The Liquefaction Sand Boils in the San Francisco Marina District During the 1989 Loma Prieta Earthquake

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SYNOPSIS The paper presents and analyzes the observations of the sand boils that emerged in the Marina District after the Loma Prieta Earthquake of October 17, 1989. The sand boils left behind by liquefaction revealed an old lagoon, the periphery of which had experienced severe damage in the 1906 San Francisco earthquake. The buildings in the Marina District were damaged primarily as the liquefied ground spread laterally along the shoreline of the 1906 lagoon that was filled to host the 1915 Panama-Pacific International Exposition in San Francisco. The present work infers that the sand boils are not random phenomena but instrumental sensors to understand the ground failure induced by liquefaction.

INTRODUCTION

An earthquake registering 7.1 on the Richter scale occured at 5:04 p.m., October 17, 1989, along the San Andreas Fault in the Santa Cruz Mountains, approximately 50 miles southeast of San Francisco. The earthquake epicenter was located near the Loma Prieta lockout which gave its name to the October 17 earthquake. This is the largest earthquake to occur in Northern California since the catastrophic San Francisco earthquake of 1906.

In San Francisco alone, 10 people died and 566 more were injured. About forty houses were destroyed or condemned in the Marina District, in spite of the fact that the Marina District is 67 miles away from the epicenter. The displacement of the ground underlying the Marina District caused the vertical settlement and lateral displacement of most buildings as well as the buckling of sidewalks, the cracking of asphalt pavement and the rupture of underground pipes.

Shortly after the main shock, a large number of sand boils of various shapes and sizes were reported to develop in the Marina District. One house had its basement flooded by sand four feet deep that was pushed upward by the quake. In some other houses, the water-sand mixture emerged through the garage floors, then flowed onto the driveways and amassed at the curbs.

Although sand boils are a well known phenomenon in soil mechanics, they have been rarely taken into account in liquefaction analyses. Up to now, only a few attempts have been made to extract information from the sand boils left behind by liquefaction (Housner, 1958; Ambraseys and Sarma, 1969; and Scott and Zuckerman, 1973). The lack of scientific data on sand boils in earthquake engineering literature may be due to the perishability of sand boils that become rapidly washed out by rain or destroyed by man.

The objective of the research reported in this paper was to collect data on the sand boils in the Marina District in order to compile and document our observations for subsequent analyses of liquefaction and site amplification. Our need for collecting data on sand boils was prompted by the following questions of interest to geotechnical engineering: 1) Is there a relation between the size and distribution of sand boils and the ground deformation caused by liquefaction?, 2) Are the sand boils in the Marina District arranged in a given pattern or are they randomly distributed?

This paper summarizes the findings of Bardet and Kapuskar (1990) and Bardet (1990). Following the introduction, the first section summarizes the past work on sand boils. The second section describes the collection of data in the Marina District of San Francisco shortly after the main shock of October 17, 1989. The third part analyzes the collected data and illustrates how the observations of sand boils can be used to understand the structural damage in the Marina District.

PAST WORKS ON SAND BOILS

The 1985 report of the National Research Council on liquefaction provides a state of the art review about the liquefaction of soils but only an elementary description of sand boils and an embryonic explanation for the formation of sand boils. Sand boils alone seldomly constitute a ground failure although their sudden appearance is frightening. During an earthquake, an upward flow of water is established when excess pore pressure develops at some depth. If the upward gradient is large enough, the flowing water will buoy up the soil particles. With a homogeneous soil, this could result in a widespread quicksand condition. It is more likely however that the flow will break through to the surface in places where the topmost stratum is especially thin or where there are cracks or other weaknesses in the superficial soil. The water, which may flow violently, usually transports considerable suspended sediments that settle and form a conical sand boil deposit around the vent.

The first plausible basic mechanism underlying the development of sand spouts is that suggested by Housner (1958). Housner suggested that an earthquake liquefies the underlying soils which thereafter consolidate as does a compressible soil under an applied load. His theory was followed and elaborated on by Ambraseys and Sarma (1969).

During the 1964 Niigata, Japan earthquake, Kawakami (1965) reported that sand blows occured after a lapse of 2 to 3 minutes following the earthquake and did not appear during the main shock. The blows were as high as 1.2 to 1.5 m initially and diminished with the duration of spouting that was as long as several minutes. The deposits around the spouts contained materials from depths as great as 15 to 20 m.

Based on laboratory experiments, Scott and Zuckerman (1973) showed how the excess water produced by liquefaction makes its way to the surface by an unstable process of cavity formation and then of channel formation in the upper layers. Scott (1973) and Muir and Scott (1981) analyzed the patterns of the sand blows during the 1971 San Fernando, California earthquake and 1979 Imperial Valley, California earthquake. They observed that the greater the thickness of the layer overlying the liquefied soils, the fewer and larger the boils, because the breakthrough of the first vents inhibits the concurrent development of cavities. In a thick layer, fewer cavities reach the surface.

During the 1906 San Francisco earthquake, sand boils, referred to as craterlets at that time, were reported to have occured on practically all the saturated alluvial deposits within the zone of destructive effects (Lawson, 1908). Surprisingly, sand boils were not mentioned to have occured within the city limits of San Francisco.

Youd and Hoose (1976) reported evidence of liquefaction in several areas of San Francisco. However he admitted that sand boils were not reported although they may have developed. "Shortly after the 1906 earthquake, most of the area was burned over. This devastation and the ensuing clean up operations obliterated much of the evidence of ground failure before it could be carefully examined. Thus only fragmentary information is available on the direct effects of the ground failure on structures. Also, sand boils, if any erupted, were likewise destroyed or for some other reason not reported. There are indications, however, that sand boils did occur in the Foot of the Market Zone during the 1906 earthquake."

METHOD AND RESULTS OF SURVEY

Fig.1 represents the 900 x 600 m area of the Marina District of San Francisco which is the object of our investigation. This area was sealed off by police right after the main shock on October 17, 1989. Located to the east of the Presidio Military Reservation, the area extends from Fillmore to Baker Streets going east to west, and from north to south it stretches from Marina Boulevard to Chestnut Street which is located one block north of Lombard Street.

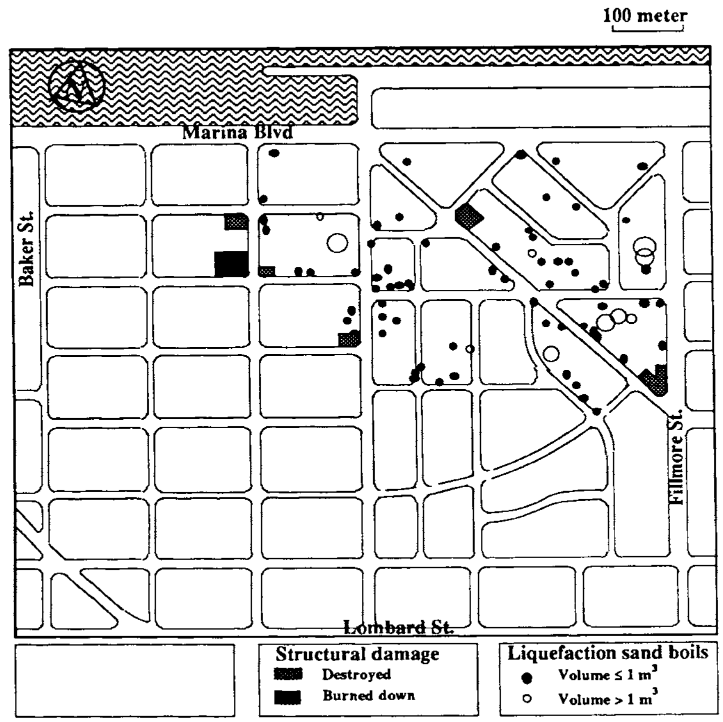

Fig 1. Locations of the liquefaction sand boils recorded in the Marina District and the collapsed buildings on October 22, 1989.

The survey team systematically inspected the area of Fig.1, and recorded the location, size, shape, and presumed origin of the sand boils. To our knowledge, this is the first time that sand boils have been systematically surveyed in a residential area. Scott (1973) and Muir and Scott (1981) reported sand boils in nonresidential areas without buildings, sidewalks or pavements.

A total of seventy-four sand boils were recorded in the Marina District. In Fig.1, solid circles represent the sand boils with a volume smaller than 1 m^3, and empty circles represent these events with a volume larger than 1 m^3. As shown in Fig.1, the sand boils did not completely cover the Marina District, but instead surfaced mainly in the northeast part of the Marina District, over a 600 x 350 m area located at the corner of Fillmore St. and Marina Blvd. The area covered by the sand boils will hereafter be referred to as the liquefied area.

The schematic diagram of Fig.2 shows how the sand boils were distributed with respect to buildings, streets and backyards. Based on aerial pictures of the Marina District, the asphalt pavement and sidewalks were estimated to occupy 32% of the surface surveyed, while the buildings and their backyards were assessed to cover 54% and 14%, respectively. The data collected indicates that 33% of the sand boils surfaced in structural areas, 36% at the boundaries of these areas, 15% on sidewalks and at curbs and 16% in backyards. No sand boil was reported to have broken through the asphalt pavement which is made of impervious subsoils.

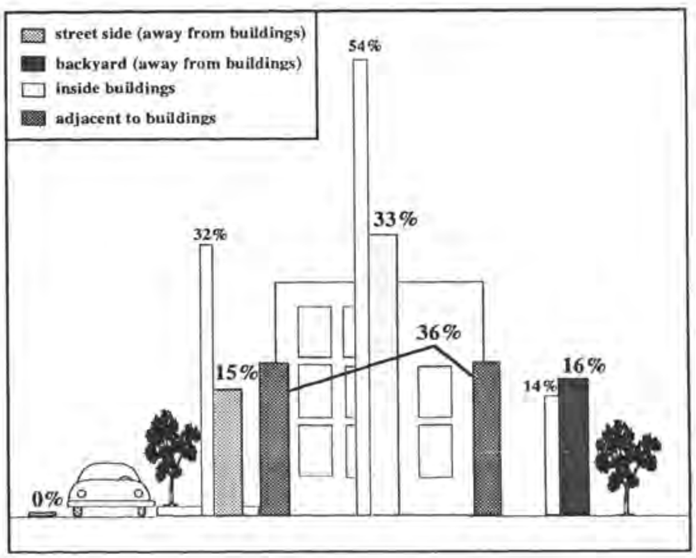

Fig 2. The location of the sand boils relative to the buildings, backards and pavement in the Marina District.

From Fig.2, it is not apparent that sand boils were uniformly distributed with respect to the streets and buildings of the Marina District. If the sand boils had emerged uniformly on the surveyed area, 32%, not 15% as observed, should have broken through the asphalt pavement and sidewalks. Fig.2 indicates that 69%, instead of 54%, of the sand boils emerged inside or at the periphery of the buildings. Presumably in some instances, the emergence of sand boils was induced by the overburden of buildings. It is likely, however, that sand boils encountered difficulty to break through the firm and impervious strata of the asphalt pavement and found an easier way out through the closest cracks of the sidewalks and garage floors.

As shown in Fig.3, the largest sand boil had a volume in excess of 3.5 m^3. However, 42% of the observed sand boils had a volume of less than 0.2 m^3. The cumulative volume of the observed sand boils exceeded 37 m^3.

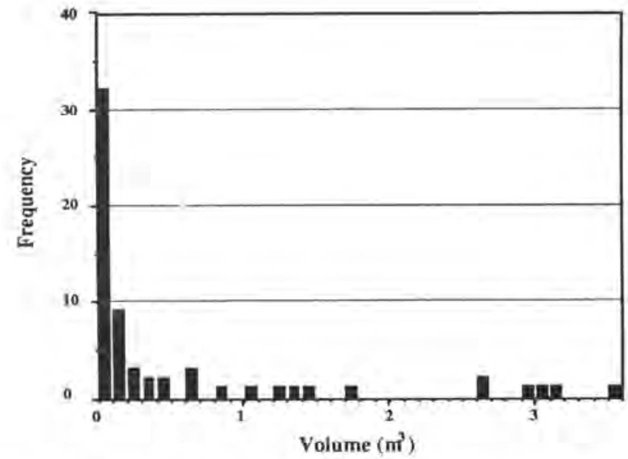

Fig.3. Relation between volume and frequency for the sand boils recorded in the Marina District.

Samples were taken from sand boils at several locations. All the samples were gray and odorless. Their gray coloration is typical of the San Francisco Bay mud. Fig. 4 shows that the grain size distribution curves of the samples are very similar although from different origins. They have a very uniform grain size distribution with a D_{10} and D_{60} equal to 0.15 and 0.2 mm, respectively. They belong to the category of sands which the geotechnical criterion of Seed et al. (1976) classifies as very prone to liquefaction. Fig.4 also compares the grain size distribution of our samples with the ones of sands from the Northern Quadrangle of San Francisco which were tested by Schlocker (1974). From this comparison, it may be concluded that the soils underlying the Marina District contained, among other soils, dune sands.

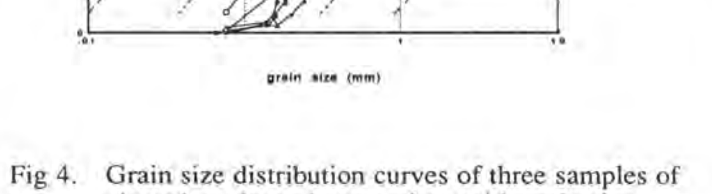

Fig 4. Grain size distribution curves of three samples of ejected sands, and comparison with grain size distributions of beach and dune sands (Schlocker, 1974).

Fig.1 also shows that the largest events were not randomly distributed but were systematically located about one hundred meters away from the border of the liquefied area. Surprisingly, the collapsed buildings were not located close to the sand boils but about 100 m away from them. Severe structural damage was observed at the periphery of the liquefied area, incriminating the relative displacements between liquefied and nonliquefied soils.

The ground deformations in the middle of the liquefied area were characterized by the ripples and undulations that accompanied the spreading motion of liquefied materials.The fact that many undamaged buildings were close to sand boils suggests that liquefaction may have been beneficial to buildings in the center of the liquefied area. It is possible that the liquefaction of superficial soils may have decreased the amplitude of the cyclic shear stresses that the earthquake waves apply to foundations. Liquefaction may have isolated some buildings from the shear waves in the same way as electrical fuses protect electrical circuits from shorting out.

HISTORY OF THE MARINA DISTRICT

Liquefaction is not the only source of damage to the buildings of the Marina District during the 1989 Loma Prieta earthquake. There is an additional cause which may be tracked down by retracing the history of the area.

Lawson (1908) reported a severe ground shaking at the present location of the Marina District. He considered the ground shaking in this area to be as violent as the ones in the Market zone (west of the Post Office), the Ferry building, and the Mission Creek area (west of Mission Dolores).

Fig.5 shows the 1906 lagoon with its protective seawall and the 1892 shoreline. In 1892, the Marina District did not exist. The 1906 lagoon was formed after the construction of the Fair's Seawall that started in 1893. The lagoon was filled in 1915 to host the Panama-Pacific International Exposition. After the closure of the exposition and the demolition of the Fair's buildings, some residential buildings were erected on the debris left over by the exposition while others were constructed on landfill.

Therefore, the site on which the Marina District was constructed after 1915 was predisposed to ground amplification. The amplification of the motion in the ground underlying and surrounding the 1906 lagoon triggered the liquefaction of the sands filling the lagoon. Without exception, all our 1989 observations of sand boils fall within the perimeter of the 1906 lagoon. The grain size distribution curves of Fig.4 suggest that dune sands from neigboring sites, among other materials, were used for filling the lagoon. This remark was later corroborated by archives document; it was found out that an approximate mixture of 30% of clay and 70% of dunes sands was used in filling the 1906 lagoon.

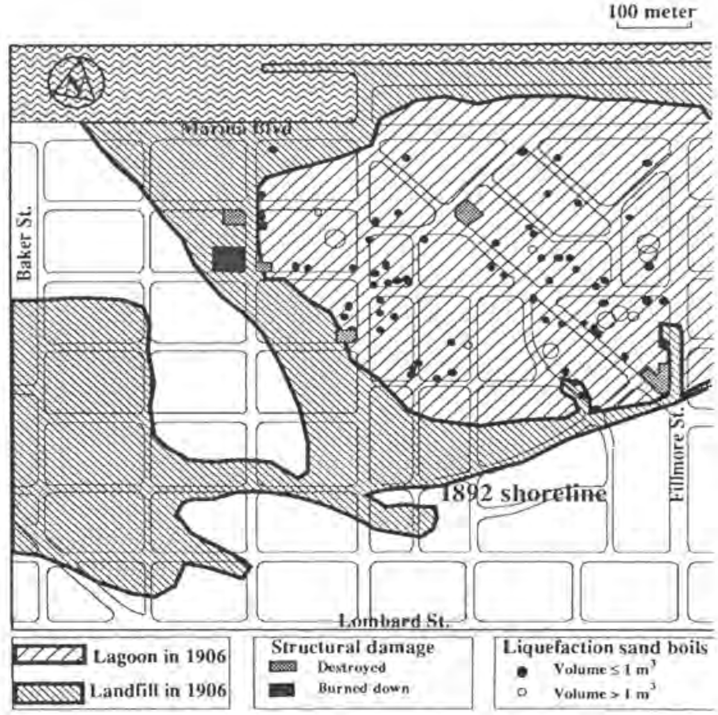

Fig.5. The 1892 shoreline, the landfill and the lagoon of 1906, and the liquefaction sand boils and the ground displacement in 1989.

The collapsed buildings are located along the shoreline of the 1906 lagoon. The relative displacements between liquefied and nonliquefied materials contributed largely to the structural damage of the buildings that had foundations overlying the shoreline of the lagoon.

From the observations made during the 1906 San Francisco earthquake, it is clear that the liquefaction of the sands filling the 1906 lagoon is not the only causative mechanism of the ground displacement and structural damage observed in 1989. The history of the Marina District indicates that the liquefaction observed in 1989 was triggered by the susceptibility to vibration of the ground surrounding and underlying the 1906 lagoon, a susceptibility which was already noticed during the 1906 San Francisco earthquake.

CONCLUSION

The sand boils left behind by liquefaction have yielded crucial information on the ground displacement and the structural damage in the Marina District of San Francisco. The sand boils revealed an old lagoon, the periphery of which was severely damaged in the 1906 San Francisco earthquake. The buildings of the Marina District were mostly damaged as the liquefied ground displaced along the shoreline of the 1906 lagoon. The present work infers that the sand boils are not random phenomena but instrumental sensors to understand the ground failure that liquefaction may induce during an earthquake. A rational interpretation of sand boils provides a simple and efficient technique to analyze the stability and displacement of the grounds liquefied during an earthquake.

The results that we have reported are preliminary. There is a need for additional research on the liquefaction and site amplification of the Marina District as well as on the mechanism of sand blows in general.

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