LIQUEFACTION SUSCEPTIBILITY AND GEOLOGIC SETTING

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SYNOPSIS

Liquefaction-induced ground failures that occur during earthquakes are confined to specific geologic settings. An analysis of published earthquake reports shows that shallow, saturated, Holocene fluvial, deltaic and aeolian deposits and poorly compacted artificial sand fills have highest susceptibilities to liquefaction and ground failure. Generally smaller susceptibilities are found in Holocene alluvial-fan, alluvial-plain, beach, terrace and playa deposits. Pleistocene sand deposits are generally even less susceptible, and glacial till, clay-rich and pre-Pleistocene deposits are usually immune to liquefaction.

INTRODUCTION

Liquefaction-induced ground failures, such as flow landslides, lateral-spreading landslides, bearing capacity failures and ground settlement (Youd, 1975), have been a common cause of major damage during past large earthquakes. These ground failures have been confined to specific geologic settings. Thus past experience can provide a useful guide for estimating possible ground failure hazards associated with liquefaction during future earthquakes. An analysis of published earthquake reports is made here to identify geologic settings most susceptible to liquefaction.

GEOLOGIC FACTORS CONTROLLING LIQUEFACTION SUSCEPTIBILITY

A summary of ground failures and other effects attributable to liquefaction during many past earthquakes as a function of geologic setting are listed in Table I. These data show that the following geologic and hydrologic factors control liquefaction susceptibility.

Environment of deposition. -- Deposits most commonly disturbed by liquefaction have been those laid down in a fluvial environment. Deltaic deposits, though not so widespread as fluvial deposits, have also been commonly and, in many instances, catastrophically disturbed. Colluvial and aeolian sand deposits, in instances when they were saturated have been commonly affected as well. Alluvial-fan, alluvial-plain, beach, terrace, playa and estuarine deposits have been affected in many instances, but not so commonly as the deposits listed above. Glacial till and laterite deposits have been generally immune to liquefaction. It is inferred from these rankings that degree of sorting, amount of compaction during sedimentation, and grain-size class are major factors controlling liquefaction susceptibility; the greater the sorting and the looser the packing during sedimentation, the greater the liquefaction susceptibility. Clay-rich sediments are generally immune to liquefaction.

Age of deposit. -- Holocene deposits have been much more commonly disturbed by liquefaction than Pleistocene deposits, and pre-Pleistocene deposits have rarely been affected by liquefaction. Even within the Holocene, liquefaction susceptibility apparently has diminished with age.

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Cementing and compaction by natural processes are important factors that reduce susceptibility with age. Changes in topography, water table depth, and depth of burial due to post-depositional geologic processes are indirect factors that commonly reduce, and occasionally increase, the liquefaction susceptibility with age.

Water table depth and depth of burial. -- Most episodes of liquefaction have apparently developed at relatively shallow depths (probably less than 10 m) and in areas where the water table (free or perched) was near or within a few meters of ground surface. Vulnerability to liquefaction has decreased with water-table and sediment depth, and only a few instances of liquefaction were reported at depths as great as 100 m. Increase of overburden pressure and general increase in sediment compactness with depth are likely the primary factors controlling this tendency.

CONCLUSIONS

Fluvial deposits pose the greatest hazard for damage from liquefaction-induced ground failures because they are highly susceptible to liquefaction, are widespread in occurrence and are frequently sites of considerable development. Deltaic deposits also pose a considerable hazard but their areal extent is smaller and frequently they are less developed sites. Saturated aeolian deposits are susceptible to flow landslides which constitute a serious hazard in many developed areas. Poorly compacted artificial sand fills may also present a hazard to construction from bearing capacity failures and lateral spreading landslides during seismic shaking.

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TABLE I. -- EFFECTS ATTRIBUTABLE TO LIQUEFACTION DURING MANY LARGE EARTHQUAKES AS A FUNCTION OF GEOLOGIC SETTING

EARTHQUAKE (Magnitude, M)	DEPOSIT	EFFECTS ATTRIBUTED TO LIQUEFACTION	APPURTENANT INFORMATION	REFERENCE
1811-1812, New Madrid, Missouri USA (M unknown)	Holocene and Pleistocene fluvial deposits and alluvial-fan and -plain deposits along Mississippi and tributary rivers	Pervasive to abundant lateral spreading, ground settlement, fissures and sand boils over a 3,600 km^2 area and sporadic to abundant occurrences of these effects over at least an additional 10,000 km^2	Water table was near or above surface in much of the intensely affected area. Holocene sediments were much more severely affected than Pleistocene sediments	Fuller, 1912
1819, Cutch, India (M unknown)	Holocene fluvial deposits along Sandham and other rivers in Cutch highlands	Sporadic to abundant fissures, sand boils with diameters as large as 6 m, occurred in a 15,000 km^2 area		Oldham, 1926
	Holocene or Pleistocene alluvial-plain deposits east of Cutch	Fissures and sand boils at two separate locations		Oldham, 1926
	Holocene sebkha deposits in Rann of Cutch (a large, low-lying flat, open to the sea, on which sands blown by winds in dry seasons are reworked by shallow flood waters in monsoon seasons)	Sporadic to locally abundant sand boils with cones as high as 2.4 m occurred in an 8,000 km^2 area	Water table generally less than 1 m deep	Oldham, 1926
1897, Assam, India (M 8.7)	Holocene and Pleistocene fluvial and alluvial-plain deposits in Brahamaputra and Ganges River valleys	Generally pervasive to abundant lateral spreading, ground settlement, fissures and sand boils with numerous bearing capacity failures in a 7,600 km^2 area. Sporadic to abundant occurrences of these effects over an estimated additional 200,000 km^2 area	Effects decrease in severity with increasing depth to water table	Oldham, 1899
	Holocene and Pleistocene Laterite (Khiar) deposits (hard red soils of the epicentral district)	Specifically noted that fissures accompanied by sand boils did not occur and that damage was much less severe on the laterites.		Oldham, 1899
1905, Kangra, India (M 8.3)	Holocene fluvial and alluvial-plain deposits in upper Ganges and Solani River valleys and in narrow mountain valleys	Sporadic to locally abundant fissures and sand boils in a 500-km-long zone		Middlemiss, 1910
1906, San Francisco, California, USA (M 8.3)	Holocene fluvial and alluvial-plain deposits in intermontane valleys of coastal ranges	Sporadic to locally abundant lateral spreading, ground settlement, fissures and sand boils in a 560-km-long zone	Severity of effects generally decrease with increasing depth of water table and with age of sediment	Lawson, Chm., 1908 Youd and Hoose, *in press*
	Holocene and Pleistocene alluvial-fan deposits	No significant effects attributable to liquefaction reported		Lawson, Chm., 1908
	Holocene deltaic deposits at mouths of Eel River and Lagunitas Creek	Abundant lateral spreading, fissures and sand boils		Lawson, Chm., 1908 Youd and Hoose, *in press*
	Holocene beach deposits along northern California coast	Few fissures and sand boils in back-beach deposits. No effects reported in fore-beach deposits		Lawson, Chm., 1908 Youd and Hoose, *in press*
	Holocene and Pleistocene aeolian deposits on San Francisco peninsula and near Monterey Bay	Shallow flow landslides on several hillsides. Few fissures and sand boils in dunes	Sediments were wetted by heavy rains in 6-week period prior to earthquake	Lawson, Chm., 1908 Youd and Hoose, *in press*
	Holocene colluvium in coastal ranges	Shallow flow landslides on several hillsides and in a single narrow valley	Materials were sandy in nature and were wetted by heavy rains in 6-week period prior to earthquake	Lawson, Chm., 1908 Youd and Hoose, *in press*
	Pleistocene marine terraces in northern California	No significant effects reported		Lawson, Chm., 1908
	Cretaceous marine sandstone bluffs at False Cape (Cape Fortunas)	A single, large (800-m-wide) landslide (lateral spreading?), in 150-m-high bluffs, ran out into the ocean 400 m	Liquefaction is only one of several possible mechanisms that could have led to the large lateral movement	Lawson, Chm., 1908
	<100-year old artificial fills in San Francisco	Lateral spreading and ground settlement in three separate fills	Fills constructed with loose-dumped dune sand. Average N (standard penetration resistance) generally less than 10 in upper 10 m	Youd and Hoose, *in press*
1918, Srimangal, India	Holocene fluvial and alluvial-plain deposits in the Brahamaputra and tributary river valleys	Sporadic to locally abundant lateral spreading, bearing capacity failures, ground settlement, filling of wells and borrow pits, fissures and sand boils in a 180-km-long zone		Stuart, 1920
1920, Kansu, China (M 8.6)	Pleistocene loess deposits in Kansu Province	Abundant flow landslides including 17 large flows (incorporating areas up to several km^2) occurred in three separate areas in a 300-km-long zone	Liquefaction was apparently due to pore-air rather than pore-water pressures	Close and McCormack, 1922
1923, Kwanto, Japan (M 8.3)	Holocene fluvial and alluvial-plain deposits and reclaimed land over these deposits in east-central Honshu Island	Abundant lateral spreading, ground settlement and sand boils in a 750 km^2 area traversed by the Tone River prior to 1600 AD. Sporadic to locally abundant occurrences of these effects in a 130-km-long zone		Home Office, 1926 Kuribayashi and Tatsuoka, 1975

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1931, Hawkes Bay, New Zeland (M 7.9)	Holocene and Pleistocene fluvial and alluvial-plain deposits in east-central North Island	Sporadic to locally abundant lateral spreading, slumping of stream banks, fissures and sand boils in a 200-km-long zone	Artesian water pressures occur under many affected areas	N. Z. Department of Scientific and Industrial Research, 1933
	<100-year-old artificial fills over Holocene fluvial deposits, chiefly in Napier and vicinity	Locally abundant lateral spreading, bearing capacity failures, ground settlement and fissures	Effects were most severe in areas with high water table	N.Z. Dept. of Sci. and Ind. Res., 1933
	Holocene lagoonal deposits near Napier	Lateral spreading, bearing capacity failures and ground settlement near and beneath a causeway and pier		N.Z. Dept. of Sci. and Ind. Res., 1933
	Holocene beach deposits between Napier and Gisborne	Locally abundant lateral spreading and fissures with few sand boils in 90-km-long zone	Effects were most severe in beaches near mouths of rivers and streams	N.Z. Dept. of Sci. and Ind. Res., 1933
	Upper Tertiary mudstone bluffs	Five deep-seated large landslides (lateral spreading?) with widths up to 2 km and runouts into the sea as far as 700 m developed in 180-m to 360-m high coastal bluffs in a 30-km-long zone	Liquefaction is only one of several possible mechanisms that could have led to the large lateral movements. The bluffs are composed of soft, friable mudstones.	N.Z. Dept. of Sci. and Ind. Res., 1933
1934, Bihar-Nepal, (M 8.4)	Holocene and Pleistocene fluvial and alluvial-plain deposits in the Upper Ganges and tributary river valleys	Abundant lateral spreading, bearing capacity failures, ground settlement, collapsed and filled wells, fissuring and sand boils over a 12,000 km^2 area and sporadic to locally abundant occurrences of these effects in an additional 70,000 km^2 area		Roy, 1939
1948, Fukui, Japan (M 7.2)	Holocene fluvial and alluvial-plain deposits in Fukui alluvial plain	Abundant lateral spreading, ground settlement, fissures and sand boils with some bearing capacity failures in a 300 km^2 area	Water table was near surface in most of the area	U. S. Army, 1949 Tsuya, 1950
	Holocene and Pleistocene aeolian sand dune deposits on the west edge of Fukui plain	Sporadic fissures and sand boils in a 7 km^2 area	Damage to buildings on sand dunes was slight	U. S. Army, 1949 Tsuya, 1950
1954, Fallon-Stillwater, Nevada, USA (M 6.8)	Holocene fluvial deposits in old river channels in the Fallon-Stillwater area	Locally abundant ground settlement, fissures and sand boils in a 30-km-long zone	Old stream beds had been both naturally and artificially filled with sand	Tocher, 1956 Steinbrugge and Moran, 1956
	Holocene playa deposits in Carson Sink and Alkali Valley	Locally abundant lateral spreading, ground settlement, fissures and sand boils in a 30-km-long zone	Failures occurred both in cultivated lands and around superficially dry lake beds	Tocher, 1956 Steinbrugge and Moran, 1956
April 7, 1958, Alaska, USA (M 7 - 7 1/2)	Holocene fluvial deposits along Keokuk River	Abundant lateral spreading, fissures and sand boils in a 100-km-long zone		Davis, 1960
	Holocene aeolian sand dune deposits overlying fluvial deposits south of Keokuk River	Abundant flow landslides in a 70-km-long zone	Flows involved materials from both dune and fluvial deposits. Dunes were frozen to about 1-m depth	Davis, 1960
1960, Chile (M 8.4)	Holocene fluvial deposits along rivers in the mountaneous and coastal regions between Concepcion and Puerto Montt	Sporadic to locally abundant lateral spreading, ground settlement and some bearing capacity failures in a 45,000 km^2 area		Duke and Leeds, 1963
	<200-year-old fills over fluvial and alluvial-plain deposits in Concepcion, Valdivia, and Puerto Montt and some roadway embankments between these cities	Pervasive to abundant lateral spreading, bearing capacity failures, ground settlement, fissures and sand boils and some flow landslides in filled areas	Fills consisted primarily of loose dumped or hydraulically placed sands. Water tables were near or within a few meters of the surface in the affected areas	Duke and Leeds, 1963
	Holocene lagoonal deposits in Valdivia	One localized area sustained abundant lateral spreading and ground settlement	Sediments were layered silt with peat and silty sand lenses	Duke and Leeds, 1963
	Holocene beach deposits near mouth of Bio Bio River	Sporadic sand boils with throat diameters up to 0.6 m		Duke and Leeds, 1963
	Holocene and Pleistocene glacial-outwash and lacustrine terrace deposits between Valdivia and Lake Rinihue and Puerto Montt	Low-lying wet terraces around Lake Llanquihue commonly failed by lateral spreading or slumping. Nine major deep seated landslides (flow?) occurred on river cut slopes in Pleistocene terraces.	One deep-seated landslide near Lake Rinihue covered a 1.26 km^2 area, moved 300 m horizontal and 20 m vertical in less than 5 minutes. The failure plane was in saturated lacustrine silt and clay of Pleistocene age	Duke and Leeds, 1963
1964, Alaska, USA (M 8.5)	Holocene fluvial deposits along rivers in south-central Alaska	Abundant to pervasive lateral spreading, ground settlement, fissures and sand boils occurred to a distance of 160 km from the epicenter and sporadic to locally abundant effects of these types occurred up to 500 km from the epicenter	Fluvial deposits in this region contain little or no clay-size particles	U. S. Geological Survey, 1966-1970
	Holocene alluvial-fan and -plain deposits in south-central Alaska	Abundant to sporadic lateral spreading, ground settlement, fissures and sand boils up to 320 km from the epicenter		U. S. Geological Survey, 1966-1970
	Holocene deltaic deposits in south-central Alaska	Sporadic to abundant flow landslides, lateral spreading, ground settlement, fissures and sand boils in active deltas within 160 km of epicenter	The deltas are extensions of alluvial fan deposits into the sea	U. S. Geological Survey, 1966-1970

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1964, Alaska, Contd.	Holocene and Pleistocene glacial outwash terraces	No effects to locally abundant lateral spreading, ground settlement, fissures and sand boils within 160 km of epicenter	Effects were most severe where water table was near surface and terraces were dissected by streams	U. S. Geological Survey, 1966-1970
	Pleistocene glacial moraine and till deposits in south-central Alaska	No significant effects reported		U. S. Geological Survey, 1966-1970
	Pleistocene estuarine-moraine deposits (Bootlegger Cove clay) underlying Anchorage	Several large, deep-seated, lateral-spreading landslides occurred in a 100 km^2 section including Anchorage. Additional fissuring was common in areas above landslides	Principle failure planes (20m - 30m deep) passed through Bootlegger Cove clay unit which contains frequent silt and sand senses	U. S. Geological Survey, 1966-1970
	Holocene beach deposits on Homer spit and Shearwater Bay (270 km and 520 km from epicenter)	Localized occurrences of lateral spreading and fissures	Both beaches are located in bays that are somewhat protected from the open sea	U. S. Geological Survey, 1966-1970
1964, Niigata, Japan (M 7.5)	Holocene fluvial deposits and reclaimed land over fluvial deposits in the Niigata sedimentary basin	Pervasive lateral spreading, bearing capacity failures, ground settlement, fissures and sand boils occurred in a 20 km^2 area of Niigata and its environs. Sporadic to locally abundant similar effects occurred throughout the 500 km^2 Niigata sedimentary basin	Sands and silty sands generally with average N-values less than 10 in the upper 10 m extend to considerable depths in the affected areas. Water tables were within a few meters of surface in most areas. Sediments deposited or placed in the last 100 years were more severely affected than those several hundred years old	Kawasumi, 1968
	Holocene and Pleistocene alluvial-plain deposits in the Niigata sedimentary basin	Sporadic lateral spreading, ground settlement, fissures and sand boils occurred in a 500 km^2 area	Effects were much less severe than on fluvial deposits	Kawasumi, 1968
	Holocene aeolian sand dune deposits along Sea of Japan near Niigata	Sporadic to locally abundant lateral spreading, fissures and sand boils occurred in some dune areas	Some but not all effects may have originated in underlying fluvial or alluvial-plain deposits	Kawasumi, 1968
1965, Chile (M 7 - 7 1/4)	<100-year-old hydraulic fill dams in mountainous region north of Santiago	Of 22 tailings dams in a 50 km^2 area most failed by flow landslides and several were completely destroyed. One dam failure released a 1,900,000 m^3 flow that traveled 12 km and killed more than 200 people	The tailings deposits consisted mainly of silt- and clay-sized particles	Dobry and Alvarez, 1967
1968, Tokachi-Oki, Japan (M 7.9)	Holocene and Pleistocene fluvial and alluvial-plain deposits on northern Honshu and southern Hokkaido islands	Sporadic to locally abundant lateral spreading, bearing capacity failures, ground settlement, fissures and sand boils developed in a 260-km-long zone	Water tables were generally near or above surface due to topographic location of deposits and 160-210 mm of rain that fell in the 3 days prior to the earthquake. Severity of effects generally decreased with age of deposit	Suzuki, 1971
	Pleistocene volcanic ash and pumice deposits (Shirasu geologic unit). These deposits are widespread in epicentral area	Sporadic to locally abundant flow and lateral spreading landslides, bearing capacity failures, fissures and sand boils in a 260-km-long zone	Water levels were generally high due to heavy rains in 3-day period preceeding earthquake. Abundance of flow landslides was greatest in areas of highest rainfall	Suzuki, 1971
	<100-year-old artificial fills, embankments and levees over fluvial and alluvial-plain deposits in northern Honshu and southern Hokkaido Islands	Sporadic to locally abundant flow and lateral spreading landslides, bearing capacity failures, settlement, fissures and sand boils	Many failures involved only materials in the fills and embankments. The surficial materials were wet, if not saturated, due to heavy rains	Suzuki, 1971
1971, San Fernando, California, USA (M 6.4)	Holocene alluvial-fan deposits east and west of Van Norman Lake	Two separate lateral spreading landslides accompanied by fissures and sand boils	N ranged between 20 and 25 in suspect saturated alluvial layer at 16 m depth in one landslide area	Dixon and Burke, 1973 Youd, 1971
	<60-year-old hydraulic fill dams in northern San Fernando valley	Embankment failures occurred in two dams		Seed and others, 1975
1976, Guatemala (M 7.5 preliminary)	Holocene fluvial deposits along Motagua and other rivers	Sporadic to locally abundant fissures and sand boils in a 130-km-long zone	Sediments were mainly micaceous quartz and pumice sand	Hoose, 1976 unpub. data
	Holocene deltaic deposits at Lakes Amatitlan and Atitlan, Guatemala, and Lake Illopongo, El Salvador	Sporadic to locally pervasive lateral spreading, ground settlement, fissures and sand boils, and some bearing capacity failures	Sediments composed of fine silt- to cobble-size pumice. Dry density of in-place sediments about 0.6 gm/cm^3	Hoose, 1976 unpub. data
	Holocene aeolian sand dunes at Omoa, Honduras	One local instance of lateral spreading, fissure and sand boils		Plafker, George, 1976, oral commun.