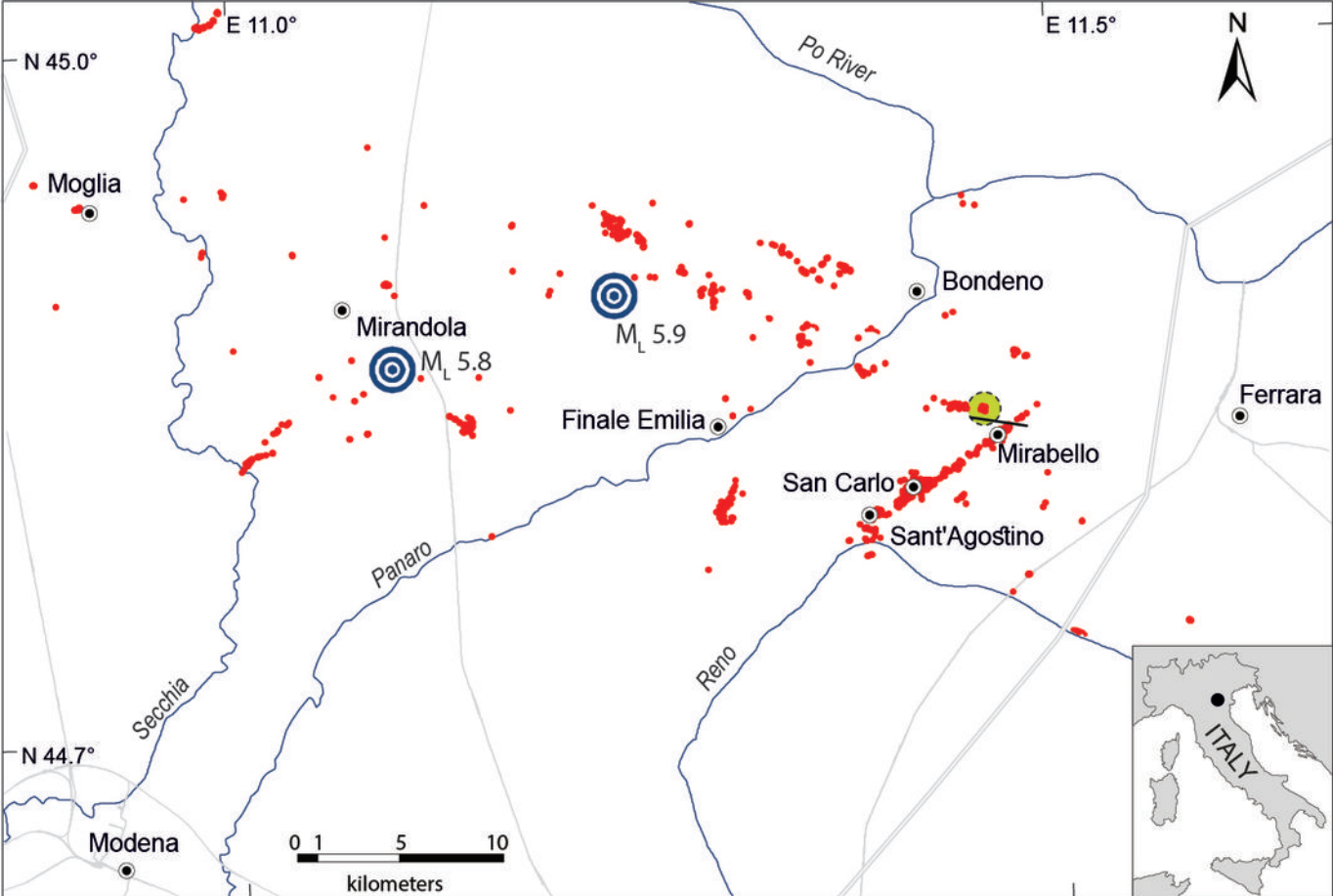
Legend:
- ⊙ urban center
- ▮ sand boils
- ◎ 2012 major earthquake epicentre
- 🟢 trial blast site
- —— Fig.2 trace of subsurface profile

Map labels: Moglia, Mirandola, M_L 5.8, M_L 5.9, Bondeno, Ferrara, Finale Emilia, San Carlo, Mirabello, Sant'Agostino, Modena, Po River, Panaro, Secchia, Reno

Coordinates: N 45.0°, N 44.7°, E 11.0°, E 11.5°

Scale: 0 1 5 10 kilometers

ITALY

| Late Holocene channel sand and silty sand | Mid and late Holocene levee silt and silty sand | Mid and late Holocene, interfluvial swamp mud | Early Holocene fluvial silt and sand | LGM fluvial sand | anthropic embankment |

A

CPTu13244

SP 468 R

N

CPTu3

CPTu2

B

CPTu1

CPTu019

Fig. 9

CPTuB11

0   150
meters

B

S3

0   10
meters

MPA4

C MPA2
C5   S1
micropile
MPA1   C2
CPTu2
BH15

C1

N

m above sea level	15	
	6	

— sand-filled cracks (2012)
– – trace of subsurface profile
● sand boils (2012)
✕ CPTu
● blast-induced sand boils (C)
▲ settlement profilometer (MP)
✳ micropile
■ borehole (S)
⬭ blast area
▭ trench

Stratigraphic Unit	Series/ Epoch	Local Unit	Borehole S1	Borehole S3	Cone resistance

Legend:

- Peat (black)
- Clay (Cl) (grey)
- Silt (Sl) (brown)
- Sand (Sn) (yellow)

^{14}C dating calibrated AD

1080±30 yr BP

A

MPA1

C1

B

BH15 TRENCH - NW WALL

1 m

1 m

S2NW

c

C

1 m
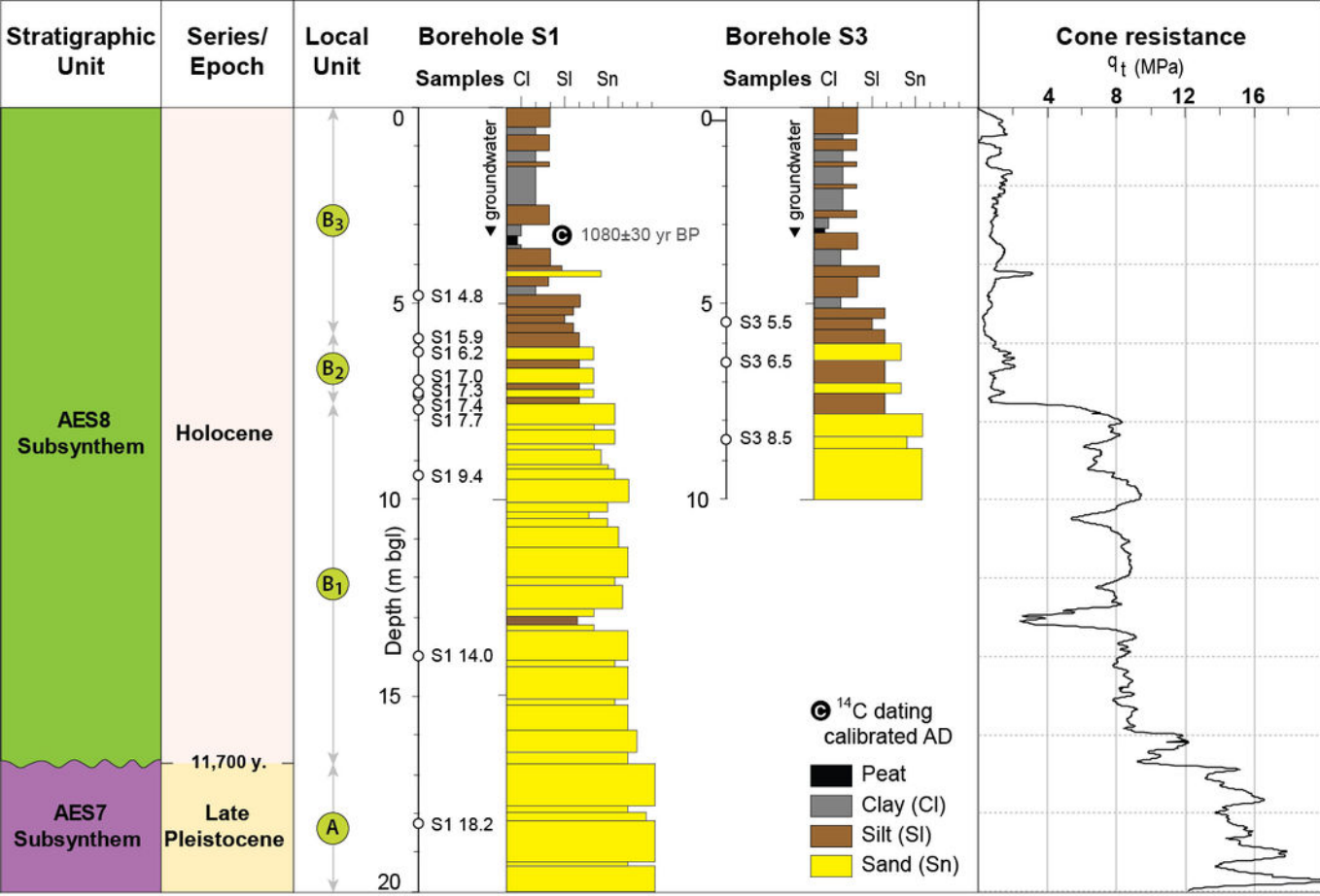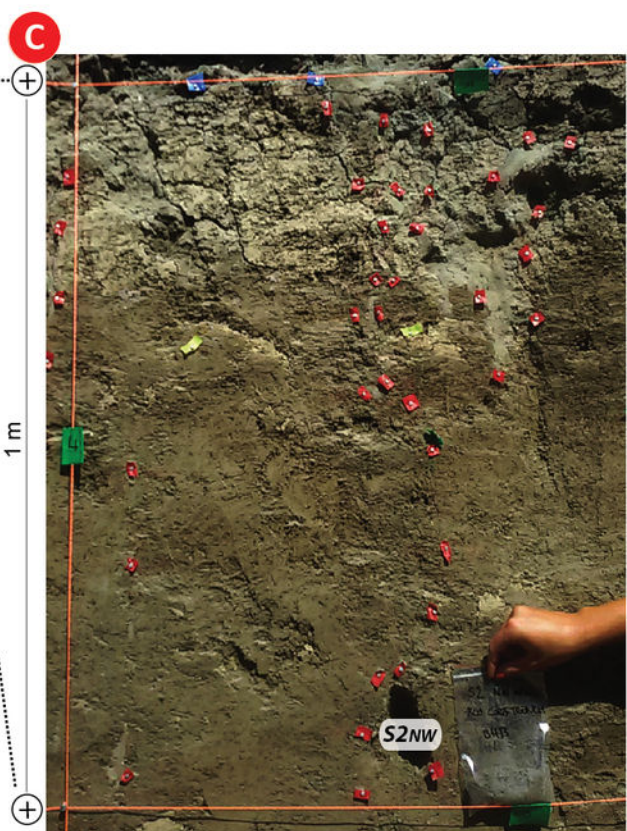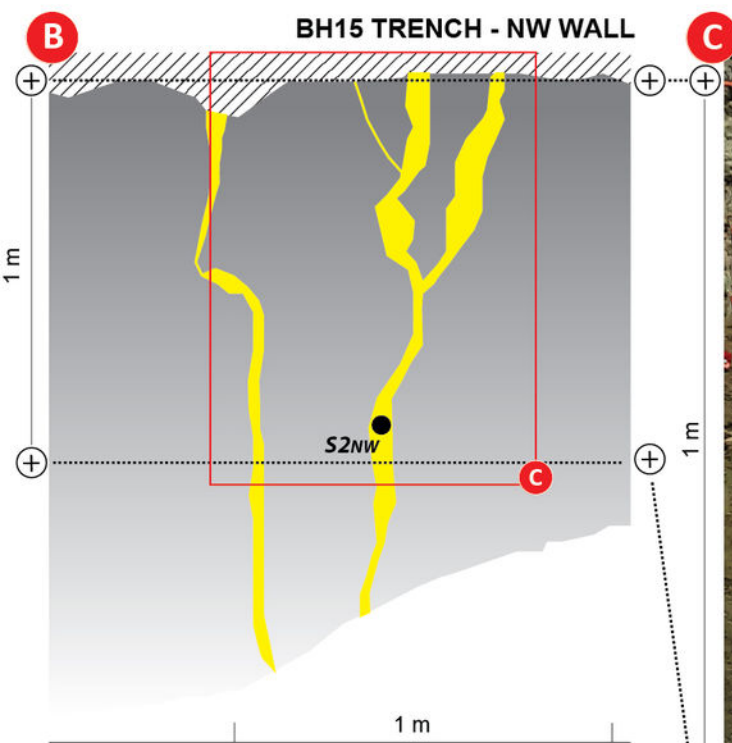
S2NW

● location of sample S2 NW

━ crack filled with sand liquefied during 2012 earthquake

▨ reworked material by agricultural practices

Figure A and B: Grain size distribution curves showing percent passing (%) versus grain size (mm) with classification zones for clay, silt, sand, and gravel (boundaries at 0.004, 0.063, and 2 mm).

Legend A:
- ANC1
- ANC2
- S1 4.8
- S1 5.9
- S1 6.2
- S1 7.0
- S1 7.3
- S1 7.4
- S1 7.7
- S1 9.4
- S1 14.0
- S1 18.2
- S3 5.5
- S3 6.5
- S3 8.5

Legend B:
- S 1B NW
- S 2 NW
- S 11 NW
- S 12 NW
- S 4 SE
- S 5 SE
- S 6 SE
- S 8 SE
- S 9 SE
- S 10 SE
- C1
- C2
- C5
- LP1
- LP2
- LPS
- MPA1
- SB 2012

A CORES
Q+F ... L
S1 14.0
S1 18.2
S1 9.4
S3 8.5
S1 7.4
S1 7.7
S1 4.8
S3 6.5
S1 7.0
ANC2
S1 6.2
ANC1
S1 5.9

B LIQUEFIED SANDS
Q+F ... L
MPA2
LP1
LP2
C5
C1
LPS
C2
MPA1

C TRENCH DIKES
Q+F ... C
S4 SE
S1B NW
S6 SE
S9 SE
S11 NW
S1A NW
S2 NW
S5 SE
S8 SE
S12 NW
S10 SE

Panel A labels: Sh, C, C, C, Sh, F, St; scale bar 0,2 mm

Panel B labels: Qpx, Q, Cs, Lm, Q, M; scale bar 0,2 mm

Panel C labels: Q, Cs, F, Q, F; scale bar 0,2 mm

Panel D labels: Sh, F, St, Cs, Cs, Q, C, St; scale bar 0,2 mm

(A)	Po River braided channel	(B₁) Po River meander channel	(B₂) Reno River levee

highly sorted
litharenitic sand boils

dispersion of fines
drained by ejected
groundwater

clay swamp

silty sand levee
laterally confined
litharenitic

segregation of
fines in dikes
due to pulse flows

source bed identified
by sand composition

thick channel-fill sands
quartz-feldspar rich

0 m

20 m

B_3

B_2

B_1

A

Samples	Description	FC (%)	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	U	C
Anc 1	Anchor of CPTu2 piezocone test	80.75	0.0081	0.0014	-	-	-
Anc 2	Anchor of CPTu2 piezocone test	91.67	0.0047	-	-	-	-
S1 4.8	Borehole S1 4.8-4.9 m	71.52	0.0378	0.0040	-	-	-
S1 5.9	Borehole S1 5.9-6.1 m	77.81	0.0473	0.0161	0.0013	36.6	4.2
S1 6.2	Borehole S1 6.2-6.3 m	61.40	0.0724	0.0248	0.0021	34.6	4.1
S1 7.0	Borehole S1 7.0-7.3 m	41.62	0.1325	-	-	-	-
S1 7.3	Borehole S1 7.3-7.4 m	32.24	0.2008	-	-	-	-
S1 7.4	Borehole S1 7.4-7.5 m	39.99	0.1570	0.0447	0.0047	33.1	2.7
S1 7.7	Borehole S1 7.7-7.8 m	39.80	0.1552	0.0434	0.0046	33.4	2.6
S1 9.4	Borehole S1 9.4-9.5 m	28.52	0.2178	0.0843	0.0066	33.1	5.0
S1 14.0	Borehole S1 14.0-14.1 m	36.05	0.2141	0.0420	0.0040	53.2	2.0
S1 18.2	Borehole S1 18.2-18.3 m	28.12	0.2868	0.0890	0.0068	42.1	4.1
S3 5.5	Borehole S3 5.5-5.6 m	96.20	0.0206	0.0073	-	-	-
S3 6.5	Borehole S3 6.5-6.6 m	75.59	0.0388	0.0099	-	-	-
S3 8.5	Borehole S3 8.5-8.6 m	39.80	0.1921	0.0268	0.0021	93.4	1.8
S 1B NW	BH15 trench 0.2 m	10.15	0.2726	0.1574	0.0743	3.7	1.2
S 2 NW	BH15 trench 1.4 m	25.26	0.2059	0.1245	0.0047	43.4	15.8
S 4 SE	BH15 trench 0.2 m	14.37	0.2543	0.1534	0.0306	8.3	3.0
S 5 SE	BH15 trench 1.3 m	19.73	0.2489	0.1410	0.0339	7.3	2.4
S 6 SE	BH15 trench 0.5 m	15.29	0.2922	0.1636	0.0201	14.6	4.6
S 8 SE	MPA4 trench 0.3 m	23.62	0.2028	0.1027	0.0060	33.9	8.7
S 9 SE	MPA4 trench 0.6 m	21.40	0.2105	0.1169	0.0059	35.7	11.0
S 10 SE	MPA4 trench 1.6 m	24.71	0.1965	0.1011	0.0068	28.7	7.6
S 11 NW	MPA4 trench 2.2 m	19.76	0.3029	0.1557	0.0057	53.4	14.1
S 12 NW	MPA4 trench 2.0 m	22.22	0.3118	0.1493	0.0028	113.1	25.9
C1	Blast sand boil	7.13	0.3271	0.1998	0.1058	3.1	1.2
C2	Blast sand boil	6.89	0.3051	0.1870	0.1085	2.8	1.1
C5	Blast sand boil	11.70	0.3643	0.2294	0.0320	11.4	4.5
LP1	Micropile sand boil	4.61	0.3292	0.2066	0.1313	2.5	1.0
LP2	Micropile sand boil	22.54	0.1803	0.0963	0.0399	4.5	1.3
LPS	Micropile trench	10.70	0.2477	0.1560	0.0710	3.5	1.4
MPA1	MPA1 profilometer trench	11.43	0.3490	0.2097	0.0523	6.7	2.4
SB 2012	2012 Sand boil	7.30	0.250	0.175	0.095	1.4	0.7

	SAMPLES	ANC 1	ANC 2	S1 4.8	S1 5.9	S1 6.2	S1 7.0	S1 7.4	S1 7.7	S1 9.4	S1 14.0	S1 18.2	S3 6.5	S3 8.5	S1A NW	S1B NW	S2 NW	S11 NW	S12 NW	S4 SE	S5 SE	S6 SE	S8 SE	S9 SE	S10 SE	C1	C2	C5	LP1	LP2	LPS	MPA1	MPA2
Q	Quartz (single crystal)	25.3	29.0	41.3	32.0	43.3	38.7	27.7	39.3	33.0	26.0	41.3	32.7	37.0	33.3	38.0	34.0	35.3	35.7	37.1	37.3	40.3	34.0	42.7	29.7	25.7	30.7	40.0	32.7	37.9	32.0	31.7	36.7
	Quartz (coarse-grained polycrystalline)	8.0	12.3	4.7	5.7	2.0	6.0	14.0	5.0	9.7	10.0	9.3	7.0	12.0	7.0	3.3	5.0	6.0	3.3	7.7	5.0	4.7	5.7	4.3	2.7	11.0	10.0	8.3	8.0	4.3	6.3	4.3	17.0
	Quartz (fine-grained polycrystalline)	-	2.0	1.0	0.3	-	-	2.0	-	4.0	5.7	3.7	1.0	2.0	-	-	0.3	-	-	-	-	-	-	-	-	-	2.0	3.0	1.0	0.3	1.2	-	-
	Quartz in plutonic/gneissic rock fragment	3.3	1.7	1.3	-	-	1.7	2.3	1.0	4.7	2.3	1.3	-	3.7	2.3	1.0	1.3	2.3	0.3	1.3	1.0	2.3	1.3	1.0	1.0	1.7	2.3	3.3	3.3	1.9	1.3	0.3	6.7
F	K-feldspar (single crystal)	8.3	5.7	10.0	6.7	3.0	5.3	5.3	13.0	6.7	9.7	3.7	1.7	6.3	9.0	9.3	6.7	9.3	7.3	7.4	5.3	8.3	6.3	5.0	8.7	8.7	4.0	3.0	7.7	10.6	9.3	6.3	3.0
	K-fedspar in plutonic/gneissic r.f.	-	-	-	-	-	-	0.3	-	-	0.3	0.3	-	-	-	-	0.3	-	-	-	-	-	-	-	-	0.3	-	0.3	-	-	-	-	0.3
	Plagioclase	7.3	7.0	2.7	3.7	3.3	6.7	11.7	5.3	12.3	20.3	12.3	5.3	8.7	8.3	10.7	8.3	6.3	8.0	7.4	8.3	4.7	9.0	5.7	10.7	6.7	4.0	3.7	8.0	4.0	6.7	6.7	5.0
	Plagioclase in plutonic/gneissic r.f.	1.0	0.3	-	-	-	0.3	-	-	0.7	0.3	-	-	-	0.3	-	2.0	-	-	-	-	-	0.3	-	0.3	-	-	-	-	-	-	0.3	-
L	Low-grade metamorphic r.f.	9.3	9.3	9.0	4.7	8.0	9.0	5.3	2.7	5.0	3.3	2.3	13.7	3.3	4.0	3.3	7.3	9.3	9.0	6.8	3.7	5.3	8.0	7.3	13.7	10.3	14.7	4.0	9.7	9.6	9.7	16.3	5.0
	Volcanic r.f.	0.3	1.7	1.0	0.3	-	-	-	-	0.3	-	0.7	2.0	3.0	0.7	0.3	2.0	3.7	3.0	2.6	1.3	1.7	0.3	-	0.7	0.7	0.7	2.7	-	0.9	-	1.3	-
	Serpentinite	0.7	-	-	-	-	-	1.0	-	-	1.0	-	-	-	-	-	-	-	-	-	-	-	-	0.7	-	-	-	-	-	-	-	-	-
	Shale	12.7	7.7	13.7	16.0	13.7	8.0	6.7	9.0	3.0	4.7	2.7	3.7	4.3	10.0	8.0	11.3	6.3	6.7	4.2	13.7	10.7	11.3	7.3	7.7	13.0	7.0	7.3	4.7	5.9	7.0	10.0	8.3
	Siltstone	1.3	0.7	3.3	3.0	1.0	2.0	0.7	4.0	-	0.3	2.3	-	1.0	2.7	1.0	1.0	1.3	1.0	2.3	0.7	1.3	2.0	1.3	1.7	-	2.7	1.0	2.0	2.8	6.3	3.0	2.3
	Micas and chlorites	6.0	1.7	3.7	13.7	11.3	3.0	7.3	3.7	4.7	4.0	2.7	19.3	4.0	2.7	3.0	2.3	2.7	3.3	3.9	5.3	5.0	3.7	4.0	4.0	4.0	4.0	4.3	3.7	3.7	2.0	4.3	3.0
	Micas and chlorites in r.f.	-	0.3	-	-	-	0.3	-	-	0.3	0.3	1.3	2.0	-	-	0.3	0.7	0.3	-	0.3	-	-	0.3	-	-	1.0	-	0.7	0.3	-	-	-	0.3
	Heavy mineral	0.7	1.3	1.3	1.0	0.7	2.0	0.3	0.7	0.7	1.0	1.0	0.3	-	2.3	1.3	1.7	2.0	0.3	2.2	-	-	1.0	1.3	-	1.0	0.7	1.3	3.0	0.6	2.3	1.0	-
C	Calcite (single spar)	8.3	9.0	6.0	6.7	9.3	8.3	6.7	12.7	6.7	6.3	9.0	6.7	6.7	9.3	14.7	9.3	9.3	12.7	11.0	10.3	10.0	8.7	9.3	10.3	7.7	7.7	9.7	10.0	8.1	9.3	7.3	7.0
	Sparitic limestone	2.7	1.7	-	1.7	-	2.0	3.3	1.7	2.7	1.0	1.3	0.3	5.7	5.7	1.3	3.3	3.3	3.3	2.9	2.7	4.0	3.3	4.7	4.7	3.3	2.7	4.7	4.3	3.4	3.7	4.7	0.7
	Micritic limestone	2.7	2.0	0.3	2.7	2.3	4.0	4.7	1.3	4.7	2.7	4.3	2.0	0.7	1.3	2.7	1.7	1.3	3.3	1.9	2.3	-	2.3	2.3	2.7	-	3.3	2.0	0.7	2.2	1.3	1.3	2.7
	Bioclast (clastic)	-	1.7	-	-	-	-	0.3	-	-	-	-	-	-	-	0.7	0.3	-	-	-	0.3	-	-	-	-	0.3	1.0	0.3	-	0.3	0.7	-	0.3
	Glauconitic grain	0.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Carbonate concretion (diagenetic)	0.3	0.3	-	1.7	1.3	2.0	-	0.3	0.3	-	-	1.3	1.0	1.0	-	0.3	0.3	1.0	-	1.7	0.7	0.7	1.7	1.0	2.0	0.7	1.3	1.0	1.6	1.3	1.3	1.7
	Iron oxides	1.3	4.3	-	-	-	-	-	-	-	-	-	0.3	-	-	-	1.0	-	-	0.6	-	-	0.7	1.0	0.3	-	-	-	-	-	-	-	-
	Undetermined grain	-	0.7	0.7	0.3	0.7	0.7	0.3	0.3	0.7	0.7	0.3	0.7	0.7	-	1.0	-	0.3	1.7	0.4	1.0	1.0	0.7	1.0	0.3	1.0	0.3	1.0	0.7	0.9	0.3	-	-
		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0