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Spatial correlation structures of CPT data in a liquefaction site

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A R T I C L E I N F O

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A B S T R A C T

In this paper the spatial structures of cone penetration test parameters in a liquefaction site in Taiwan are estimated based on multiple CPTs conducted in-situ. The study area was divided into three sub-regions based on the geological condition of the study area. The results show that in the vertical profile, cone tip resistance (q_c) has a larger scale of fluctuation (SOF) than that of sleeve friction (f_s). The soil profile which is composed of various sources and complex process of deposition has a smaller SOF in q_c parameter. However, the spatial structure in f_s parameter is not sensitive to the geological formation. The analysis results of the CPT data in horizontal direction indicate that the correlation distances of q_c and f_s in horizontal direction are similar. The horizontal spatial structure is dominated by the anisotropy of the geological and river systems. In conclusion, this study demonstrates that a proper geological zonation is necessary for estimating the spatial structure in both the vertical and horizontal directions.

1. Introduction

Due to the variability inherent in soils and the measurement process, measured soil properties typically vary with the different soil samples and in-situ test location. The complex soil formation process determines the extent of homogeneity of soil properties. Sampling from adjacent locations in a relative homogeneous soil mass may produce similar results with variation. This variation of soil properties exists even for highly homogeneous soil deposits, though this variation between tests may be less for more homogeneous soil deposits. Therefore, soil properties could be described as spatially correlated with variation.

The corresponding effects of spatial variation on a geotechnical system have been examined in previous studies. For example, Popescu et al. (1997) looked at the effects of spatial variability on soil liquefaction. Griffiths et al. (2006) conducted a probabilistic study on the interference of two parallel rough strip footings considering randomly distributed undrained shear strength. Fenton and Griffiths (1996) modeled soil permeability that varies randomly in the study domain in order to improve earth dam models. Phoon and Kulhawy (1999) compiled comprehensive information about inherent variability of soil structures. Jaksa et al. (1997) modeled the spatial variability of the undrained shear strength of clay soils. The scale of fluctuation of the undrained shear strength was found to be as large as 300 m.

The Chi-Chi Earthquake in Taiwan occurred on September 21, 1999, with the epicenter at 23.86°N and 120.81°E, and a focal depth of 11 km. Many liquefaction phenomena such as sand boiling and ground settlement were observed as a result of this severe seismic event. In the years following its occurrence, the National Center for Research on Earthquake Engineering (NCREE) in Taiwan funded the effort to begin mapping liquefaction hazards in each county. The collection of field data included numerous in-situ tests and other soil samples. Because limited field data are available, the assessment of liquefaction potential in an extensive area often requires interpolation and extrapolation of data, and thusly, it is essential to estimate the spatial correlation characteristics of the study area. Information retrieved from the spatial correlation characteristics may be further used in the later interpolation analyses for liquefaction mapping by applying random field theory (Liu and Chen, 2006) or geostatistics.

The goal of this study is to present the results of estimating vertical and horizontal scales of fluctuation (SOF) at Yuanlin, a town that experienced widespread liquefaction damage in the 1999 Chi-Chi earthquake. In the study area of approximately 25 km^2, 71 CPTs were conducted, or one CPT per 0.35 km^2. This field test data provides a basis to estimate the vertical and horizontal spatial structures. The horizontal correlation distances of two orthogonal directions in the study area are investigated to examine the anisotropy of the geological and river systems. Specifically, the concept of zonation is applied to consider the soil deposit process when the scale of fluctuation at Yuanlin is estimated. The effects of geological zonation on these spatial structures are discussed.

2. Study area descriptions

The town of Yuanlin is located approximately 30 km west of the epicenter of the Chi-Chi earthquake, covering an area of about 5 km by

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5 km. Yuanlin suffered severe damage from soil liquefaction during the 1999 Chi-Chi earthquake. Fig. 1 shows the geological map of this town and the CPT locations conducted for the purpose of mapping liquefaction hazards in the area. The western part of the town is on a thick alluvial deposit of the old Jhuoshuei River and its eastern boundary is at the foothill of Baguashan (mountain) in the east. The alluvial plain of Yuanlin is relatively flat and sloping slightly from the south down to the north with a difference in elevation of 10 m over 5 km. The groundwater table in this area is shallow, ranging approximately from 0.5 m to 4 m. According to the investigation by MAA (2000), who collected 50 exploration borings and 45 CPTs, the main soil layers above the depth of 50 m include sand, sandy silt, and silty clay layers. Multiple layers of loose sandy soils that are susceptible to liquefaction are found as a result of these borings. A thick layer of clayey soil sandwiched with a few thin layers of silt mixtures and sand mixtures exists at the western part of Yuanlin, which becomes thinner towards the eastern side of the town. However, at many locations no such capping clayey layer is found.

3. Geological zonation at Yuanlin

Many liquefaction phenomena such as sand boiling and ground settlement were observed at Yuanlin after the Chi-Chi Earthquake. Most liquefaction phenomena clustered in the mid-eastern parts of Yuanlin, while some were observed in the southwestern and mid-northern parts (Liu and Chen, 2006). The scattered distribution of liquefaction mainly resulted from the discrepancy of soil strata. The town of Yuanlin is located in a region where rich soil strata have been formed by various formation processes. The various types of formation processes and different types of soil deposits may result in different spatial correlation structures within the study area. In this section, the approach of how to subdivide the study site into three sub-regions is presented. The details of the geological conditions and formation of each sub-region are also described.

3.1. Zonation

The study area is divided into sub-regions based on the geological conditions. The purpose of dividing the study area into several sub-regions is to identify soils with similar geological conditions and to estimate the spatial structures in each sub-region. Zonation was conducted based on CPT data and SPT data. The CPT profiles with similar trends are treated as in the same sub-regions. For example, Fig. 2 presents the trends of the q_c profiles for three adjacent CPT soundings, C-9, Y-9, and C-13. The vertical trends of the q_c profiles C-9 and C-13 appear to have considerable differences, however, similar trends are observed between C-9 and Y-9. Here, C-9 and Y-9 are classified as in the same sub-region while C-9 and C-13 are not classified in the same sub-region. A similar comparison was made between each possible pair of adjacent q_c and f_s profiles. The results show that zonation conducted utilizing q_c and f_s data are similar. A comparison between adjacent profiles of soil strata identification referred to the CPT-based soil classification (Robertson, 1990) was also performed. For example, Fig. 3 shows the soil classifications of C-9, Y-9, and C-13. It is also evident that C-9 and Y-9 are classified as in the same sub-region while C-9 and C-13 are not classified in the same sub-region. The alluvial plain of Yuanlin is divided into three sub-regions: southern west sub-region (SW), northern west sub-region (NW), and east sub-region (EAST). Fig. 4 presents the zonation results and the general soil profiles of each sub-region. The zonation results were further verified by comparing the SPT data. SPT data, such as profiles of SPT-N values, fine content, clay content, and the plasticity index of adjacent boreholes, were used in the comparison. The zonation results from the SPT data match well with that from the CPT data, as shown in Fig. 5.

3.2. Soil strata of each sub-region

A summary of soil strata in each sub-region is shown in Fig. 4. In the SW sub-region, the strata contains an average of 8.2-m thick layers containing a mixture of silts and sands (soil types 4 and 5 from Robertson 1990, respectively) near the ground surface, an average of a 6.2-m deposit of sand (soil type 6) directly beneath the first layer, and a thick layer (more than 15 m) of clays (soil type 2) and some silty material making up the deepest third soil layer. The intermediate sand layer deposit is found to be deepest in the southeastern portion and shallowest in the northwestern portion.

In the NW sub-region, there is an average of 8.1-m thick silty soils that sometimes contain sandy and clayey materials. A layer of sand underlies this thick silty layer, Beneath the sand layer, a layer of approximately 17.5 m consisting primarily of clays with some silty material is found. The intermediate layer of deposit sands (average

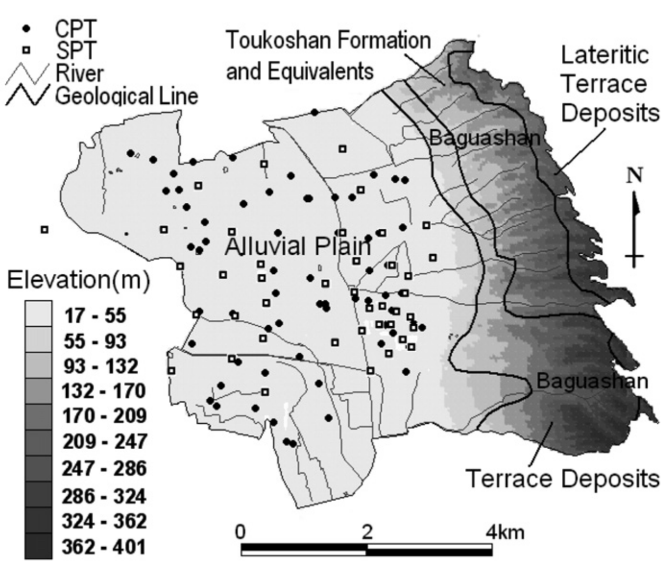

Fig. 1. Terrain map and geological conditions and locations of CPTs in Yuanlin.

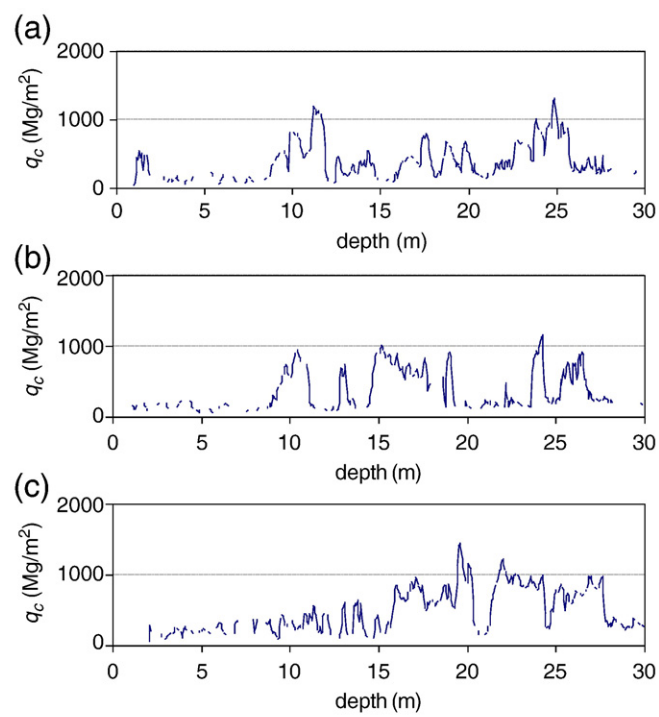

Fig. 2. The q_c profiles at some locations: (a) C-9, (b) Y-9, (c) C-13.