Engineering Geology 112 (2010) 1–12

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Mapping liquefaction potential of aged soil deposits in Mount Pleasant, South Carolina

Tahereh Heidari, Ronald D. Andrus *

Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911, USA

ARTICLE INFO

Article history:
Received 31 August 2009
Received in revised form 29 January 2010
Accepted 3 February 2010
Available online 10 February 2010

Keywords:
Aging
Cone penetration tests
Earthquake
Liquefaction
Shear wave velocity
South Carolina

ABSTRACT

Liquefaction potential of aged soil deposits in Mount Pleasant, South Carolina, based on the 1886 Charleston earthquake is characterized in this paper. The characterization involves reviewing available first-hand accounts of 1886 ground behavior, analyzing cone penetration test (CPT) and shear wave velocity data, and correlating the results with geology. Careful review of the first-hand accounts reveals that nearly all cases of surface effects of liquefaction can be associated with the younger sand deposits that lie adjacent to the harbor, rivers, and creeks. Only one documented case of minimal surface effect of liquefaction can be definitely associated with the older sand deposits of the 100,000-year-old Wando Formation. Ratios of measured-to-estimated shear wave velocity indicate that the younger sand deposits and the older sand deposits have measured velocities that are 9% and 38%, respectively, greater than 6-year-old sand deposits with the same CPT tip resistance. Liquefaction potential is expressed in terms of the liquefaction potential index (LPI) proposed by Iwasaki and others. LPI values for the Wando sands computed from the CPT profiles are incorrectly high, if no age corrections are applied. If age corrections are applied, computed LPI values match well the observed field behavior in both the younger sands and the older sands. The results are combined with a 1:24,000 scale geologic map to produce a liquefaction potential map of Mount Pleasant. The findings of this study agree remarkably well with a previous liquefaction potential study of aged soil deposits on Charleston peninsula.

1. Introduction

Liquefaction hazard maps are useful tools for identifying areas with high likelihood of liquefaction-induced ground deformation, a major cause of damage in many earthquakes. Information about areas with high likelihood of ground deformation can be used for effective regional earthquake hazard planning and mitigation. Liquefaction hazard maps are also useful for identifying areas where specific investigations for liquefaction hazard are needed or should be required prior to project development, but in general these maps should not be used for site-specific engineering design.

Youd and Perkins (1978) introduced the basic procedures used in liquefaction hazard mapping. Many investigators since then have applied and further developed the procedures, including Youd et al. (1978), Dupré and Tinsley (1980), Anderson et al. (1982), Tinsley et al. (1985), Youd and Perkins (1987), Elton and Hadj-Hamou (1990), Mabey et al. (1993), Sowers et al. (1994), CDMG (1996), Knudsen et al. (1996), Holzer et al. (2006), and Hayati and Andrus (2008b). Summaries of these and other mapping efforts are presented in Power and Holzer (1996) and Holzer (2008).

Liquefaction hazard maps can be grouped into four general categories (Power and Holzer 1996)—historic maps, susceptibility maps, potential maps, and ground failure maps. Historic maps identify areas where liquefaction has occurred in the historic past and will likely occur again. Susceptibility maps identify areas with materials that can liquefy based on historic information, geology (e.g., environment of deposition, age of deposit, and groundwater table depth), composition, and initial density (Youd and Hoose 1977; Youd and Perkins 1978). Potential maps consider both the susceptibility of the deposit and the earthquake ground shaking, either for a certain exposure time period or a scenario earthquake. Ground failure maps attempt to predict the amounts of liquefaction-induced permanent ground displacements associated with an exposure time period or a scenario earthquake.

Aged soil is an expression that is often used in geotechnical engineering to refer to the results of various diagenetic processes that occur naturally in soil (or sediment) over time. As explained by Friedman and Sanders (1978, p. 145), "diagenesis involves, among other things: (1) compaction, (2) addition of new material, (3) removal of material, and transformation of material by (4) change of mineral phase or (5) replacement of one mineral phase by another." The removal of material creates new pore spaces and may be the source of cements. Weak cementing bonds due to dissolution/precipitation of cements, such as silica or carbonate, may start forming soon after deposition (Mitchell and Solymar 1984). During

* Corresponding author. Tel.: +1 864 656 0488; fax: +1 864 656 2670.
E-mail addresses: Theidar@clemson.edu (T. Heidari), randrus@clemson.edu (R.D. Andrus).

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doi:10.1016/j.enggeo.2010.02.001

compaction (or secondary compression), soil particles rearrange and interlock in response to the weight of overlying materials (Schmertmann, 1991). Youd and Hoose (1977) noted that cementing and compaction are important factors that reduce liquefaction susceptibility with time.

Although age of deposit was explicitly considered in characterizing liquefaction susceptibility by Youd and Perkins (1978), their criteria only provide qualitative estimates of susceptibility (e.g., <500 years beach deposit = moderate to high susceptibility, Holocene beach deposit = low to moderate susceptibility, Pleistocene beach deposit = low to very low susceptibility). In addition, their criteria incorrectly estimate low susceptibility for several Pleistocene deposits in the South Carolina Coastal Plain which liquefied during the 1886 Charleston earthquake (Martin and Clough 1990; Lewis et al. 1999). The main purposes of this study are to characterize the liquefaction potential of aged soil deposits in Mount Pleasant, South Carolina, and to develop a liquefaction potential map for the area based on 1886 ground motion parameters.

This study expands the work of Hayati and Andrus (2008b) who characterized the liquefaction potential of soil deposits on Charleston peninsula through study of cases of liquefaction and ground deformation, and analysis of 44 cone penetration test (CPT) profiles. Hayati and Andrus (2008b) found that nearly all of the 1886 cases of liquefaction and ground deformation occurred in the Holocene to late Pleistocene beach deposits and man-made fills that flank the higher-ground sediments of the 100,000-year-old Wando Formation. Only one case of documented liquefaction could be associated with the Wando Formation. They also found that an age correction factor was needed to correctly predict lower liquefaction potential of the Wando Formation on Charleston peninsula.

Previous liquefaction mapping efforts of Mount Pleasant have predicted medium to high hazard levels across much of the area in a future 1886-like earthquake (Balon and Andrus 2006; Juang and Li 2007). Balon and Andrus (2006) analyzed 87 CPTs from the greater Charleston region and predicted that over 97% of the Mount Pleasant area would experience moderate to severe surface manifestations of liquefaction. Juang and Li (2007) used many of the same CPTs and came up with a similar prediction. As discussed by Hayati and Andrus (2008b), both of these studies suffer from a lack of adequate attention to geology, a poor understanding of the relationship between 1886 ground behavior and geology, a limited CPT data set, and a lack of adequate knowledge concerning the influence of soil age on liquefaction resistance.

This paper presents for the first time a detailed summary of documented liquefaction and no liquefaction cases that occurred in and around the old town Mount Pleasant in 1886, and plots the cases on the geology map by Weems and Lemon (1993). The cases of liquefaction and no liquefaction are compared with computed liquefaction potentials from 31 CPT profiles. Based on the computed liquefaction potentials and the geologic map, a new liquefaction potential map of Mount Pleasant is developed and compared with similar sediments on Charleston peninsula.

2. Geology and seismology

The town of Mount Pleasant is located on the east side of Charleston harbor approximately 7 km from Charleston peninsula and the city of Charleston. Separating Mount Pleasant and Charleston peninsula are the Cooper and Wando rivers which flow together into the harbor. Presented in Fig. 1 is the geologic map of much of present-day Mount Pleasant by Weems and Lemon (1993). At the time of the 1886 earthquake, Mount Pleasant was a small town of about 740 people located south of Shem Creek (McIver 1994, p. 93). The town was severely shaken by the earthquake at 9:54 pm on August 31, 1886. Although there was much damage in the town, no houses were thrown down and there were no loss of life (Berkeley Gazette 1886a).

Weems and Lemon (1993) mapped six surficial geologic units in the Mount Pleasant area (see Fig. 1). Brief descriptions of these six units, as well as four other units present in the subsurface, are given in Table 1. Major Holocene deposits (af, Qal, Qht, and parts of Qhec) are confined to the low lying areas adjacent to the harbor, rivers, and creeks. Much of the af deposits were placed after the 1886 earthquake. Also abundant in the low laying areas are younger Pleistocene deposits (parts of Qhec and Qhes). The higher natural ground is formed by older Pleistocene sand deposits (Qws) that are part of the Wando Formation. The average ground surface elevation of Qws is about 4 m above mean sea level.

Plotted in the southeast corner of the geologic map shown in Fig. 1 are four areas of artificial fill (af) not previously mapped by Weems and Lemon (1993). These areas of af, which were placed before the 1886 earthquake, have been added to the map based on a review of early Mount Pleasant history. The old town of Mount Pleasant was established in the mid 1800s by incorporating several small villages and settlements (Greenwich, Mount Pleasant, Hilliardsville, and Lucasville). An early plan drawing of part of the village of Hilliardsville is presented in McIver (1994, p. 30). Shown on that drawing are the locations of three swamp areas. These swamps correspond to the three new areas of af that are surrounded by solid curves in Fig. 1. The forth new area of af is surrounded by a dash boundary, and includes Ferry Street in the old town. Concerning this area, McIver (1994, p. 29–31) writes:

> The low swampy area was considered unhealthy but Jugnot and Hilliard “By a system of thorough expensive drainage”, made the region as healthy as any. Their Ferry Company built a wharf on property known as Shell Hall, which had been the summer home of Charles Pinckney of Snee Farm. Ferry Street was then laid out and led to their long wharf and Ferry House.

Although an early detailed plan drawing of Ferry Street was not available for this study, the above citation provides strong evidence for a swamp and a fill at the Ferry Street location.

It is important to also note that the water front south of Shem Creek was not all Holocene tidal marsh (Qht) deposits in the 1880s, as illustrated in Fig. 1. McIver (1994, p. 26) writes: “Beach Street was at the time a good sandy stretch with no marsh, it is said to have changed its character when the jetties at the harbor entrance were built.” Specific areas of sandy beach are identified on a map presented in City of Charleston (1885). Thus, much of Qht along Mount Pleasant's water front south of Shem Creek (see Fig. 1) is a thin marsh deposit underlain by beach sand (most likely Qhes).

Other geologic units present in the subsurface include a clayey member of the Wando Formation (Qwc), sandy sediments of the Daniel Island beds (Qds), quartz-phosphate sand of the Marks Head Formation (Tmh), and the calcareous silts and clays of the Ashley Formation (Ta) of the Cooper Group. According to information presented by Weems and Lemon (1993), Tmh is common in the south-eastern half of the mapped area in Fig. 1 and Ta underlies the entire area. The Cooper Group is locally known as the Cooper Marl and is generally considered as nonliquefiable material (Li et al. 2007; Hayati and Andrus 2008a).

Regarding source and size of the 1886 Charleston earthquake, there is considerable uncertainty. Based on a study of displaced river channels and their relationship with the 1886 epicentral area, Marple and Talwani (2000) concluded that the southern end of the “East Coast fault system”, called the Woodstock fault, is the likely source of the Charleston earthquake. The Woodstock fault is approximately 35 km from old town Mount Pleasant. From dating of buried sand blows features in the South Carolina Coastal Plain, Talwani and Schaeffer (2001) and Talwani and Gassman, (2008) estimated a recurrence time of about 500 years for 1886-like earthquakes near Charleston.