Liquefaction-Induced Damage During the 2001 El Salvador Earthquake

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The January, 2001 Earthquake in El Salvador caused widespread damage to buildings and several kinds of civil engineering structures due to ground shaking and earthquake-induced ground failures. In addition to several large-scale landslides in the mountainous areas, extensive soil liquefaction was also observed in the alluvial plain in the Pacific lowlands. This paper discusses the results of the post-earthquake damage investigation conducted in the area after the earthquake, with emphasis on the liquefaction-induced damage.

Key Words: *soil liquefaction, earthquake damage, site investigation, lateral flow*

1. Introduction

An earthquake of magnitude (Mw) 7.6 occurred on January 13, 2001 off the Pacific coast of El Salvador. Earthquake-induced landslides, mostly in the central and western parts of the country where the terrain is rugged and mountainous, caused extensive damage to life and property. Although not very well reported, the earthquake also generated widespread liquefaction in the alluvial plain near the southern coast, notably in the area adjacent to the Lempa River (see Figure 1). In this paper, the liquefaction characteristics in the area and the extent of liquefaction-induced damage are discussed.

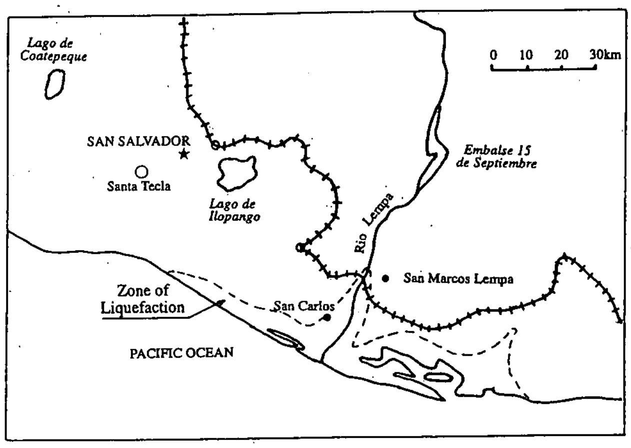

Figure 1: Map showing zone of liquefaction near Rio Lempa

2. Site Condition

Physiographically speaking, El Salvador is divided into two regions: the mountain ranges and central plateau which cover 85 percent of the country and which comprise the interior highlands; and the narrow coastal plains, referred to as the Pacific lowlands, which extend from the coastal volcanic range to the Pacific Ocean. This alluvial region has a width ranging from one to thirty-two kilometers with the widest section in the east. Surfaces in these lowlands are generally flat or gently rolling and result from alluvial deposits from nearby slopes.

El Salvador has over 300 rivers, the most important of which is the Rio Lempa, the country's only navigable river. Originating in Guatemala, the Rio Lempa cuts across the northern range of mountains, flows along much of the central plateau, and finally cuts through the southern volcanic range to empty into the Pacific. It is El Salvador's only navigable river, and it and its tributaries drain about half the country.

3. Damage to River Dikes

Because of the large volume of water draining through Rio Lempa towards the Pacific Ocean,

Figure 2: Damaged river dike in San Carlos Lempa

Figure 3: Fallen bridge girder in San Marcos Lempa

dikes were constructed on both sides of the river to protect the lowland areas, especially during periods of high flood flow during the rainy season. The dikes, which are about 17km long, have a crest width of 3.6m, side slope of 1:1.5, and height of 2~4m depending on location. Along the longitudinal direction of the dike, the crest elevation dips by about 1% towards the Pacific Ocean. The centerline of the dikes are located about 20m~500m from the river, whose banks remained unprotected. The same in-situ materials were used for the construction of the dike body.

The northern section of the dike, with a length of about 8km, had been completed in 1999. Evidence of liquefaction, such as sand boils and ground cracks, were observed in the inland portion adjacent to the dike. In some portions of the dike, particularly at Sta. 6+500 and Sta. 6+105, longitudinal cracks were noted at the shoulder of the dike and at the crest. In addition, ground subsidence occurred by as much as 30cm in one location as shown in Figure 2.

Construction of the southern section of the dike started in March 2000, was stopped in May because of the onset of the rainy season, and finally was continued in early December. Thus, a portion of the southern end of the dike was still under construction when the earthquake occurred. In San Carlos Lempa, lateral spreading of about 2.5m occurred towards the river on the western bank. At this point, i.e., at Sta. 14+770, the dike alignment is closest to the river. Ground cracks, some as wide as 20cm, and vertical offsets by as much as 30cm, were observed near the riverbank. Eyewitnesses reported that one of the trucks used in the dike construction sank into one of the cracks. Sand boils were observed sporadically at various locations on both sides of the dike. The loss of competent ground between the river and the dike now endangers the main body of the dike, especially during the rainy season.

4. Bridge Collapse due to Lateral Spreading

Upstream in the north, in San Marcos Lempa, one of the girders of an old railway bridge crossing Rio Lempa collapsed due to the lateral movement of the liquefied subsoil (see Figure 3). Ground cracks, some as wide as 20cm, and sand boils were observed in the vicinity of the fallen girder. Apparently, the lateral spreading of the ground, by as much as 1.2m in total, carried two of the bridge piers toward the river. The superstructure, which is relatively stiff, did not move sufficiently with the piers, resulting in breaking of each pier near the mid-section, apparently at the location of construction joints. Due to the discontinuity of the bridge girder at the location of the third pier, and possibly due to the short bearing length, the span west of this pier slipped off.

Another bridge, constructed between 1997-2000 and located about 300m south of the old railway bridge, did not suffer any liquefaction-induced damage although minor ground cracks and slumps of river banks were noted in the vicinity of the bridge abutment. Although minimal, this new bridge was permanently displaced in both longitudinal and transverse directions, possibly due to the inertia effect during the earthquake shaking. The bridge remained operational even after the earthquake.

5. Liquefaction in Mangrove Areas

Traces of sand boils and ground cracks were also noted near or in the mangrove fields, located further inland from the dike. These cracks, whose lengths were continuous for several hundreds of meters in some cases, were generally oriented parallel to the river. Local people reported that several wooden huts were damaged by liquefaction-induced ground cracks and subsidence.

In some locations though, ground cracks and differential settlements were observed without any sign of ejected sands. However, although the topography in the area is almost flat, the patterns of ground cracks still suggest that liquefaction-induced lateral displacement had occurred along these cracks. It is possible that liquefaction caused the deformation of sub-soil layers, but the pore pressure build-up may not be enough to bring them towards the ground surface in the form of sand blows.

6. Characteristics of Sand Boils

As mentioned earlier, sand boils were observed in various areas in the lowland plain. Samples were obtained in 3 sites in San Carlos Lempa adjacent to the river dikes, i.e., at Sta. 14+770 (where the lateral spreading took place), Sta. 15+100 (in the unfinished portion of the dike) and Sta. 6+100 (in the northern portion). Similarly, samples from sand boils observed inland in the mangrove area, i.e., about 400m from the northern section of the river dike, were obtained. In addition, sand boils found near the fallen bridge girder in San Marcos Lempa were also considered. For comparison purposes, the materials used in the construction of the main dike body were also investigated.

Figure 4 shows the grain size distribution curves for the samples mentioned above. It can be seen that

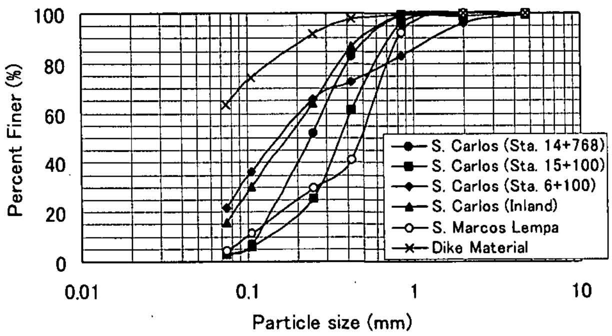

Figure 4: Grain size distribution curves of ejected sands and of dike material

the sand boils in San Carlos consist basically of poorly graded fine sands, with minimal gravel content (<4%). The fines content for the sand boils observed near Rio Lempa seem lower than those obtained at sites far from the river. On the other hand, the ejected sand sampled in San Marcos Lempa has almost uniform gradation with negligible fines content. Other characteristics of the erupted materials are given in Table 1.

The grain size distribution curve for the dike materials is also indicated in Figure 4. This curve serves as indication of the type of surface soil in the area, since such materials were used to construct the main body of the dike. Note from Figure 4 and Table 1 that these materials are predominantly clayey and silty materials, with 64% fines content.

It was also observed that all the sand boils have gray to blue-gray color, while the dike material (surface soil) has light brown color.

7. Results of Swedish Penetration Tests

Penetration tests were performed at the sites to investigate the subsurface condition in the affected areas. For this purpose, a modified version of the Swedish-type sounding test, where in-situ materials placed in sandbags were used as weights, was employed.

Table 1: Properties of the ejected sands and dike material

Sample No.	%Gravel	%Sand	%Fines	D_{50} (mm)	Cu	Cc
S. Carlos (Sta. 14+768)	0.1	97.1	2.8	0.240	2.48	0.88
S. Carlos (Sta. 15+100)	1.2	4.2	3.0	0.360	3.08	1.39
S. Carlos (Sta. 6+100)	3.7	25.2	21.5	0.152	>2.67	>0.54
S. Carlos (Inland)	0.0	84.3	15.7	0.178	>3.09	>0.67
S. Marcos Lempa	0.2	95.5	4.3	0.485	5.67	1.17
Dike Material	0.1	36.0	63.9	< 0.075	-----	-----

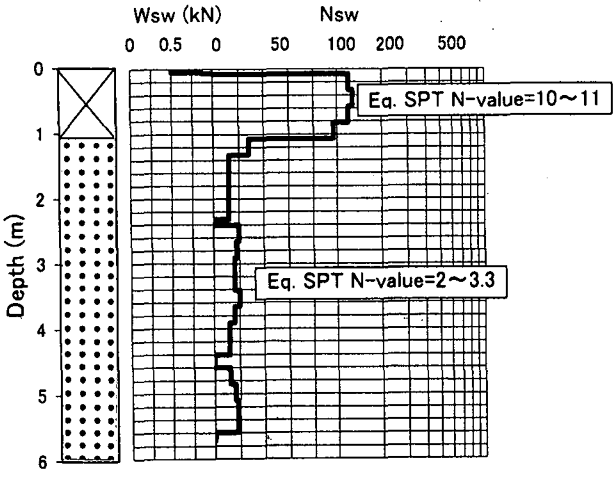

Figure 5: Results of Swedish sounding test in San Carlos Lempa

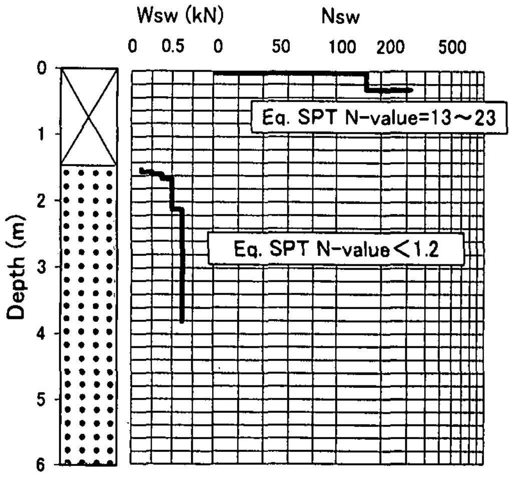

Figure 6: Results of Swedish sounding test in San Marcos Lempa

The first test was conducted in San Carlos Lempa, at the site between the dike under construction and the riverbank where lateral spreading was observed. The result is shown in Figure 5, which shows that a 1.1m thick of backfill material is underlain by a soft sandy layer with an equivalent SPT N-value between 2~3.3. The actual depth of the loose deposit was not verified because of the limited number of rods brought to the site. It was estimated that the level of water in the river was about 2m lower than the ground surface.

The second test was performed near the fallen bridge girder in San Marcos Lempa. At the initial test site located about 10m from the river bank, the sounding test showed a very hard surface layer, which made the penetration very difficult, as shown in the upper portion of Figure 6. An equivalent SPT N-value of 13~23 was computed at this site. The test site was then moved, this time between a vertical slope at the riverbank and the waterline. At this location, a 1.5m thick surface soil was exposed, and this is considered to be the thickness of the surface layer. The exposed surface soil was highly cemented. Sounding test was continued from the ground surface near the waterline, and the penetration rod simply sank into the deposit with weights less than 1kN (100kgf), indicating a very soft deposit with equivalent SPT N-value less than 1.2. Again, the total depth of this loose deposit was not confirmed because the rod hit a hard object, presumably gravel, which prevented the full-penetration into the stratum. At this point, the test was abandoned. When the rods were retrieved, gray-colored sand particles were observed adhering to the surface of the rods.

From these two test sites, it can be speculated that the area adjacent to Rio Lempa is covered by a thin layer (probably on the order of around 2m) of surface soil underlain by loose sand deposits. It is possible that the sites where the river dikes and the foundation of the bridge piers have been constructed were former river channels or coastline which have been reclaimed naturally as a result of sediment flow.

8. Concluding Remarks

Although not widely reported, soil liquefaction was widespread in the alluvial plains adjacent to Rio Lempa. Ground cracks, differential settlements and sand boils were observed at numerous sites near and in the mangrove areas. Damages to river dikes, such as cracks and subsidence, as well as bridge girder fall-off due to lateral spreading, were noted.

Since the affected area is sparsely populated with very few engineered constructions, the effect can be considered as minor. However, if this had occurred in densely populated areas, it can be surmise that extensive damages would have occurred.

Acknowledgments

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