DOCUMENTATION OF SOIL CONDITIONS AT LIQUEFACTION AND NON-LIQUEFACTION SITES FROM 1999 CHI CHI (TAIWAN) EARTHQUAKE

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ABSTRACT

The 1999 Chi Chi, Taiwan, earthquake provides case histories of ground failure and non-ground failure that are valuable to the ongoing development of liquefaction susceptibility, triggering and surface manifestation models because the data occupy sparsely populated parameter spaces (i.e., high cyclic stress ratio and high fines content with low to moderate soil plasticity). In this paper, we document results from several large site investigation programs conducted in Nantou, Wufeng and Yuanlin, Taiwan. The seismic performance of the investigated sites include non-ground failure building and free-field sites, building sites with partial foundation bearing failures, free-field lateral spread sites, and free-field level ground sites with sediment boils. Field and laboratory investigation protocols for the sites are described, including cone penetration testing (some with pore pressure and shear wave velocity measurements) and rotary wash borings with standard penetration testing (including energy measurements). Implications of the SPT energy measurements with respect to established guidelines for the estimation of SPT energy ratio (including short rod corrections) are presented. Finally, data for three example sites are shown that illustrate potential applications of the data set, and which also demonstrate a condition where existing liquefaction analysis procedures fail to predict the observed field performance.

Key words: Liquefaction, soil investigation, SPT, CPT, Chi Chi earthquake.

INTRODUCTION

The 1999 Chi-Chi Taiwan earthquake (M_w = 7.6) triggered numerous significant incidents of liquefaction in inland alluvial areas and in several coastal hydraulic fills [1]. Significant occurrences of ground failure in the form of liquefaction, ground softening, and lateral spreading were documented by NSF-sponsored reconnaissance teams as well as by Taiwanese researchers in several affected areas. Due to significant interest in the available case histories of liquefaction and non-liquefaction, a series of site investigation programs were undertaken in 2000 by researchers with the National Center for Research in Earthquake Engineering (NCREE) in Taiwan and in 2001-2002 by the authors with funding from the Pacific Earthquake Engineering Research Center (PEER). Results of both site investigation programs are synthesized on the web page http://www.cee.ucla.edu/faculty/Taiwanwebpage/Main.htm.

The principal objective of this paper is to describe the unique data resource that is now available as a result of the NCREE and PEER site investigation programs coupled with extensive post-earthquake site reconnaissance data. We provide an overview of the scope and applicability of the database by (1) reviewing the characteristics of ground failure that occurred in the investigated regions of Nantou, Wufeng, and Yuanlin; (2) discussing the field and laboratory investigation protocols and the format of the uniformly documented site data; and (3) presenting three example case histories that illustrate several applications of the site data with respect to liquefaction susceptibility, triggering, and manifestation models. While the data interpretation work is ongoing, we expect the Taiwan liquefaction data ultimately to have an important role to play in the ongoing development of empirical liquefaction assessment methodologies for two principal reasons:

- Many of the Taiwan case histories involve high cyclic stress ratios (CSR ≈ 0.4-0.6), where existing data is sparse.

- The Taiwan case histories involve primarily high fines content soils, where the existing data inventory is sparse.

INVESTIGATED REGIONS

Nantou

The city of Nantou (population ≈ 94,000, area = 72 km^2) is located within the Taichung basin, and is approximately 0 to 5 km from the fault rupture. Figure 1 shows the layout of Nantou along with the locations of observed liquefaction damage and field investigation sites. Liquefaction occurred within several reasonably well-defined zones within the city that are separated by broad areas with no evidence of ground failure. The geologic environment of Nantou generally consists of young alluvial sediments with shallow groundwater (within about 0.5-5 m of the surface). The geometric mean peak ground acceleration recorded in Nantou (station TCU076) is 0.38g. The station is located on Holocene alluvial soils. The area immediately surrounding this station showed no evidence of ground failure.

Ground failure in Nantou from the Chi Chi earthquake took on several forms. East of the Mao-Lo River, there are a number of cases of classic liquefaction involving free-field sites with sediment boils and ground subsidence. Lateral spreading occurred at many locations along the Mao-Lo River. West of the river, the city is relatively densely developed, and detailed mapping in this area provided locations where ground subsidence beneath buildings did and did not occur. Ground failure in this area generally did not occur at free-field sites, instead being localized around and beneath building foundations. A typical example is shown in Figure 2, which shows a single bay of a 4-story building with a distance between load-bearing walls of about 4.2 m. The walls and exterior columns are supported on spread footing foundations that settled approximately 25 cm, breaking the "floating" intermediate floor slab. Few sediment boils were observed west of the river.

As shown in Figure 1, site exploration at ground failure and non-ground failure sites was performed both east and west of the river. A lateral spread site with an estimated spread displacement of 4 m was also investigated.

Wufeng

The village of Wufeng (population ≈ 61,000, area = 98 km^2) is located over, and immediately west of, the surface fault rupture. Figure 3 is a map of Wufeng, showing the approximate locations of the mapped ground surface fault rupture [2], and the locations of ground failure as evidenced by sand boils, building subsidence/foundation failure, and lateral spreading. The geology of Wufeng consists of an alluvial plain crossed by several rivers and bounded to the east by the Chelungpu fault. Areas east of the fault are relatively mountainous, and are underlain by Pliocene sandstones, shales and mudstones. Groundwater occurs at shallow depths (generally within 1-2 m of the surface). Strong ground motion TCU065 in Wufeng recorded a geometric mean peak ground acceleration of 0.67g. The recording station is located slightly west of the fault (footwall side) and the site showed no evidence of ground failure.

As occurred in Nantou, ground failure in Wufeng from the Chi Chi earthquake took on several forms. In the downtown area east of the Dry Creek River, and north of Dove Nest Creek, ground failure was typically manifest around tall buildings in the form of building settlement and tilting. Sediment boils were not widely observed in these areas. Lateral spreading occurred along both rivers, and was typically accompanied by sediment boils. Liquefaction-induced sediment boils, lateral spreading, and foundation bearing failures also occurred at several locations west of Dry Creek River, which is generally sparsely developed.

As shown in Figure 3, site exploration at ground failure and non-ground failure sites was performed at a number of sites with dense development east of Dry Creek River. Four lateral spread sites with estimated spread displacement of 1 to 3 m were also investigated.

Yuanlin

The town of Yuanlin (population ≈ 116,000, area = 40 km^2) is located approximately 15 km from the Chelungpu fault rupture, yet was subject to severe liquefaction. Figure 4 is a map of Yuanlin showing locations of sediment boils, regions of building subsidence, and investigated sites. As shown in Figure 4, the township is located on flat Holocene deltaic deposits west of Shan-Jao Road, and older Pleistocene sandstone, siltstone and conglomerate east of Shan-Jao Road that slopes gently up to the east. Groundwater levels are relatively shallow, generally occurring at depths between 0.5-7 m. Ground motions records from station TCU110 in Yuanlin indicate a geometric mean peak acceleration of 0.18 g. This station is located in an area where ground failure was not observed.

Ground failure in Yuanlin from the Chi Chi earthquake typically took the form of building subsidence and sediment boils. The case histories of ground failure and non ground failure are principally from well-developed areas. Free-field sites consist of open lots within otherwise developed areas. Unlike Nantou and Wufeng, case histories of building subsidence in Yuanlin often include sediment boils as well. As shown in Figure 4, site exploration was performed both in areas with and without evidence of ground failure.

FIELD EXPLORATION PROTOCOLS

The PEER and NCREE site investigation programs resulted in a total of 92 Cone Penetration Test (CPT) soundings (of which 63 were seismic CPTs) and 98 soil borings with Standard Penetration

Testing (SPT) (typically at 1.0 m spacing). The majority of the NCREE work was performed in the city of Yuanlin, whereas the entirety of the PEER work and some of the NCREE work was performed in the cities of Nantou and Wufeng.

Site Selection

A number of technical and logistical factors affected site selection for subsurface exploration. Several of these considerations are outlined below:

1. The principal factor governing site selection was the availability of high quality field reconnaissance data, preferably performed by experienced investigators within a few weeks of the earthquake. Sources of field reconnaissance data used in the site selection process include the work of the U.S.-Taiwan reconnaissance team [1], an NCREE group [2], and dissertations of students working with individual Taiwanese faculty specializing in the respective areas (e.g., Professor P.S. Lin in Nantou; Professor B.L. Chu in Wufeng).
2. Among sites with high quality field reconnaissance data, special emphasis was given to building settlement sites, lateral spread sites, and non-ground failure sites. In each of these cases, there are significant needs for high quality case histories to support the development of semi-empirical or empirical models for liquefaction triggering or effects.
3. The presence of abundant gravels and cobbles at some sites made sursurface exploration impractical, especially for CPT. This problem was especially acute in Nantou, and as a consequence most of the data from Nantou is borings with SPT.
4. Logistical factors that impacted our ability to perform subsurface investigation at some sites included:

    a. inability to obtain drilling permit or permission from property owner,

b. conflict with underground utilities

c. height restrictions associated with over-head signs and/or power lines

These factors generally precluded performing borings or CPT soundings in streets.

Table 1 shows the distributions of investigated ground failure and non-ground failure sites with both free field and building conditions in Nantou, Wufeng and Yuanlin.

Table 1. Percentage of investigated sites sorted according to presence of structures and observed field performance

		Percentage by Location		
Bldg/Free-Field	Field Performance	Wufeng	Nantou	Yuanlin
FF	GF	45	51	22
Building	GF	36	30	15
FF	no GF	17	16	35
Building	no GF	2	3	13
Unknown	GF	0	0	7
Unknown	no GF	0	0	8

Protocol for Borings with Standard Penetration Testing (SPT) and Laboratory Testing of Collected Samples

Most of the borings were limited to depths of 10-30 m. Drilling equipment consisted of a tripod-supported rotary wash rig. The drill bit used with the rig excavated a 12 cm borehole diameter. A typical rig setup over a hole is shown in Figure 5. For SPT sampling, the percentage of the total theoretical energy delivered to the split-spoon sampler, or energy ratio, was controlled by following procedures in ASTM D6066-98 and ASTM D1586. We used a safety hammer manufactured locally in Taiwan following the specifications of Kovacs [3]. A rope/cathead hammer lift and release mechanism was used with two turns of the rope around the cathead. A standard split spoon sampler was used (5 cm outside diameter) with no internal space for liners. Standard AW rod was used to connect the split spoon sampler to the anvile, which was 9 cm in diameter. Based on these specifications, the energy transmitted to the sampler would be assumed to be 60% if no short-rod correction was applied.

We attempted to measure the actual delivered energy for each blow of the safety hammer using a rod section instrumented with accelerometers and strain gages. However, early in the site exploration program, the accelerometers failed and hence many of the energy measurements are based only on strain gage data. Abou-Matar and Goble [4] have reported that significant errors can result from energy measurements based only on strain gauge data, especially when variable rod diameters are used. Although we used consistent rod sizes, it is nonetheless possible that our energy ratio data contains errors that could increase the dispersion of the measurements relative to what would have been obtained had both sensors operated properly. Nonetheless, the data as recorded is presented in Figure 6 to show the general trend of the results. Mean energy ratios (ER) of about 75% are observed for depths > 3 m, with a small reduction in ER at shallow depths (mean of 69% in upper 3 m). These energy ratios indicate greater hammer efficiencies than would generally be expected for the rope and pulley system at depth (75% vs. the recommendation of 60% by [5]). The short rod correction effect is also negligible in our data except within the upper 3 m.

All retrieved soil specimens from the split spoon sampler were subjected to a full suite of laboratory index tests per ASTM standards including sieve, hydrometer, liquid limit, plastic limit, density and water content. In addition, in-situ vane shear tests (ASTM D 2573) were performed at selected locations and depths to estimate the undrained shear strengths of clayey soils.

<u>CPT Protocol</u>

Cone penetration tests (CPT's) were performed by RESI Inc. using a 20-ton truck with a rig manufactured by Hogentogler. The cone utilized for field testing was a standard electric seismic piezocone with 60° internal tip angle, cross-sectional area of 10 cm^2, and friction sleeve area above the tip of 150 cm^2. The pore pressure transducer for the piezocone is located between the tip and the friction sleeve (U_2 type pore pressure measurement). The cross-sectional area at the location of the pore pressure transducer is 8 cm^2; hence the cone area ratio is 0.8. The depth interval for measurements of tip resistance, sleeve friction, and pore water pressure was 5 cm. The penetration speed was kept close to 2 cm/s.

Downhole seismic velocity profiling was performed at selected sites using a cone instrumented with one geophone. The source for both shear and compressive waves was a sledgehammer striking a wooden board. Surface wave testing was also performed at selected sites in a parallel effort by Dr. Robert Kayen (*personal communication*). At sites with both SASW and downhole testing, similar shear wave velocity measurements were obtained.

Documentation of Field Data

Logs of all borings and CPT soundings were prepared in a uniform format for posting to the web (http://www.cee.ucla.edu/faculty/Taiwanwebpage/Main.htm). For the NCREE effort, this required translation from Mandarine of the original field logs. The posted boring logs include the measured SPT energy ratios and complete laboratory test data for each sample. The CPT logs include the tip resistance (without corrections for the pore pressure/area ratio effect), sleeve friction, and friction ratio. CPT data is also available in spreadsheet format, including pore pressure measurements. The horizontal and vertical locations of borings and CPT soundings are shown on the logs; these data are based on measurements by a professional land surveyor.

EXAMPLES OF COLLECTED DATA

In order to illustrate the characteristics and potential applications of the collected data, we present in this section information for three sites. The first had evidence of ground failure during the Chi Chi earthquake, the later two did not.

The example ground failure site is located in Wufeng (Site C), and consists of an open rice patty that had clear evidence of liquefaction in the form of lateral spreading towards an adjacent creek, ground subsidence, and sediment boils. A synthesis of subsurface data for this site is shown in Figure 7. As shown on the right side of the figure, the soils in the upper 7 m of the site would be considered potentially susceptible to liquefaction on the basis of the liquid limit (LL) and water content (w_n) components of the widely used Chinese criteria, which state that the soil is susceptible if LL < 35 and w_n/LL > 0.9 [6, 7] (the clay fraction component of these criteria is neglected per the recommendations of [7] and observations from the Chi Chi earthquake). Thus, given the water table depth of 1 m, the critical zone in the profile from the standpoint of liquefaction susceptibility is from 1 to 7 m. Within the 1-7 m depth range, the critical zone from the standpoint of liquefaction triggering is identified based on careful study of CPT tip resistance and friction ratio as well as SPT penetration resistance. Based on these considerations, the critical zone for liquefaction triggering at this site is from about 2 to 3.5 m, and in this zone the SPT and CPT data indicate $(N_1)_{60} \approx 5$ blows/ft, $q_c \approx 2.6$ MPa, $R_f \approx 2.4$ %, and $I_c \approx 2.5$. These data can then be coupled with the cyclic stress ratio (CSR) for the site (approximately 0.6 in the critical layer) to show that the site plots well above liquefaction triggering threshold curves (e.g., Figure 8). Hence, the site performance is consistent with expected behavior. Finally, it should be noted that because there are many borings and CPTs at this and other lateral spread sites, the data can be used to formulate valuable case histories for empirical lateral spreading models [8, 9]. This work is ongoing.

The first example non-ground failure site is located in Nantou (Site A), and consists of an open lot that was surveyed within 2 weeks of the earthquake, and no evidence of sediment boils or ground deformations were observed. Figure 9 synthesizes the subsurface data for this site. As shown by the laboratory data on the right side of the figure, there are no depth intervals above 15 m where the soil passes the LL and w_n/LL components of the Chinese criteria, which in this case suggest the layer is not susceptible to liquefaction. Note that within the critical layer indicated on the figure (2.5 to 5 m depth range), the penetration resistances are relatively low (i.e., the site data would certainly plot on the "liquefaction" side of standard liquefaction triggering curves), yet the site was too clay rich to experience ground failure. This case history highlights the importance of evaluating susceptibility criteria before using the site data in the verification or development of liquefaction triggering models.

The second example non-ground failure site is located in Wufeng (Site A-east), and consists of level ground with light wood frame houses. The area was surveyed within 2 weeks of the earthquake, and no evidence of ground failure was observed. Figure 10 synthesizes the subsurface data for this site. As shown by the laboratory data on the right side of the figure, between the depths of 6 to 10 m, the soils pass the LL and w_n/LL components of the Chinese criteria, suggesting the material within this interval is susceptible to liquefaction. Within this zone the SPT and CPT data indicate $(N_1)_{60} \approx 15$ blows/ft, $q_c \approx 8.8$ MPa, $R_f \approx 0.9$ %, and $I_c \approx 1.9$. When coupled with the cyclic stress ratio (CSR) for the site (approximately 0.63 in the critical layer), the site plots well above liquefaction triggering threshold curves (e.g., Figure 8), suggesting that liquefaction would have been expected. Moreover, if the upper 6 m of the site is taken as a non-liquefiable crust and the liquefiable layer is taken as 4 m in thickness, liquefaction effects would be expected to be manifest at the surface based on the widely used guidelines of Ishihara [10], as shown in Figure 11. Thus, the performance of this site is inconsistent with existing models, While this subject remains under investigation, a working hypothesis based preliminary analysis of this and similar sites is that driving static shear stresses may be necessary for liquefaction effects to be manifest at the ground surface when the liquefaction involves high fines content, marginal plasticity soils.

CONCLUSIONS AND LESSONS LEARNED

In this paper, we have described a data set for liquefaction-related ground failure and its effects that is based on extensive post-earthquake reconnaissance activities and subsurface exploration programs supported by NCREE and PEER. It is hoped that this database will be a valuable resource for the ongoing development of liquefaction susceptibility, triggering, and surface manifestation models. It is expected that the data will be especially valuable for parameter spaces that are currently sparsely populated – namely, high CSRs and soils with significant fractions of marginal plasticity fines.

Data collection studies such as the effort described herein will hopefully be undertaken following future significant earthquakes. Lessons learned from this study may be useful during such efforts. Some of these lessons include:

1. The most critical phase of the data collection effort is the post-earthquake reconnaissance during which locations of ground failure and non-ground failure are mapped, and the surface deformations are measured/characterized. It is absolutely essential that the post earthquake reconnaissance provide quantitative descriptions of displacements, buildings tilts, etc. The preparation of maps drawn to-scale and showing the affected areas is also critical. In general, it is preferable to do a thorough job of damage documentation within a limited geographic region than to cover a broad region but without adequate detail. Finally, it should be emphasized that post-earthquake reconnaissance should document locations of non-ground failure as well as locations of ground failure.
2. The key to successful site characterization work in foreign countries is good local contacts.

Coordination with university faculty and working engineers in the host country is absolutely vital. In-person meetings with the collaborators should take place prior to the commencement of fieldwork so that the role of all participants is well understood. Additional subjects that should be addressed in these initial meetings include availability of maps, site access issues, ability to transport equipment within urban areas, access to surveying crews, names and phone numbers of local contacts, and local customs (holidays, and religious restrictions, etc).

3. Drill rigs used to make SPT measurements should use standard equipment (hammers, rods, anvils, augers) whenever possible. For research-quality work, it is essential to measure the energy delivered to the rod.
4. A thorough suite of index tests should be performed on as many soil samples as possible. Even samples judged in the field to be “non-plastic” should be subject to liquid limit tests so that liquefaction susceptibility criteria can be checked.
5. The importance of documenting ground conditions in non-ground failure areas cannot be over-emphasized.

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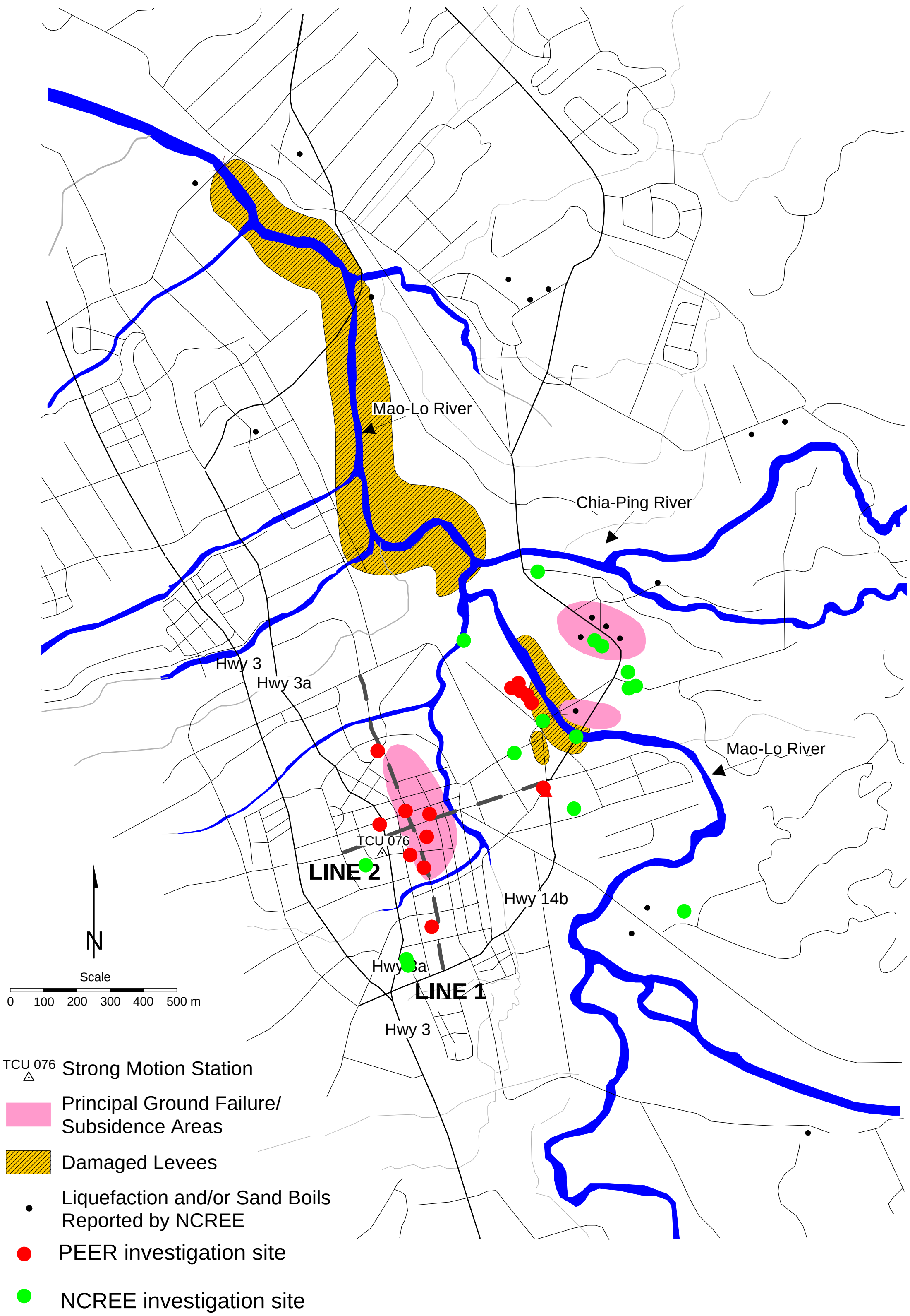

Fig. 1. Map of Nantou showing ground failure zones and locations of investigated sites

Fig. 2. Floating floor slab fractured by 25 cm settlement at walls/columns

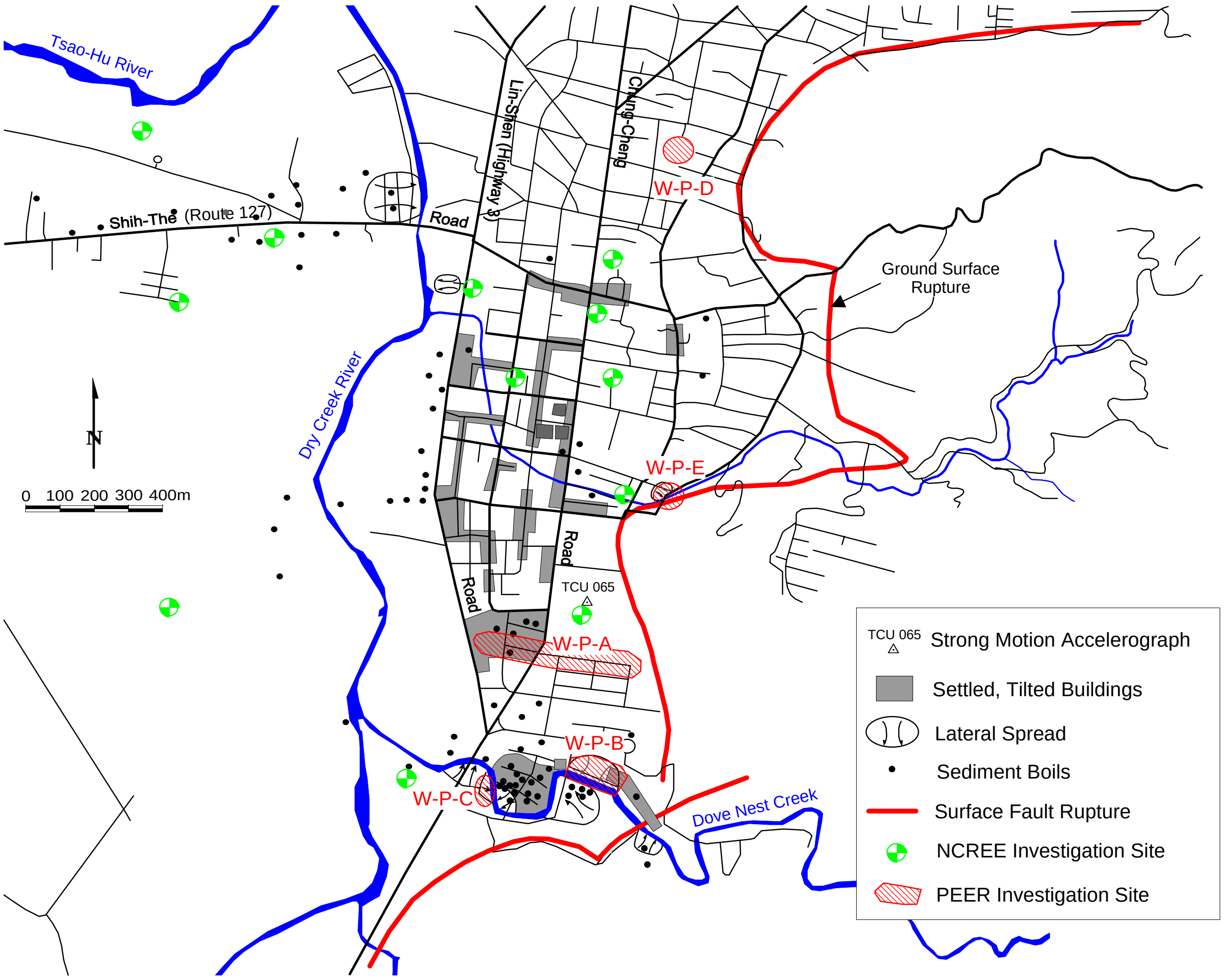

Fig. 3. Map of Wufeng showing ground failure zones and locations of investigated sites

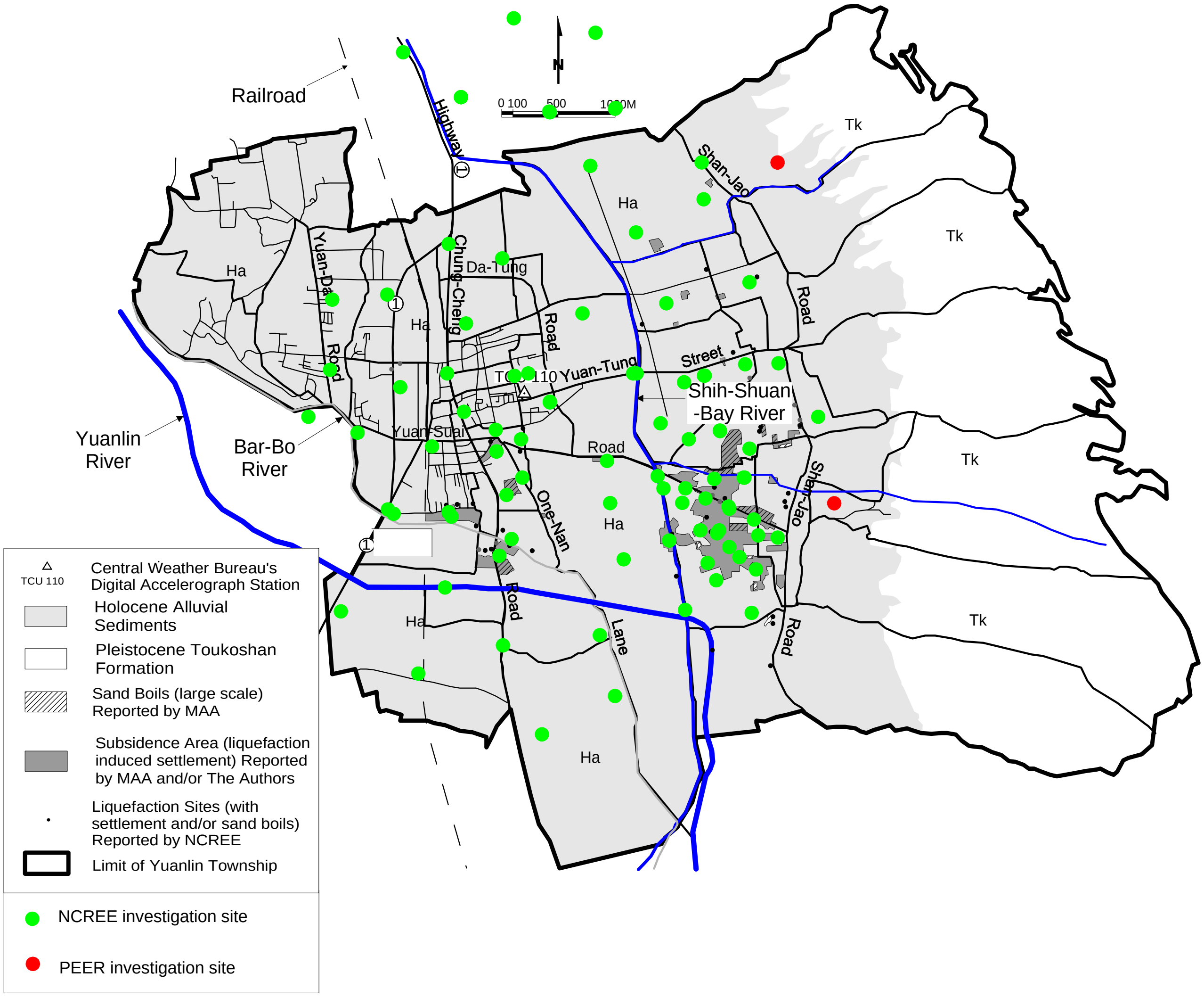

Fig. 4. Map of Yuanlin showing ground failure zones and locations of investigated sites

Fig. 5. Tripod supported drilled rig with a safety hammer for SPT

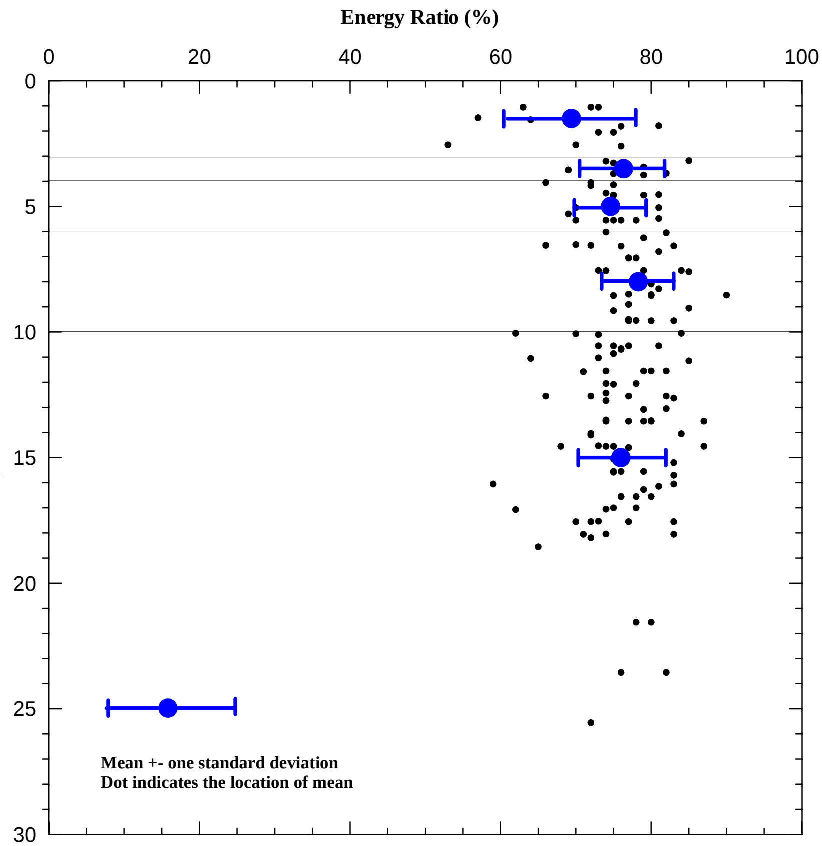

Fig. 6. Field energy ratio measurements during SPT testing

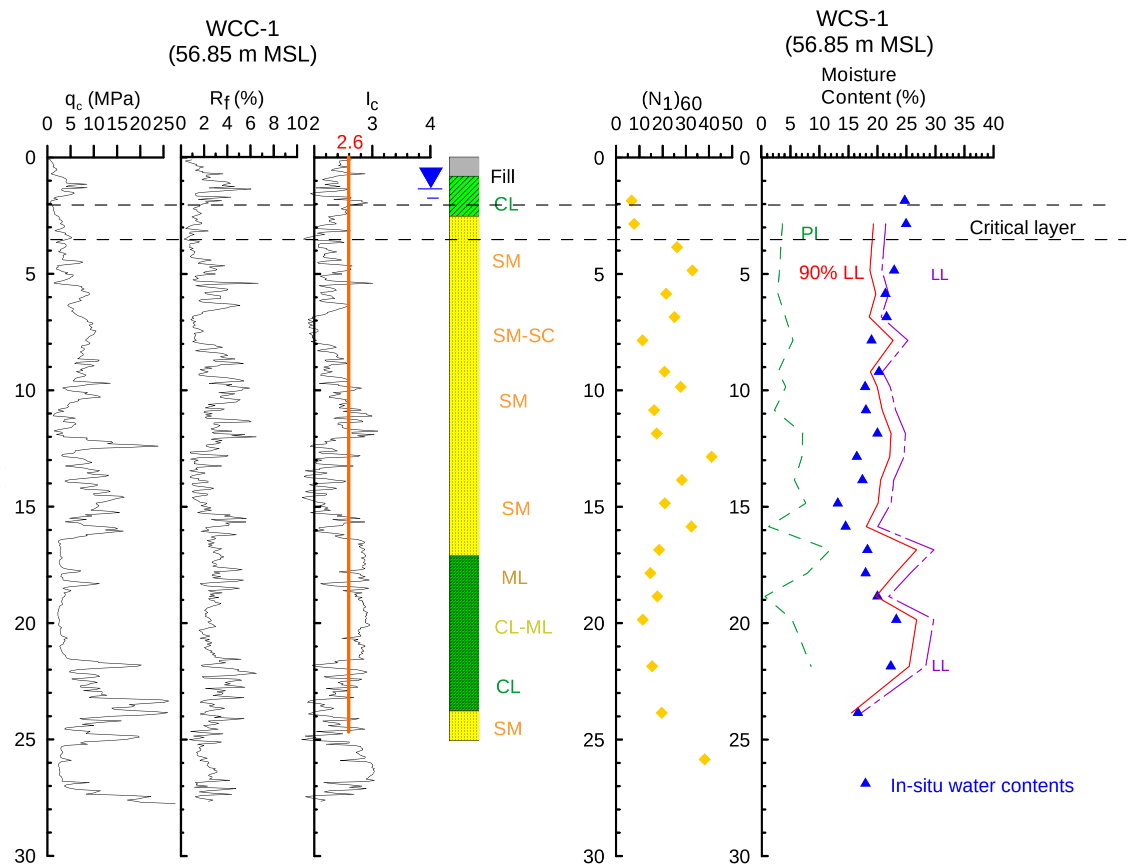

Fig. 7. Subsurface data for example site that experienced liquefaction (Wufeng Site C).

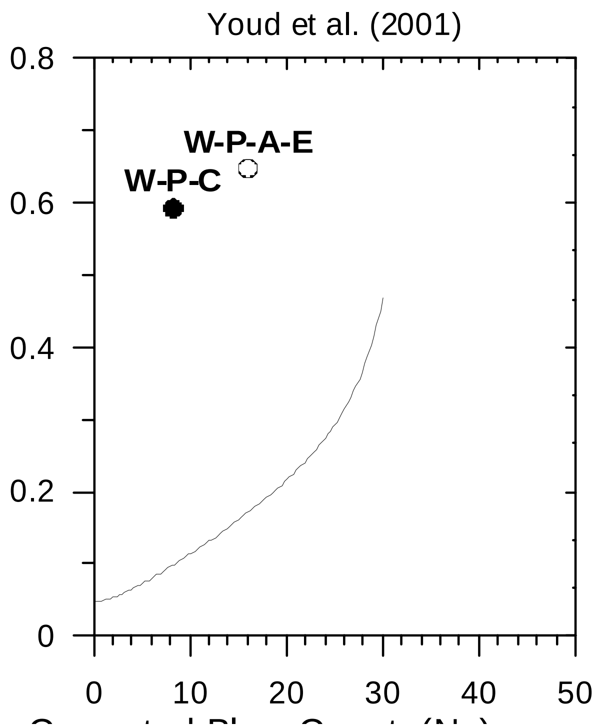

Fig. 8. SPT-based liquefaction triggering threshold curve of Youd et al. (2001) along with data from a liquefaction site (W-P-C) and a non-ground failure site (W-P-A-E) in Wufeng

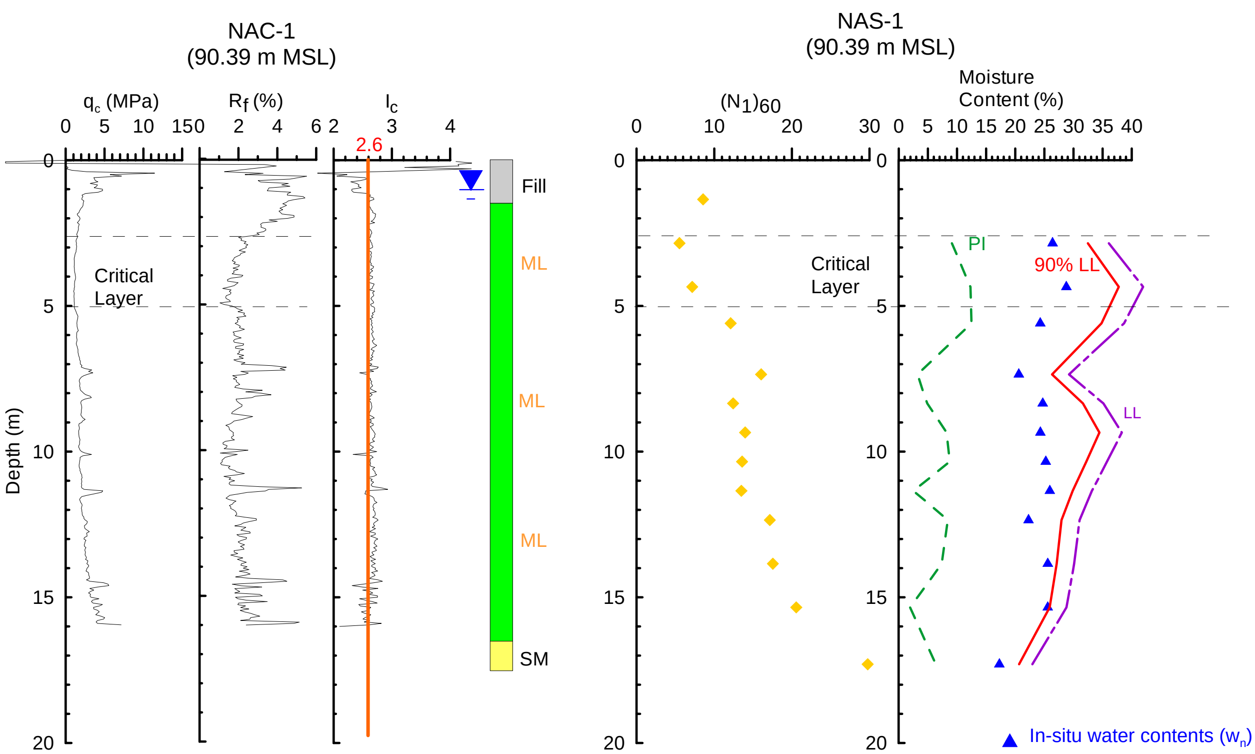

Fig. 9. Subsurface data for first example site that had no evidence of ground failure (Nantou Site A)

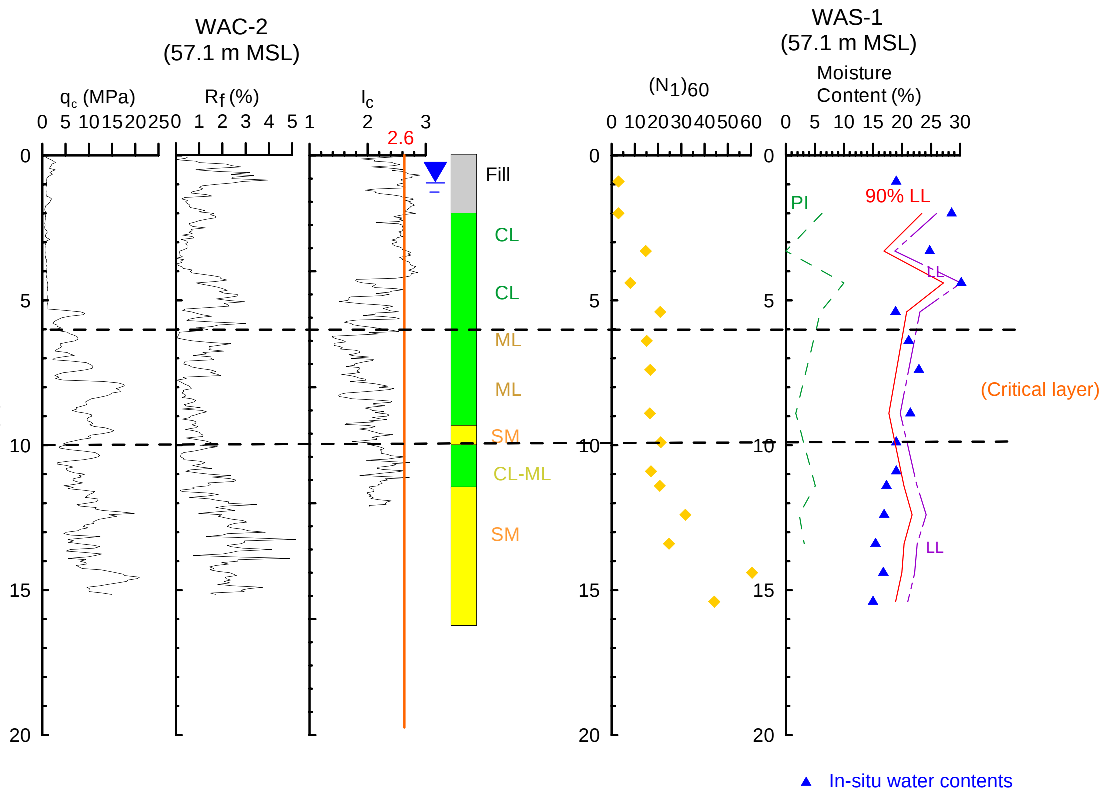

Fig. 10. Subsurface data for second example site that had no evidence of ground failure (Wufeng Site A-east)

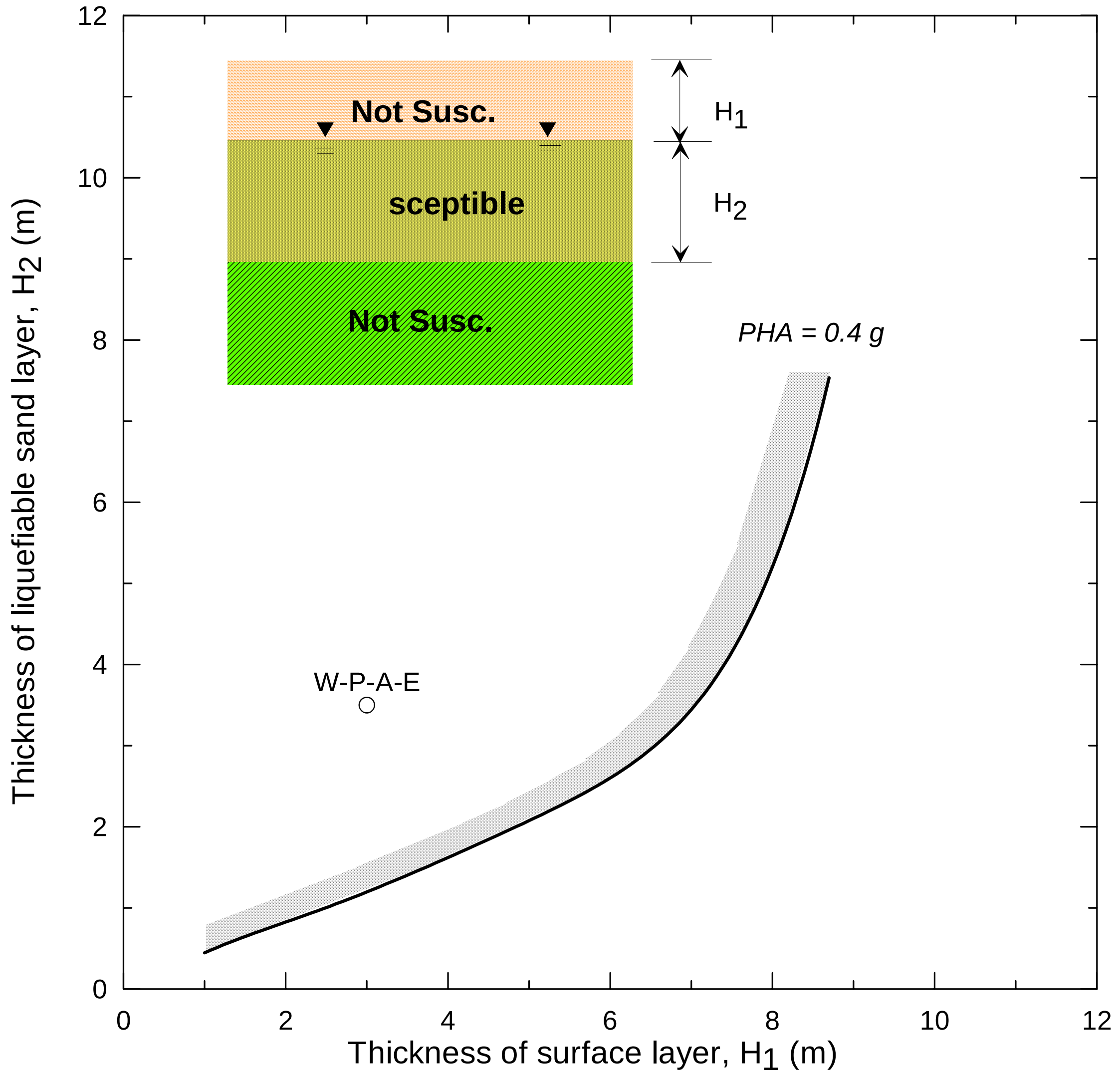

Fig. 11. Threshold curve for surface manifestation along with data point for Wufeng Site A – east.