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CASE STUDY OF LIQUEFACTION SUSCEPTIBILITY FROM FIELD PERFORMANCE OF HYDRAULIC FILLS

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ABSTRACT

A region in Mihama-ward, Chiba, Japan was developed using hydraulic fill techniques during the 1960s. Soil types vary from plastic clays to nearly clean sands reflecting the depositional environment related to the hydraulic fill discharge process. Clays are soft and sands have low relative density; groundwater throughout the area is relatively shallow (< 2 m). During the M9.0 Tohoku-Oki earthquake, the area was subjected to shaking of modest amplitude and long duration (peak horizontal accelerations of 0.2g to 0.35g and 100-180 sec, respectively). Post-earthquake observations show highly variable field performance, from non-ground failure to massive liquefaction. The intensity of shaking was clearly sufficient to trigger liquefaction of loose sandy materials. Hence, the key factor distinguishing the variable field performance in the region is liquefaction susceptibility. In this study, we describe this case history based on the information available to date focusing on (1) hydraulic fill placement operations, (2) results of post-event reconnaissance, (3) ground motions from the M9.0 Tohoku-Oki earthquake, and (4) results of geotechnical site characterization relevant to liquefaction susceptibility assessment.

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Introduction

Liquefaction evaluation assessments are commonly performed using a three-stage approach that involves the following distinct steps [1]: (1) susceptibility (is liquefaction given the soil type and ground water elevation?); (2) triggering (what is the likelihood of liquefaction occurring given a certain level of demand and the soil's resistance to triggering?); and (3) consequences (i.e. post-liquefaction shear strength, volume change, permanent shear deformation). Susceptibility analysis often represents a pivotal step in the liquefaction risk assessment process for soils with high fines

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content. We present in this paper a case study that is of exceptional value in its ability to discern conditions giving rise to liquefaction susceptibility.

The subject case study pertains to the Mihama-ward district of the city of Chiba, Japan. The whole ward was developed using hydraulic fill techniques from the 1960s to mid-1980s [2]. Soil types in this region vary from plastic clays to nearly clean sands reflecting the depositional environment related to the hydraulic fill discharge process and configuration. In this area, clays are soft, sands have a relatively low relative density, and the ground water table is shallow. During the 2011 **M**9.0 Tohoku-Oki earthquake, this region experienced ground motions characterized by relatively large amplitudes (~0.3g) and long durations (~ 120 sec) [2, 3]. Post-earthquake observations show highly variable field performance, from non-ground failure to massive liquefaction [2]. The intensity of shaking was clearly sufficient to trigger liquefaction of loose sandy materials. Hence, the key factor distinguishing the variable field performance in the region is the susceptibility of the hydraulic fill materials.

In this paper we describe this important case history given information available to date. We present (1) hydraulic fill placement operations, (2) post-event reconnaissance in the region, (3) ground motions in Mihama Ward from the **M**9.0 Tohoku-Oki earthquake, and (3) geotechnical site characterization in the region, with an emphasis on information relevant to susceptibility assessment procedures.

Procedures for Analysis of Liquefaction Susceptibility

The selection of appropriate engineering procedures to evaluate the potential for ground failure and soil strength loss in saturated soils, depends on the presence and distribution of soil types for which high pore pressures can be generated by cyclic loading (approaching 100% of the initial vertical effective stress, or $r_u = 1.0$, from cyclic loading) within the deposit. Also known as initial liquefaction [4], this type of behavior is traditionally associated with clean sands, but can also occur in non-plastic (or very low plasticity) fine-grained soils. In contrast, fine-grained soils with significant plasticity behave in a fundamentally different manner, with limited potential for pore pressure generation and strength loss (e.g., Boulanger and Idriss [5], Chu et al. [6]). Distinguishing between these two types of soil behavior is referred to as a susceptibility analysis, and is the first step in an analysis of liquefaction risk.

The first modern study on liquefaction susceptibility was performed by Wang [7, 8] in China, following the **M**7.0 1975 Haicheng and the **M**7.5 1976 Tangshan earthquakes. Wang [7, 8] observed that clays with less than 15–20% particles by weight smaller than 0.005 mm and having a water content to liquid limit (w_c/LL) ratio larger than 0.9 are susceptible to liquefaction. Based on data from Wang [4, 5], Seed and Idriss [9] concluded that a clay is susceptible to liquefaction if all of the following conditions are met: (1) percent of particles less than 0.005 mm < 15%, (2) LL < 35, and (3) w/LL > 0.9. These criteria, commonly referred to as *Chinese Criteria*, became the standard for liquefaction susceptibility screening procedures in the 1980s.

Some criticism on the use of the Chinese Criteria was advanced by Koester [10], who noticed that the evaluation of LL in Chinese (i.e. using the fall cone device) and US practices (i.e. using the Casagrande cup) were different and thus led to different LL values for the same material. As a result, Koester proposed modifications to the Chinese Criteria when LL is determined using the Casagrande cup. Based on a larger database of case histories, Andrews and Martin [11] proposed modifications to the Chinese Criteria, while subsequent studies [e.g. 12-15] introduced the plasticity index (PI) as an additional parameter to assess liquefaction susceptibility. The consensus document published by Youd et al. [16] adopted the Chinese Criteria, along with additional considerations based on *in-situ* tests to assess liquefaction susceptibility. In particular, Youd et al. [16], suggest to use the soil behavior type (I_c) from cone penetration test (CPT), to distinguish between clayey soil (non-susceptible to liquefaction; $I_c > 2.6$) and granular soil (susceptible to liquefaction; $I_c < 2.6$).

Following significant occurrences of liquefaction, ground failure, and non-ground failure in fine-grained soils from 1999 earthquakes in Taiwan and Turkey [17, 18], a number of studies recommended to discontinue use of the Chinese Criteria (and similar approaches) for liquefaction susceptibility analysis [18-22]. Bray and Sancio (hereafter BS) [21] and Boulanger and Idriss (hereafter BI) [22] recommend the evaluation of liquefaction susceptibility based on laboratory testing, in which they distinguish between *clay-like* (BI) or *not susceptible* (BS) soils and *sand-like* or *susceptible* materials. The BS criteria define materials susceptible to liquefaction if PI < 12 and w/LL > 0.85, while BI consider a material sand-like (i.e. susceptible to liquefaction) if PI < 7 (i.e. the below the A-line in the Atterberg limits chart). A comparison between the two criteria is shown in Figure 1. The analysis of Figure 1 suggests significant differences between the BS and BI criteria. These differences lead to practical difficulties in many cases [23]. Some critical differences in the text protocols may also contribute to the differences. Chu et al. [24] found neither method to be particularly effective for analysis of case histories from alluvial sites subjected to strong shaking during the 1999 Chi-Chi Taiwan earthquake. That study showed that more advanced testing could lead to more accurate susceptibility assessments.

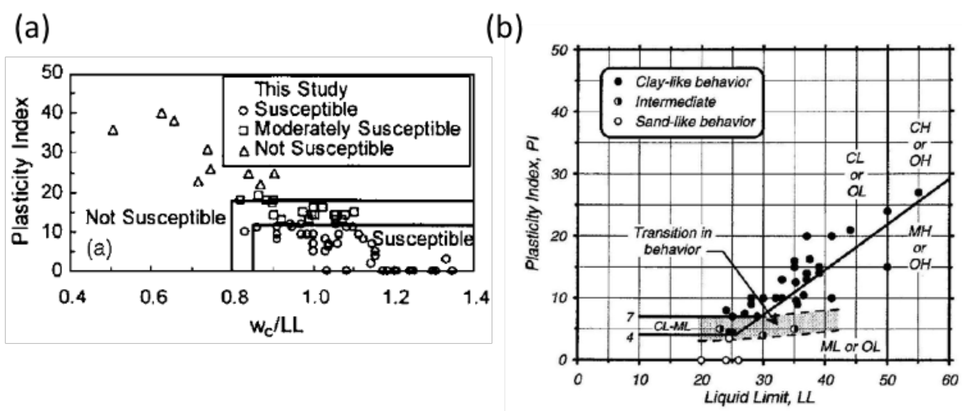

Figure 1. Susceptibility criteria by (a) Bray and Sancio (BS) [21], and (b) Boulanger and Idriss (BI) [22].

Mihama-ward Reclamation History and Field Performance during 2011 Tohoku Earthquake

From the 1960s to the mid-1980s, Mihama-ward was reclaimed by discharging dredged soil from the Tokyo Bay sea bed using soil discharging pipes (Figure 2a). The source material from the sea bed consists of sand and sandy, clayey silt. Presumably, these different material types were roughly evenly mixed in the pumping and transport process, but some segregation occurred following discharge. Basic principles of sedimentation suggest that clean sand or soil with low fines content are deposited near the outlets of the pipes, whereas soils with high fines content are transported away from the outlets and will tend to accumulate in areas between pipes. Figure 2b shows aerial photographs from the time of reclamation in 1972 [3], including the locations of discharge pipes.

Sand boils occurred near the pipes, but not in intermediate areas.

After the **M**9 Tohoku-Oki event on March 11, 2011, a reconnaissance team from Chiba University inspected the Mihama-ward from 12-20 March 2011 [2]. They targeted all accessible public roads and parks and mapped locations of sand boils. Based on the diameter of the boil overflow area, they classified the sand boiling as 3 levels; heavy (diameter > 1 m), minor (diameter < 1 m), and none (no soil boiling). Figure 3b shows the distribution of sand boiling levels in 100 m square grids. Most portions of the ward were inspected, so this reconnaissance documents locations of ground failure and non-ground failure in a comprehensive manner. White grids indicate areas that were not inspected.

Nakai and Sekiguchi [3] created a PGA distribution map in Mihama-ward as shown in Figure 3a using the procedure following:

1. Construct shear-wave velocity profile models for 7439 meshes with the size of 50×50 m in Mihama-ward interpolating soil layers from 540 borings.
2. Perform deconvolution for the recording in the Masago station and get the motion equivalent to the bed-rock condition.
3. Perform 1-D equivalent site response analysis for all meshes using the motion from (2).

The range of PGA is 0.2-0.35g, which is strong enough to trigger liquefaction in this soft reclaimed soil if susceptible. Most of SPT blow counts are less than 10 except the unsaturated crust (< 3 m depth).

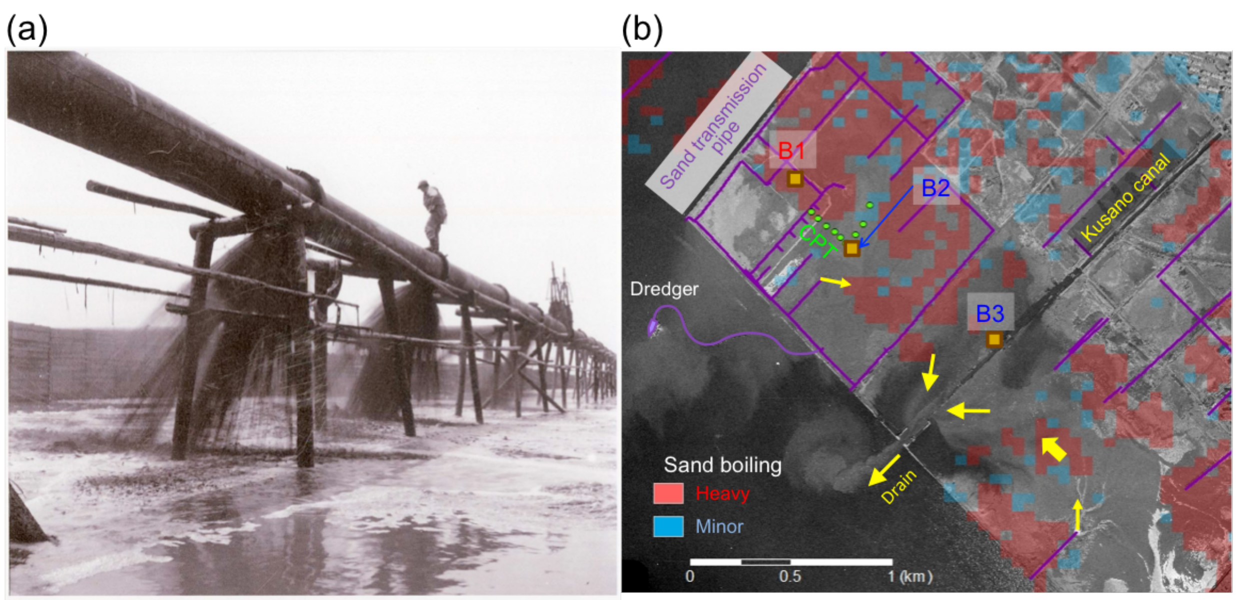

Figure 2. (a) Reclamation process for Mihama-ward during 1970s [3]; (b) Aerial photo in Mihama-ward at the time of reclamation with location of soil discharging pipe [3].

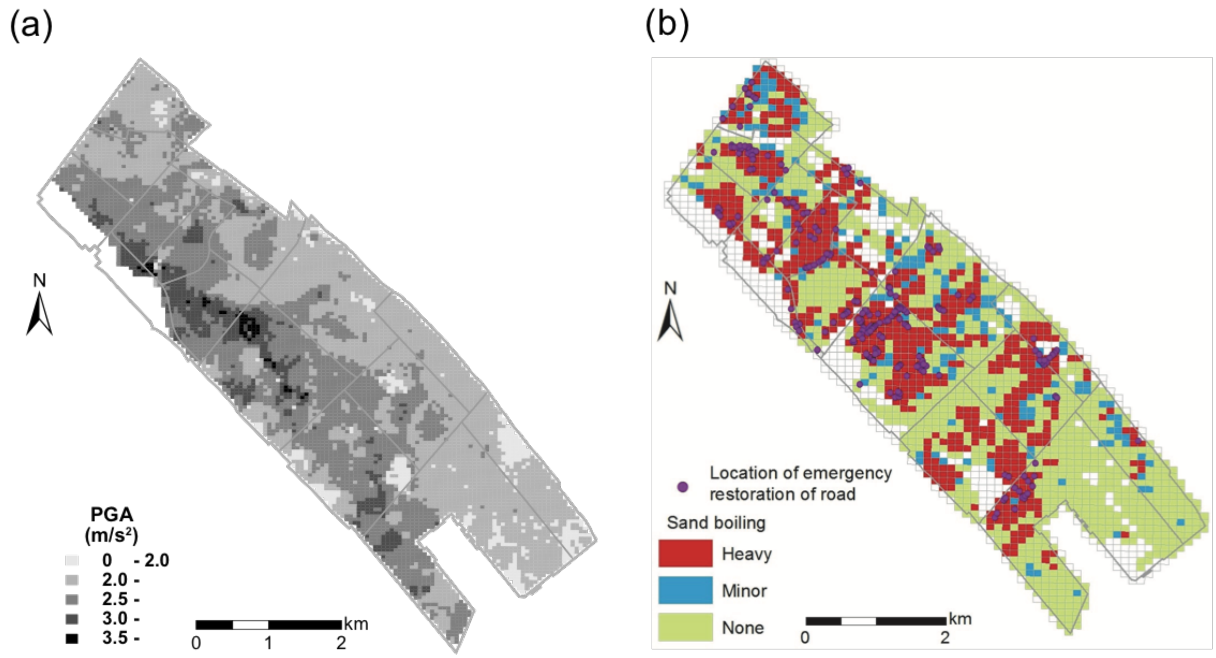

Figure 3. (a) PGA distribution in Mihama-ward during the **M**9 Tohoku event [3]; (b) Liquefaction performance map in Mihama-ward [2].

Geotechnical Site Characterization

Field Investigations in Mihama-ward

Hundreds of boreholes have been performed and are publically available in Mihama Ward. However, most of these boreholes include only stratigraphic logs and penetration resistance values, and lack laboratory data to establish soil type. The limited field investigations that include laboratory test data can be summarized as follows:

- By Chiba Prefecture: There are 10 borings with Standard Penetration Tests (SPT) performed by Chiba Prefecture as part of a liquefaction evaluation project following the 2011 **M**9 Tohoku-Oki event [25]. All 10 locations have index test results, and consolidated-drained and cyclic tri-axial testing was performed for one location on sandy soil layers.
- By Chiba City: As part of a liquefaction mitigation project for Mihama-ward, Chiba City performed borings with SPTs for 64 locations in 2012 [26]. All locations include index test results for all SPT samples. Specimens from 13 boreholes were subjected to one-dimensional consolidation and uniaxial compression testing, and one specimen was subjected to tri-axial testing.
- By Chiba University and UCLA: Chiba University performed 9 Cone Penetration Test (CPT) soundings and one borehole with SPT in a district with variable liquefaction performance [2]. To enhance this data set, we selected three locations for which tube sampling was performed in critical layers (described in next section), which was followed by index, consolidation, and undrained strength testing.
- By PWRI: Five borings with SPTs were performed in 2005-2013, the results of which were provided by Public Works Research Institute through Geo-Station (National database for

geotechnical data: http://www.geo-stn.bosai.go.jp). Among those five boreholes, two locations have samples for which index tests and consolidation test results are available.

Although there is no laboratory test data, there is one K-NET station in Mihama-ward (K-NET code: CHB024), for which a borehole with SPT was performed and the data is available. Table 1 describes attributes of sites for which subsurface data is available. Standard penetration testing is generally performed without energy measurement. For reclaimed layers, soil materials vary from soft clay to clean sand, and the cumulative thickness of fill materials is 3-10 m depending on the distance to the original shoreline. There are three levels of laboratory tests; 1) Index: only index tests (e.g., unit weight, gradation, water content, Atterberg limit) are available; 2) Index+: 1-D consolidation or uniaxial compression tests are available in addition to Index; 3) Index++: Advanced tests (e.g., tri-axial test or resonant column test) are available in addition to Index+. Figure 4 shows the locations of all boreholes and CPTs in the Mihama-ward area.

Table 1. Statistics of field investigations in Mihama-ward

Type	All	No test	Index*	Index+**	Index++***
SPT	81	5	59	15	2
CPT	9	6	0	0	3
Total	90	11	59	15	5

* Unit weight, gradation, water content, or Atterberg limit tests are available;
** 1-D consolidation or compression tests are available in addition to Index;
*** Tri-axial or simple shear tests are available in addition to Index+.

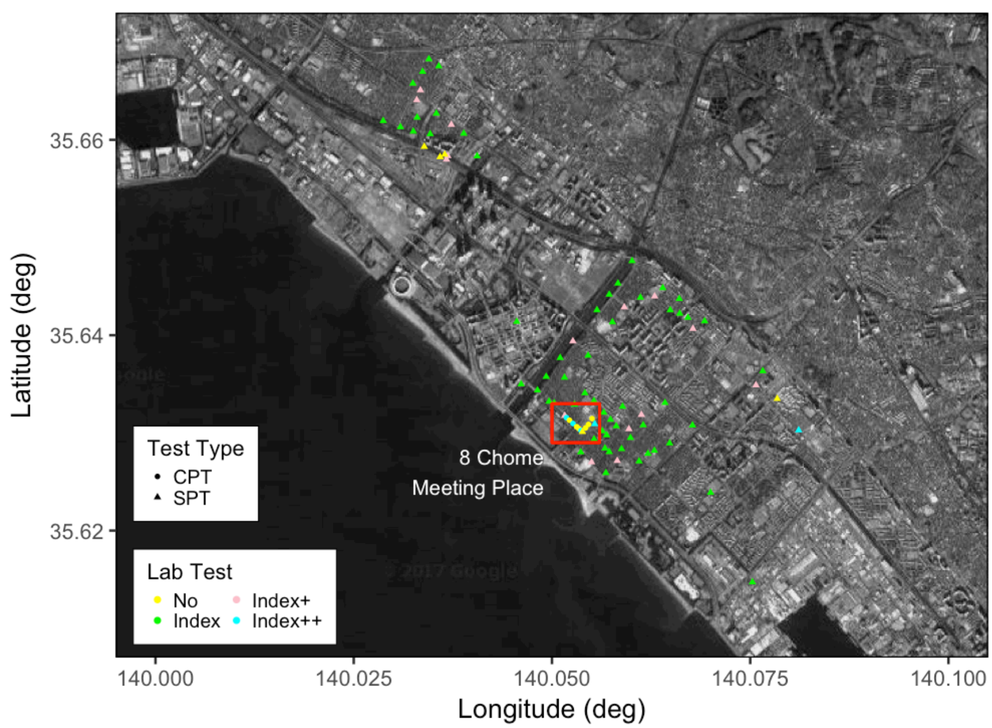

Figure 4. Map of available boreholes and CPT soundings for Mihama-ward. Test type is distinguished by shape, the availability of lab test is distinguished by colors.

8 Chome Meeting Place Site

The site '8 Chome Meeting Place' was selected for detailed field investigations for reasons of variable surface manifestation and site accessibility for subsurface exploration. Figure 5 shows the layout of the soil discharging pipe, areas with liquefaction manifestation (sand boils), and locations of field investigation (borings with SPTs and CPTs). Areas near soil discharging pipe tend to have sediment boiling, whereas areas away from the pipes tend to have no observed ground failure. In 2011, Chiba University performed 9 CPTs and 1 boring with SPTs in an L-shaped pattern that spans from areas with heavy liquefaction to no ground failure (Figure 5). Figure 6 shows a cross-section of the site that illustrates the soil layering. Subsequently, the first and last author selected three locations having heavy (CPT1), marginal (CPT3), and no liquefaction manifestation (CPT6) for further investigation involving boreholes with tube sampling. The intention is to perform laboratory testing on the soil samples, including index, consolidation, and consolidated-undrained tri-axial tests. Sample locations were selected based on CPT results, targeting layers considered critical for liquefaction potential.

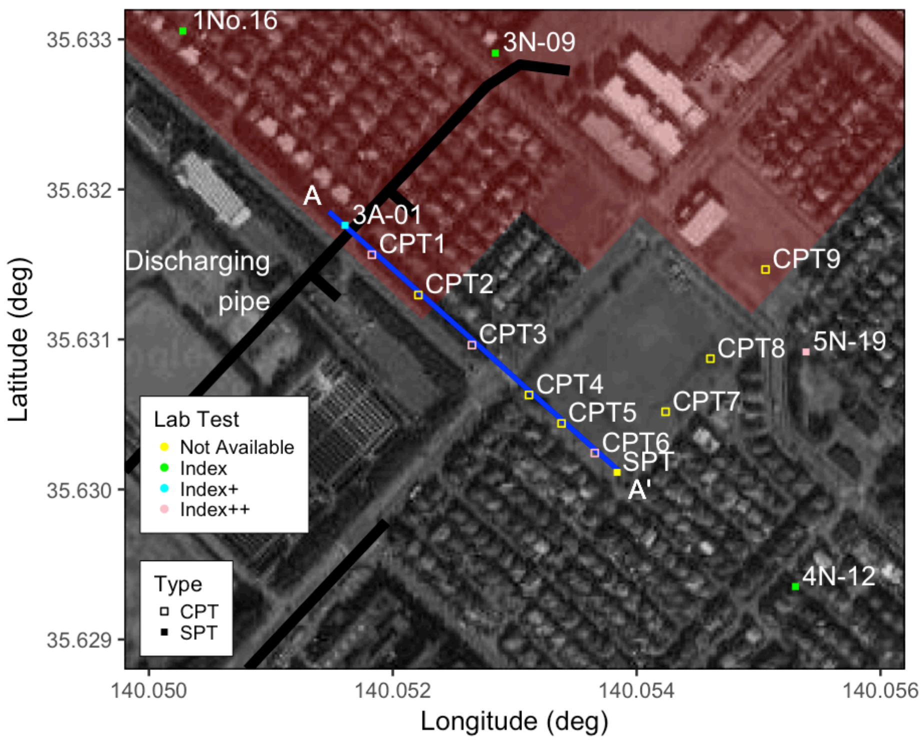

Figure 5. Plan view of 8 Chome Meeting Place site. Soil discharging pipe and area with sand boil (red shade) are shown [2].

Table 2 shows the index test results, and Figure 7 shows consolidation test results for each specimen from the samples. Note that TX01 is the location with heavy soil boiling, TX02 is marginal, and TX03 is the location with no ground failure. For TX01, specimen 1-1-1, 1-1-2, and 1-3 have fines content (FC) lower than 7% indicating that these layers are likely susceptible to liquefaction. Specimen 1-2 has a marginal FC whereby the fines fraction may or may not control the mechanical soil behavior. The consolidation curve for 1-2 (Figure 7a) is similar to that for 1-1-2. Hence, we anticipate that the mechanical behavior of this material is likely controlled by the coarse fraction, which in turn suggests sand-like behavior.

Table 2. Laboratory test results for 8 Chome Meeting Place site.

Location	Specimen Name	Depth (m)	ρ_s (g/cm^3)	w_c (%)	FC (%)	LL	PL
TX01	1-1-1	3.75-3.78	2.656		5.3		
	1-1-2	4.00-4.03	2.713		6.7		
	1-2	5.38-5.41	2.713		28.4		
	1-3	7.24-7.27	2.687		4.7		
TX02	3-1-1	3.27-3.30	2.646		42.4		
	3-1-2	4.07-4.10	2.680		1		
	3-2	4.33-4.36	2.695		6		
	3-3	5.13-5.16	2.697		7.7		
TX03	6-1	4.18-4.22	2.654	85.1	97.9	75.5	30.3

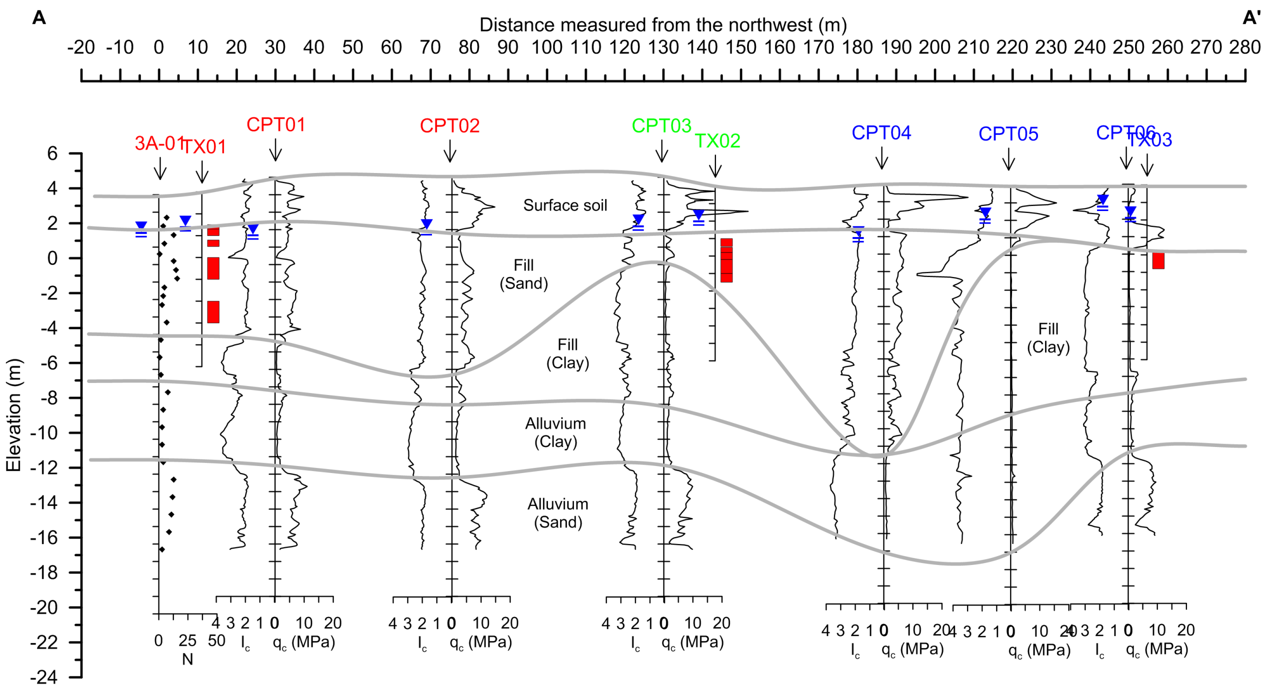

Figure 6. Cross sectional view of 8 Chome Meeting Place site (AA' in Figure 5), and the location of samples. The colors of titles indicate areas with sand boil (red), marginal (green), and no sand boil (blue).

For location TX02, specimen 3-1-1 has FC > 40%, suggesting that the fines fraction controls the soil behavior. We do not yet have plasticity information for this specimen. The consolidation curve for the specimen 3-1-1 indicates higher initial void ratio and increased compressibility relative to other specimens (3-1-2, 3-2, and 3-3) judged as sand-like materials (FC < 8%). Materials above specimen 3-1-1 have high penetration resistance and/or lack saturation, and hence comprise a non-liquefiable crust. If specimen 3-1-1 is not susceptible, the thickness of the non-susceptible crustal layer increases, which impacts the potential for liquefaction manifestation [27, 28]. For TX03, specimen 6-1 is an obviously clay-like material (FC > 97%; plasticity index ~ 45.2), where we can clearly ditinguish over-consolidated and virgin compression portions of the consolidation curve in Figure 7c.

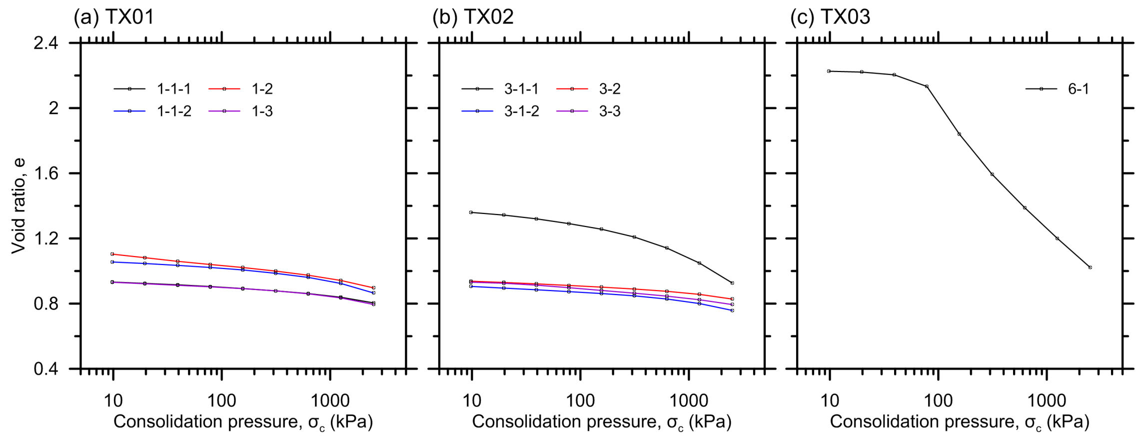

Figure 7. Consolidation test results.

Conclusions

In this study, a case history data set in Mihama-ward, Chiba, Japan is presented, which has varying liquefaction performance in a reclaimed fill area shaken by **M**9.0 Tohoku-Oki earthquake. This data set is of substantial significance for the study of liquefaction susceptibility, because soil type is the primary variable controlling spatially variable levels of soil liquefaction and related ground failure. We have shown available data sets in this region from various sources, and an example site with detailed field investigations including laboratory test results. Consolidation test results are shown as a potential indicator of the liquefaction susceptibility. Our analysis of this site remains in progress and final results will be presented in future publications. The data from these sites will be included in the Next-Generation Liquefaction database [29].

Acknowledgments

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