NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

State University of New York at Buffalo

LIQUEFACTION POTENTIAL OF SURFICIAL DEPOSITS IN THE CITY OF BUFFALO, NEW YORK

by

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NOTICE

ABSTRACT

The potential for earthquake-induced liquefaction of cohesionless sediments in Buffalo, New York was calculated from geotechnical data using a probabilistic method. The essential geotechnical data used were the standard penetration number, the depth of ground water and the grain size of the soils. Although the selected area of this study (approximately 48 square miles) has a moderate amount of seismic activity, it was found that the probability of liquefaction is generally less than 10 percent for a peak ground acceleration of 0.15 g. An area about 2 square miles trapped between Lake Erie and the Buffalo River, however, was found to have a moderate potential (probability 10-50 percent) for liquefaction.

ACKNOWLEDGEMENT

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INTRODUCTION

Liquefaction-induced ground deformation and failure can cause extensive damage to structures and lifeline utilities as attested, for example, by the Great Alaskan earthquake in 1964 and the San Francisco earthquake in 1971. Thus, a knowledge of the location of potentially liquefiable soils in seismicity active areas should be an integral part of an earthquake hazards reduction program. The term liquefaction is commonly used to define a condition in which a saturated cohesionless soil is transformed from a solid condition to a viscous fluid condition by dynamic loading. Some areas in the city of Buffalo, especially along the waterfront of Lake Erie and the Buffalo River, contain loose cohesionless sediments. These types of sediments generally have very high potential to liquefy if the ground water level is at or near the ground surface.

In this report, an evaluation of the potential for earthquake-induced liquefaction of sediments in the City of Buffalo, New York is presented. The study area selected, based on a preliminary study of the geology and the seismicity of western New York, is shown in Figure 1-1. Preliminary findings for a portion of the selected area were reported in NCEER Technical Report NCEER-87-0009 (Budhu et al., 1987).

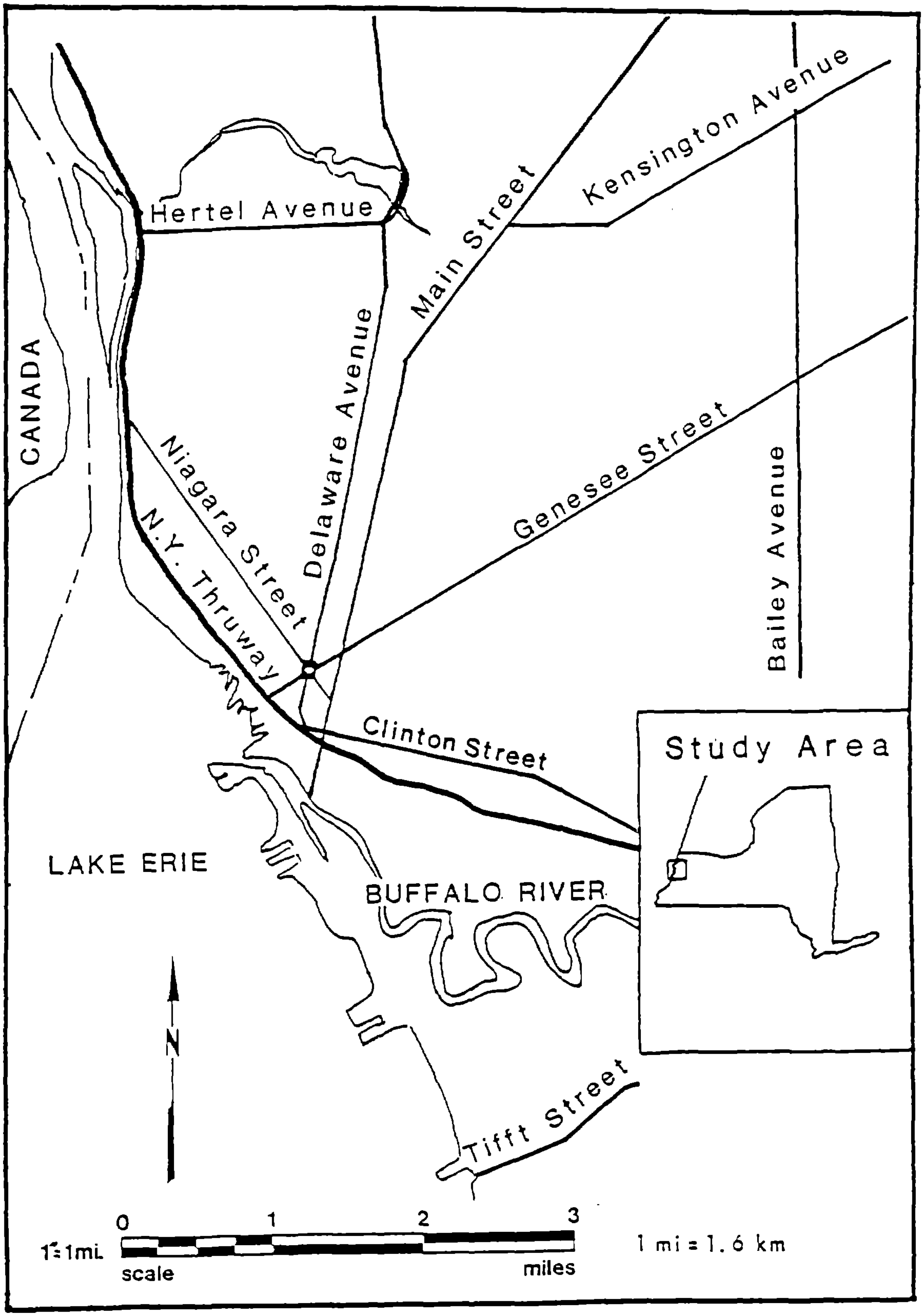

FIGURE 1-1 Site Location Encompassing the City of Buffalo

SECTION 2

GEOLOGIC CONDITIONS OF STUDY AREA

2.1 Area Seismicity

The eastern United States and Canada are in an intraplate zone of moderate seismic activity. Looking at event with Modified Mercalli intensities greater than or equal to VIII, these are located in Quebec (La Malbaie), the zone from northern New York to Kirkland Lake, Boston, New Madrid, Charleston, Attica and Massena, and a few other, apparently isolated events. Four active seismic zones in the eastern United States and Canada have been identified by Sbar and Sykes (1977): a northwest trending belt from northern New York to Kirkland Lake, Ontario; a north- northwest trending zone from Boston, Massachusetts through central New Hampshire; a cluster of activity approximately 130 km northeast of Quebec City and the Attica-Dale region of western New York (Figure 2-1). Additional zones of moderate seismic activity in New York are present in western Lake Ontario, the Adirondack mountains and the Hudson highlands. Figure 2-2 shows epicentral locations and Modified Mercalli intensity values for historical New York State earthquakes. A listing of historical earthquakes from 1737 to 1977 along with hypocenter, time, date, and intensity information is presented in Appendix A (after Stover at al., 1981).

According to Barosh (1985), earthquakes in the eastern U.S. are due to coastal downwarping, adjacent bulging, and interior subsidence caused by widening of the Atlantic basin. All major historical earthquakes have occurred within or near these zones. Two sets of fracture zones are related to the opening of the Atlantic basin; an initial set of north-trending fractures and a subsequent set of northwest-trending fractures.

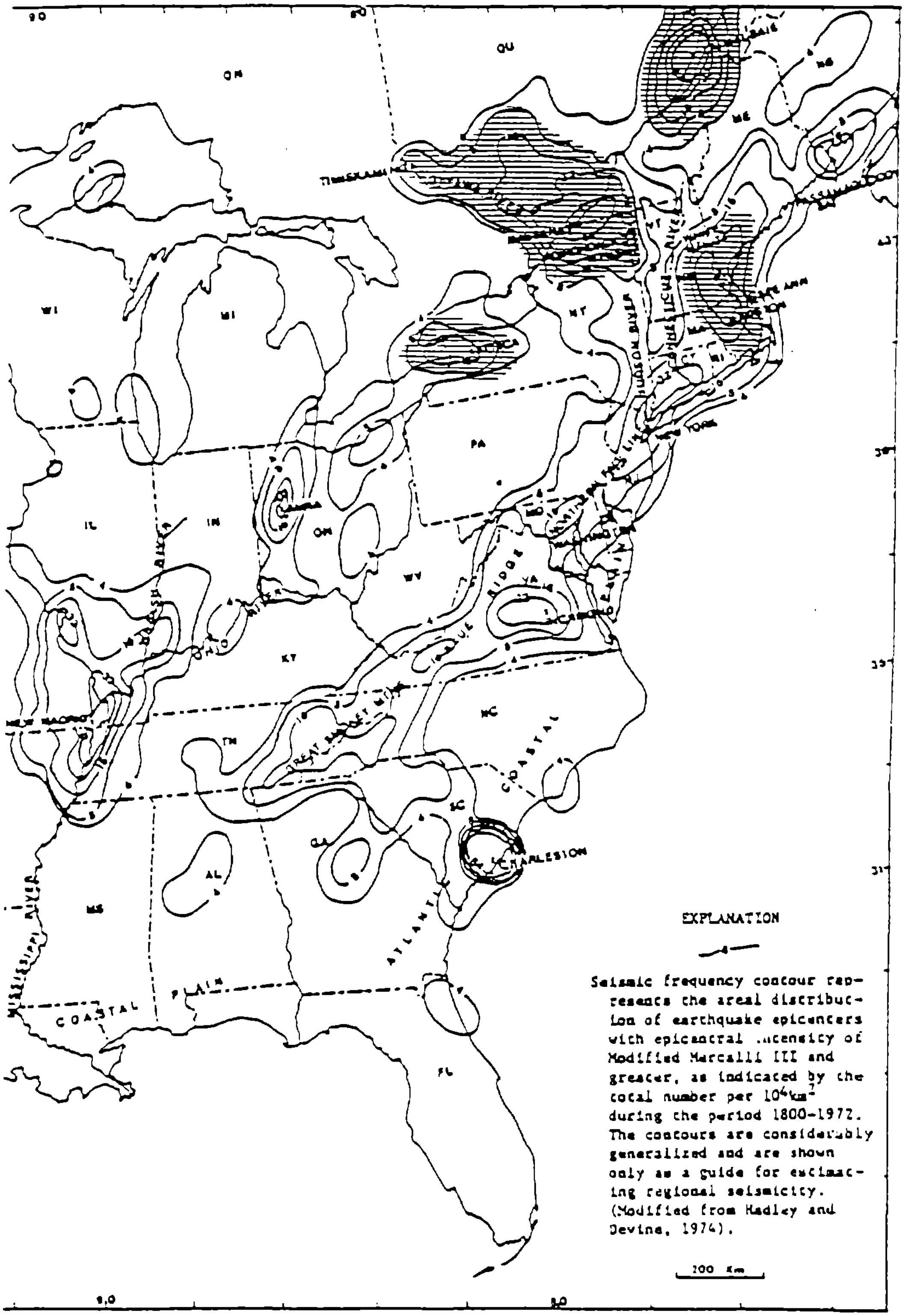

FIGURE 2-1 Eastern United States Seismicity. Shaded Areas Depict Seismicity Zones of Sbar and Sykes (1977). After Barosh (1985).

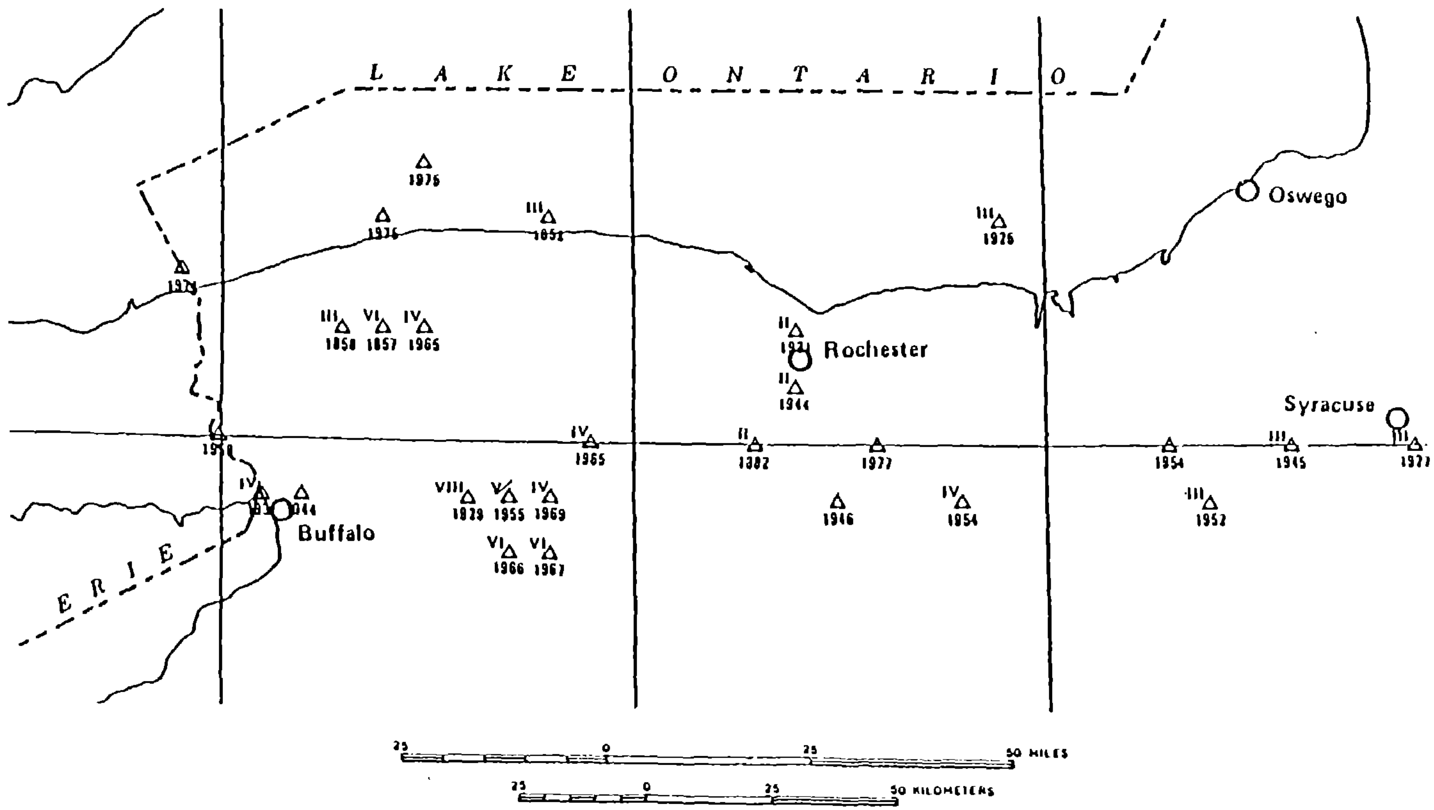

FIGURE 2-2 Epicentral Locations and Intensities of Western New York Earthquakes. Roman Numerals Denote Modified Mercalli Intensity Values. After Stover et al. (1981).

Earthquakes in New York generally occur where the two fracture zones intersect belts of vertical movement (Barosh, 1985). Analysis of the geographic distribution of earthquakes in New York since 1720 and the seismic energies released by these earthquakes as a function of time indicates a cyclical nature of earthquake occurrence (Mitronovas and Nottis, 1985). According to Mitronovas and Nottis (1985), secular variations in seismicity throughout New York do not occur randomly but instead reflect the forces which trigger the seismicity. Sbar and Sykes (1977) proposed the existence of different stress domains in the eastern and central United States. A domain of ENE oriented horizontal compressive stress extends approximately from Hudson Bay on the north to the Mississippi embayment on the south. This zone possibly ranges westward to the Rocky Mountains and eastward to Baffin Island. This stress domain is characterized by dominantly normal faulting near the Mississippi embayment and thrust faulting to the north of the embayment. The ENE stress orientation is relatively uniform from Ohio to eastern New York and southern Ontario, with the exception of the Attica-Dale area. The Attica-Dale stress domain trends WNW as evidenced by fault plane solutions, hydrofracture stress measurements, and pop-ups (Sbar and Sykes, 1977). The origin of this deviation is unknown, but may be attributable to past earthquakes.

The Attica-Dale area is the site of the largest earthquake recorded in western New York. This earthquake occurred on August 12, 1929 and had a Modified Mercalli intensity of VIII and an estimated magnitude of 5 to 6. Its principal shock had a duration of 12 seconds and tremors occurred for six minutes. The earthquake was experienced over an area of 130,000 square kilometers (Fletcher and Sykes, 1977). The overall damage incurred by this earthquake was slight. However, the effects were strongly felt at some locations throughout the area (Buffalo Courier Express, 8/13/29). The seismicity of the Attica-Dale area is attributed to the Clarendon-Linden fault system (Figure 2-3). This system is a north-northeast trending 5 to 15 kilometer wide zone of steeply dipping reverse and normal faults in Precambrian basement and lower Paleozoic bedrock (Fakundiny et al., 1978). Vertical offset is estimated to range between 30 and 90 meters in Ordovician through Devonian rocks (Hutchison et al., 1979). The Clarendon-Linden fault zone extends from north of the Pennsylvania border to Lake Ontario. Seismic and magnetic data indicate that the fault zone continues beneath Lake Ontario as the Scotch Bonnet Rise, and for an additional 100 kilometers into the Bancroft area of southern Ontario (Hutchison et al., 1979). The Clarendon-Linden fault system is perhaps the longest and oldest active fault in the eastern United States as evidenced by activity over several intervals (Fakundiny et al., 1978). Fakundiny et al., (1978) suggest the following evidences for the Clarendon-Linden activity (1) aeromagnetic anomalies suggest strike-slip movement in Precambrian basement rocks; (2) thickened Trenton group carbonate rocks to the east of the fault system indicate growth faulting during Ordovician time; (3) the system forms an open down-to-the-west monoclinal fold above Silurian bedrock; and (4) intermittent activity may have occurred during Pleistocene time.

2.2 Bedrock Geology

Precambrian Canadian Shield rocks consisting of metagabbros, granites, marbles, and mafic rocks are exposed approximately 150 kilometers to the north of the study area (Fakundiny et al., 1978). It is probable that this suite of crystalline rocks also underlies the sedimentary section of western New York. Exposed bedrock ranges in age from Late

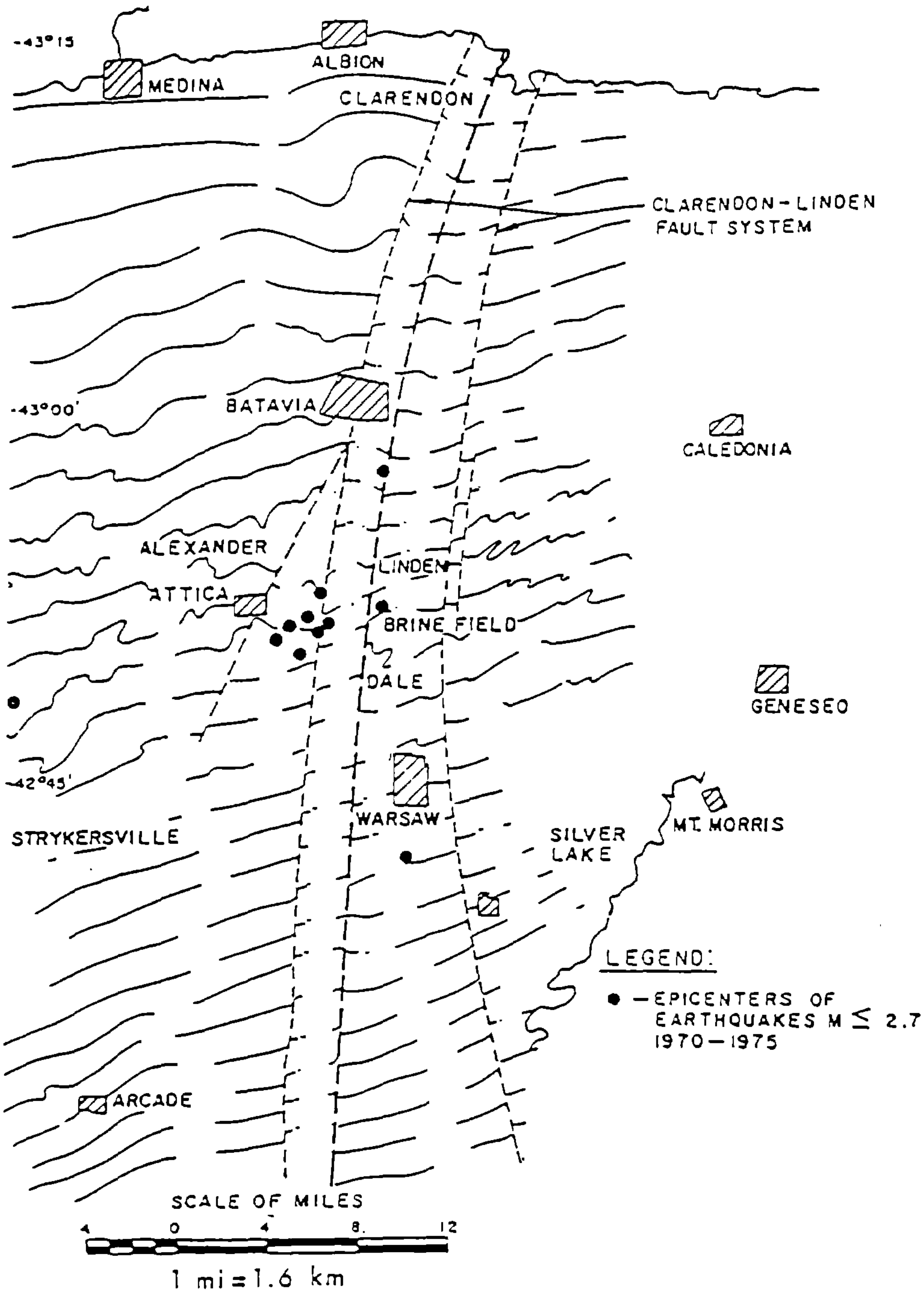

FIGURE 2-3 Clarendon-Linden Fault Zone. (After Van Tyne, 1975).

Silurian to Middle Devonian. Lower Devonian rocks are not represented in the stratigraphic record. Sedimentary rocks have a regional southerly dip of approximately 40 ft. per mile (Buehler and Tesmer, 1963). Figure 2-4 shows area bedrock and Figure 2-5 shows elevations of the bedrock surface. Several channels have been incised into this surface. Two main channel systems are located generally in the present Scajacquada Creek and Buffalo River drainage basins. The origin of these channels is uncertain. Some or all may be relicts of subaerial drainage during interglacial intervals. However, some may be products of subglacial meltwater movement.

2.3 Surficial Geology

A surficial geologic map and a fence diagram of the study area are shown in Figure 2-6 and Figure 2-7 respectively. General descriptions of the sediments were compiled from drilling logs. Sediment descriptions and in-situ density values given on drilling records have been interpreted to correlate major depositional units and formulate a general geologic description of the study area (Table 2-I). Regional deposits are designated as units 1 through 4, youngest to oldest, respectively. Unit 4 is divided into sub-units 4A and 4B to denote facies change. Localized deposits (i.e. channel deposits) are not numerically designated.

The Main Street channel is filled with sand and gravel deposits that are course in upper reaches and grade to fine sand at the south end of the system. Lenses and thick seams of silty sand are interfingered between the bedrock and Unit 4 at the south end of the Main Street-Buffalo River bedrock channel. Sediments in this system range in thickness from 2

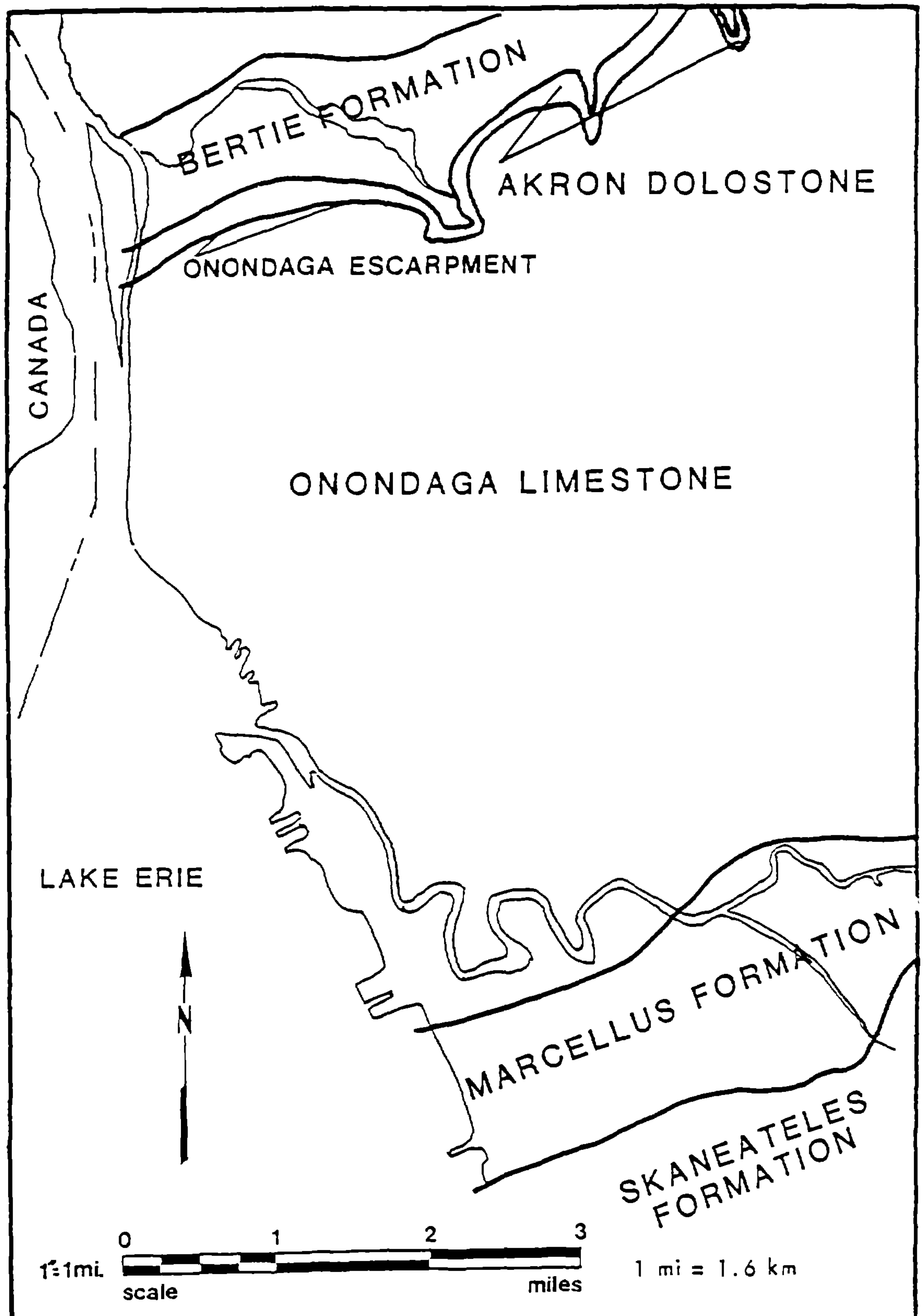

FIGURE 2-4 Bedrock Formations of Study Area. After Buehler and Tesmer (1963).

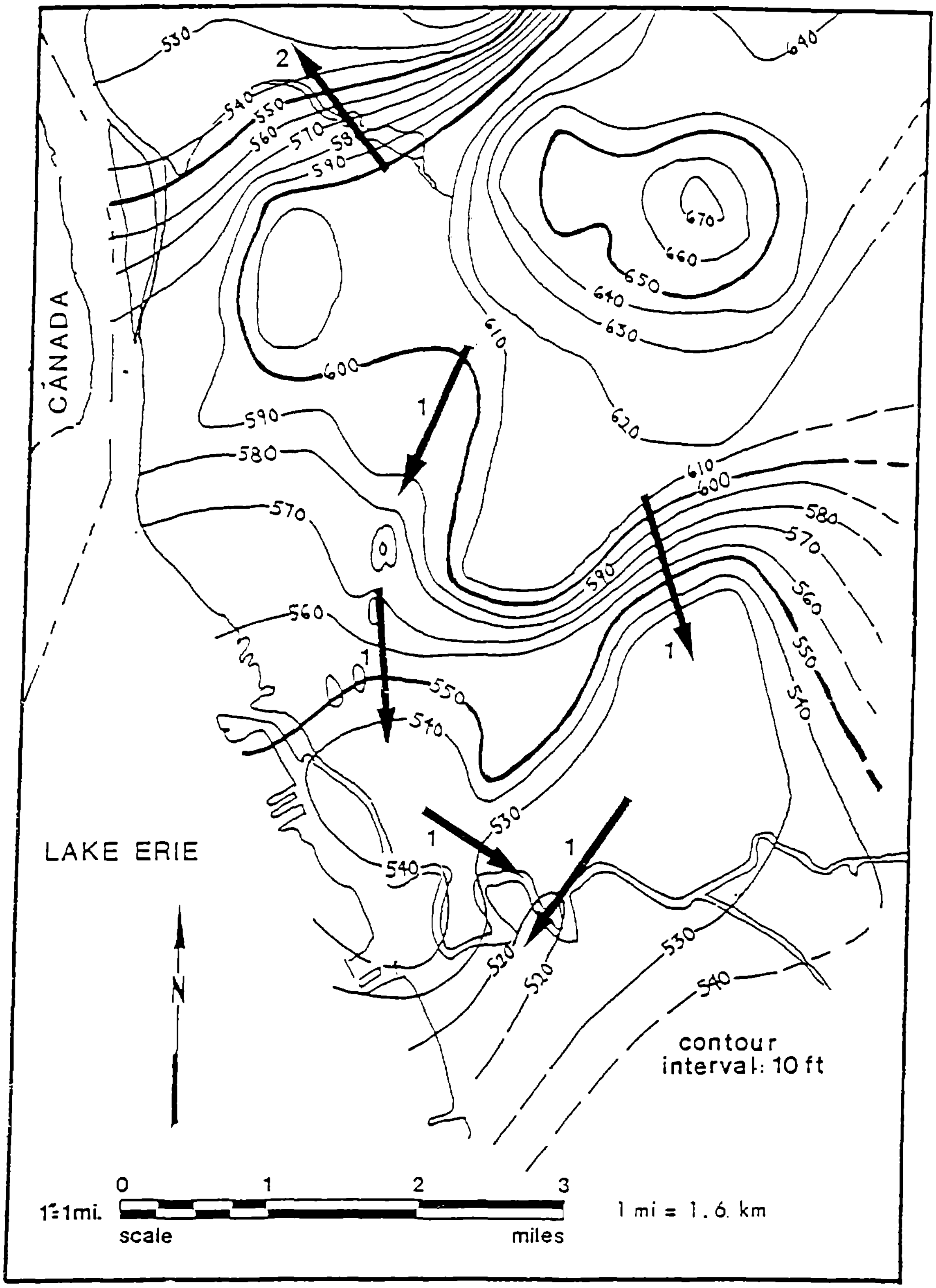

FIGURE 2-5 Bedrock Elevations. Arrows Show Flow Directions of Bedrock Channels. (1) Main Street-Buffalo River Channel; (2) Scajacquada Creek Channel.

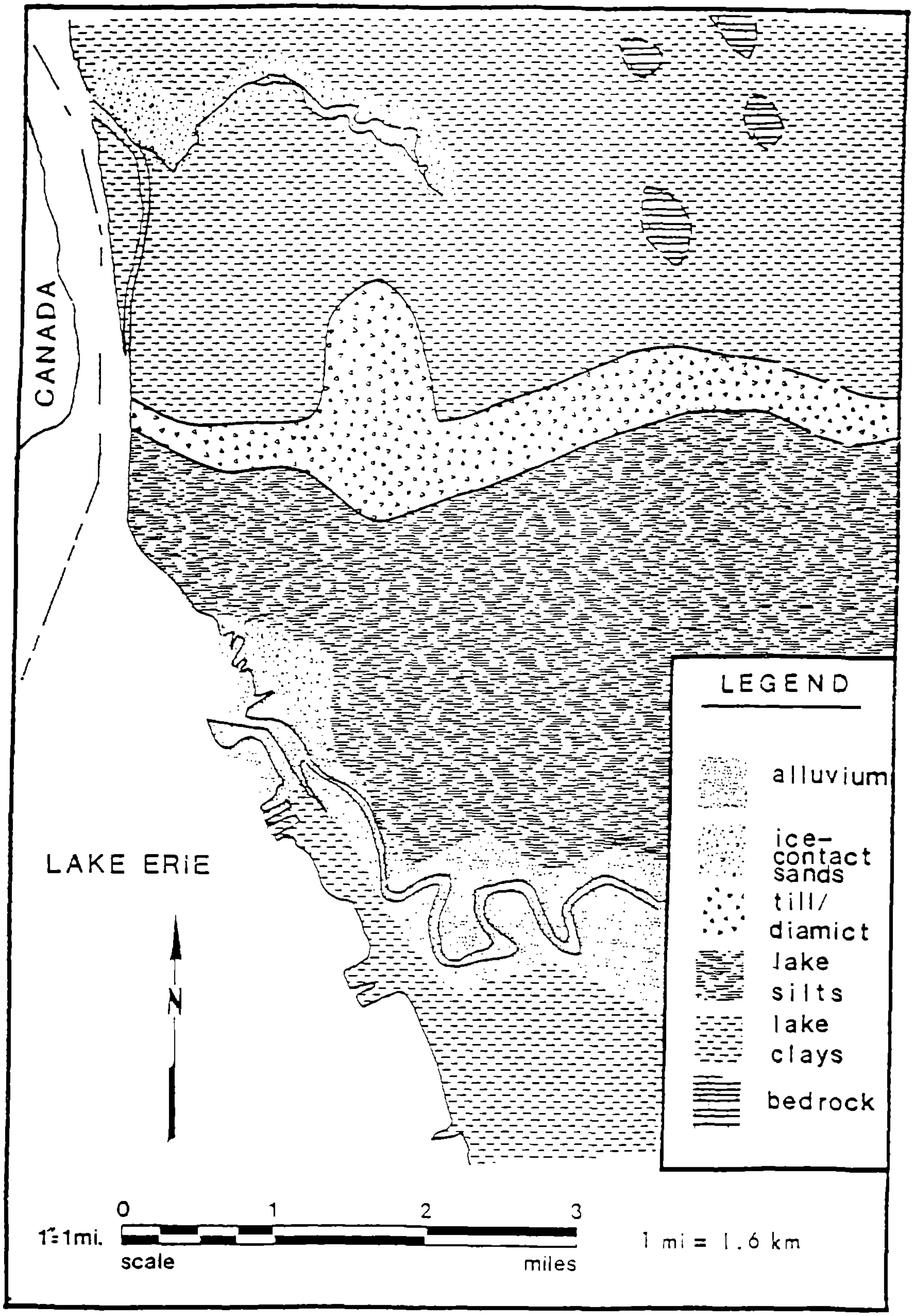

FIGURE 2-6 Surficial Geologic Map of Buffalo

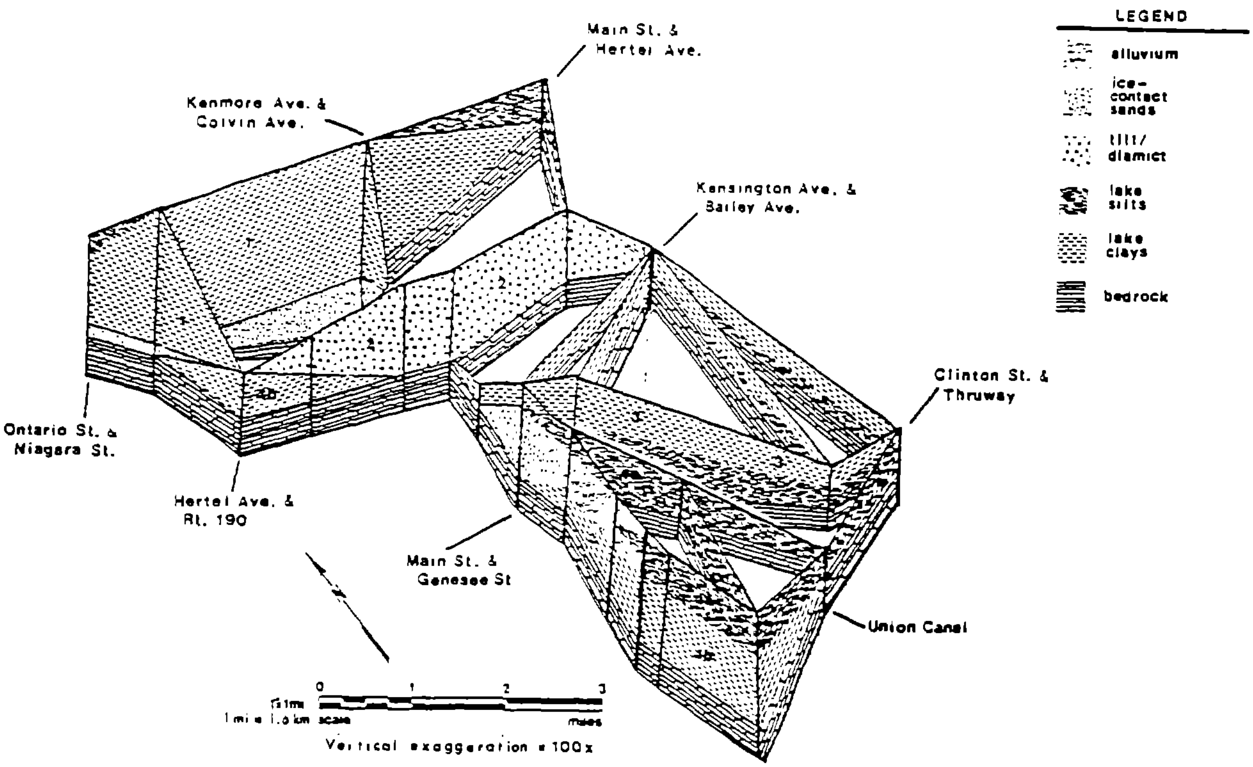

FIGURE 2-7 Fence Diagram of Study Area. See Table 2-I for Explanation of Unit Members.

to 80 ft. The Scajacquada Creek channel is filled with gravelly sand which overlies an approximately 12 ft thick layer of diamict. Sediments in this system typically consist of firm to very compact gravelly sand and sandy gravel with a trace of silt.

2.4 Disturbed Sediments

Surficial deposits have been disturbed by dredging and landfilling at many locations throughout the waterfront area (Figure 2-8). A network of inland waterways, canals, and slips were constructed in the 1800's in the Tifft Street, Black Rock Harbor, and Buffalo Harbor areas. These inland waterways were filled in the early 1900's as alternate transportation systems were implemented. The present Lake Erie shoreline has been extended 600 to 800 ft. lakeward of its natural position by extensive filling since the 1800's. Off-shore deposits are presently being dredged or filled over by Army Corps of Engineers diked disposal area projects. The fill consists of dredgings and debris.

Table 2-I. General Stratigraphic Sequence of the Study Area in Buffalo.

Unit	Thickness	Description
1	2-75 ft. 0.6-23 m	Layered clayey silt and silty clay, grey, with fine stones; firm to very dense.
2	25-50 ft. 8-15 m	Interbedded diamict* consisting of till, stony silt/clay, and sand; silt and clay stiff to hard; sand compact to dense.
3	15-20 ft. 5-6.5 m	Silty clay brownish-grey; with sand laminae and fine stones; stiff to hard.
4a	2-20 ft. 0.6-6 m	Layered clayey silt and clay with trace clay; grey to greyish brown; medium to soft; rhythmically bedded in areas.
4b	2-40 ft. 0.6-12 m	Silty clay with fine sand laminae; red-brown to grey; soft to stiff; rhythmically bedded in areas.

Notes:

* *Diamict* is a non-genetic tern meaning a "poorly sorted, unlithified gravel-sand-mud admixture" (Eyles, 1983).

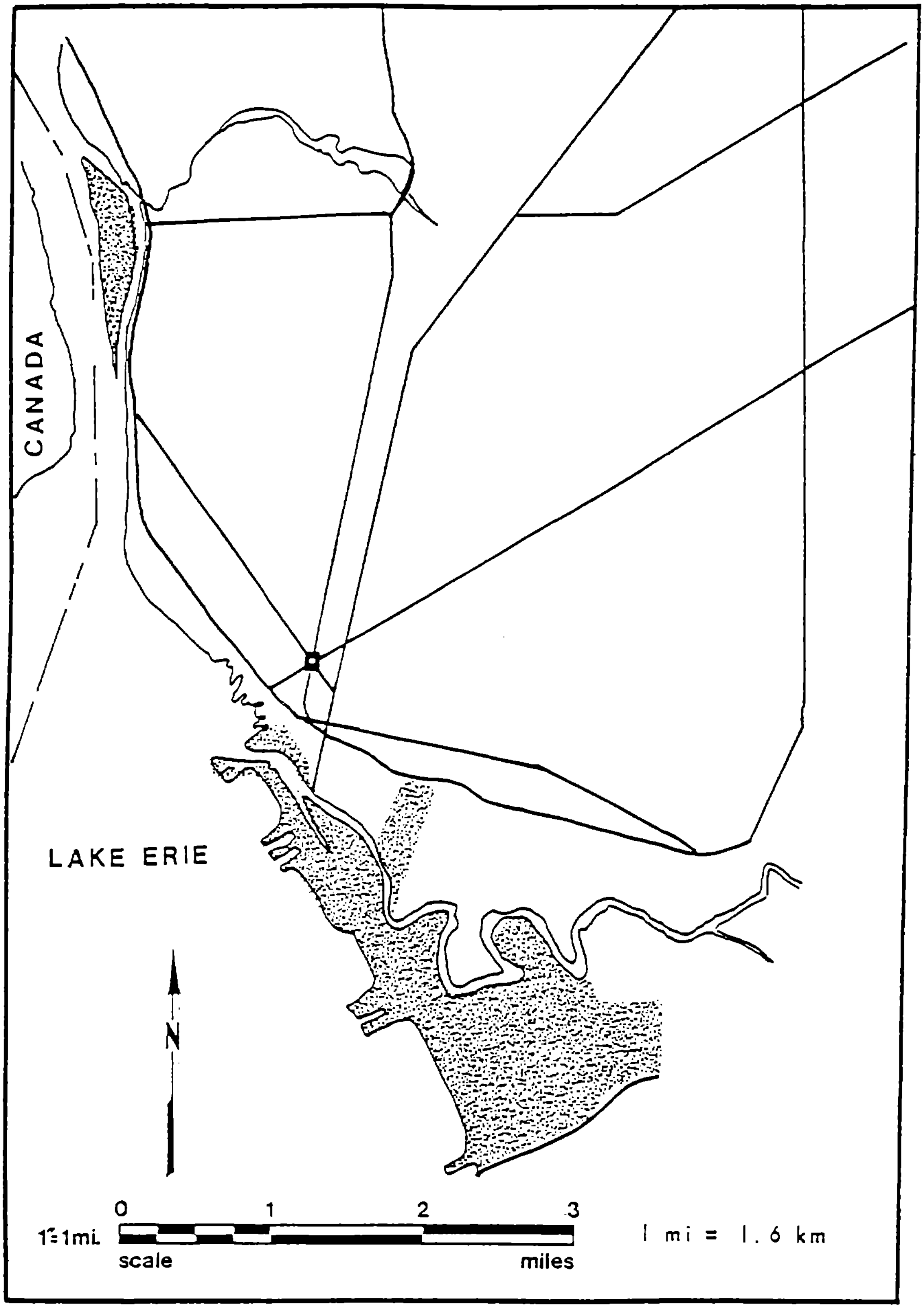

FIGURE 2-8 Locations of Filled Areas. Shaded Zones Depict General Areas of Waterfront Land Created by Landfilling.

SECTION 3

LIQUEFACTION POTENTIAL EVALUATION

3.1 The Influence of Geologic Setting

The primary geologic criteria of liquefaction susceptibility are (1) depositional age, (2) depositional environment, (3) depth of burial and (4) water table depth (Youd and Hoose, 1977). Liquefaction due to earthquakes has rarely, if ever, been observed in deposits older than Pleistocene. This is primarily due to induration of units with age via processes of intergranular cementation and by overburden preconsolidation in the case of glaciated terrains. In general, fluvial and deltaic sediments are most susceptible to liquefaction. Other types of deposits sensitive to liquefaction include alluvial fans, plains, beaches, terraces, playa, and estuarine deposits. In these deposits, liquefaction does not occur as commonly as in fluvial and deltaic sediments. The process of deposition is an important factor in the sorting and density of a sediment. Fluvial and deltaic sediments typically have a lower percentage of fines (clay and silt size particles) than other water-laid deposits (with the exception of beach deposits) because of relatively greater current velocities during their deposition. A high percentage of fines lends some cohesion to a sediment and thereby increases its shear strength. The depth to the water table, or height of the saturated soil column, is one of the critical factors in determining liquefaction susceptibility. Cohesionless soils with perched water zones are likely to be as susceptible as zones beneath the actual groundwater table. However, perched water tables are less likely to cause extensive damage due to their isolated occurrences.

3.2 Field Test to Determine Liquefaction Susceptibility

In current practice, the potential of a soil to liquefy is related to the Standard Penetration Test (SPT) (ASTM D1586-84). The SPT test involves the dropping of a hammer of a certain weight from a fixed height and counting the number of blows required to penetrate each of 3 six inches of a split sampling tube of length 18 inches into the soil. The SPT number called the N-value is the average number of blows for the last 2 of 6 inches of a full penetration of 18 inches. ASTM D1586-84 standard (referred to in this report as the standard) stipulates that the hammer should weigh 140 lbs. and the height of fall should be 30 inches. There are many shortcomings of the SPT which raise doubts on its usefulness as a reliable test not only for liquefaction studies but also for soil properties determination. Nevertheless, the SPT is a simple test, a large body of test data is available and SPT numbers (N) have been correlated to sites which have liquefied.

In order to make use of the available SPT data (many from non-standard tests, that is, the weight of the hammer, the height of the drop and the drive systems vary from ASTM (D1586-84), the N values were corrected for a hammer energy ratio of 60%, N_{60}, (Seed et al., 1984), and to an effective overburden pressure of 1 ton per square foot, $N_{1(60)}$, (Seed et al., 1983). For this study, N values were corrected as shown in the following sections.

3.2.1 Correction for Hammer Ratio and Relative Soil Density

The hammer ratio (R_s) was calculated from (Lowe and Zaccheo, 1975):

$$R_s = \frac{D_o^3 - D_i^3}{144WH} \qquad (3.1)$$

where D_o and D_i are the outer and inner diameters of the sampling tube in inches (respectively); W is the hammer weight in lbs; and H is the distance of the hammer fall in inches. Relative soil densities of less than 50% were corrected using Equation 3.2.

$$N_e = \frac{N}{4050 R_s^{5/7}} \qquad (3.2)$$

where N_e is the corrected value and N is the field value. This equation was derived by Budhu et al. (1987) from the graphs produced by Lowe and Zaccheo (1975).

3.2.2 Normalization of Effective Overburden Pressure

The effective overburden pressure is normalized to a value of 1 ton per square foot by (Liao and Whitman, 1985):

$$N_{1(60)} = C_n N_{60} \qquad (3.3)$$

where C_n is a correction coefficient equal to $(\sigma^{-1/2})$.

3.3 Calculations of Liquefaction Potential

A procedure for evaluating liquefaction potential on the basis of observed field performance data has been established by Seed et al. (1984). This method employs a correlation between sediment penetration resistance and the average cyclic shear stress ratio (τ_{av}/σ) required for liquefaction.

To evaluate liquefaction potential by this method, a peak ground acceleration value (a_{max}) for a design earthquake is selected and the average cyclic shear stress ratio value for each soil layer is calculated from

$$\frac{\tau_{av}}{\sigma} = 0.65 \frac{a_{max} \sigma^t}{g \sigma} r_d \qquad (3.4)$$

where g is the acceleration due to gravity, σ^t is the total vertical stress, σ is the effective vertical stress and r_d is an average stress reduction factor that decreases approximately linearly from a value of 1 at the ground surface to a value of 0.9 at a depth of 35 ft.

Figure 3-1 shows the coordinate values of $[N_{1(60)}, (\tau_{av}/\sigma)]$ for sites with similar average grain size which have liquefied. Coordinates of $[N_{1(60)}, (\tau_{av}/\sigma)]$ that lie above the field performance curve will liquefy under an earthquake of magnitude 7.5.

3.4 Liquefaction Probability

Probabilistic models for evaluation of liquefaction potential have been developed by Liao et al. (1988) using regression analyses of SPT data from 278 sites at which liquefaction occurred. One of these models, the Cyclic Stress Ration (CSR) model assigns probability of liquefaction values to average cyclic shear stress ratio vs. corrected SPT curves. This model is similar to that of Seed et al. (1984) except that, rather than having one demarcation curve, there are now several curves each delimiting a different probability for liquefaction (Figure 3-2)

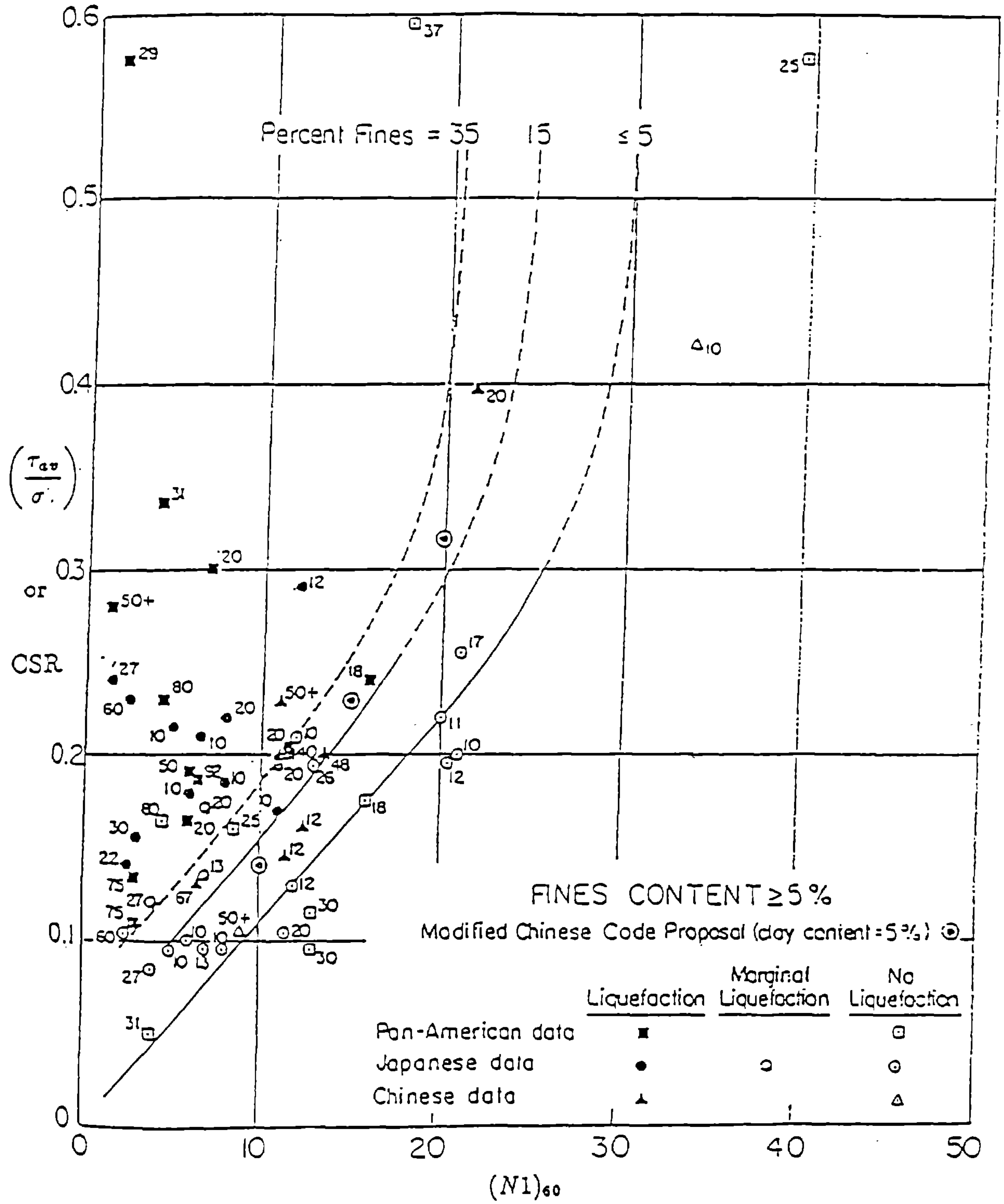

FIGURE 3-1 Seed's $(N1)_{60}$, CSR Relationship (Seed's Criteria Plot) - Silty Sands (After Seed et al., 1984).

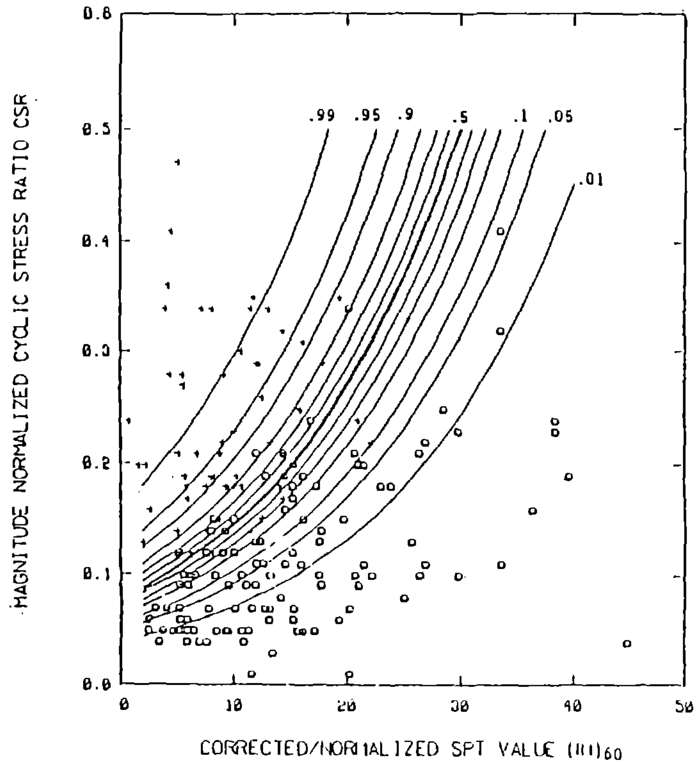

FIGURE 3-2a Liao's $(N1)_{60}$, CSR Relationship Indicating Probability of Liquefaction (Liao's Criteria Plots) - Clean Sands - Fines Content ≤ 12% (After Liao et al., 1988).

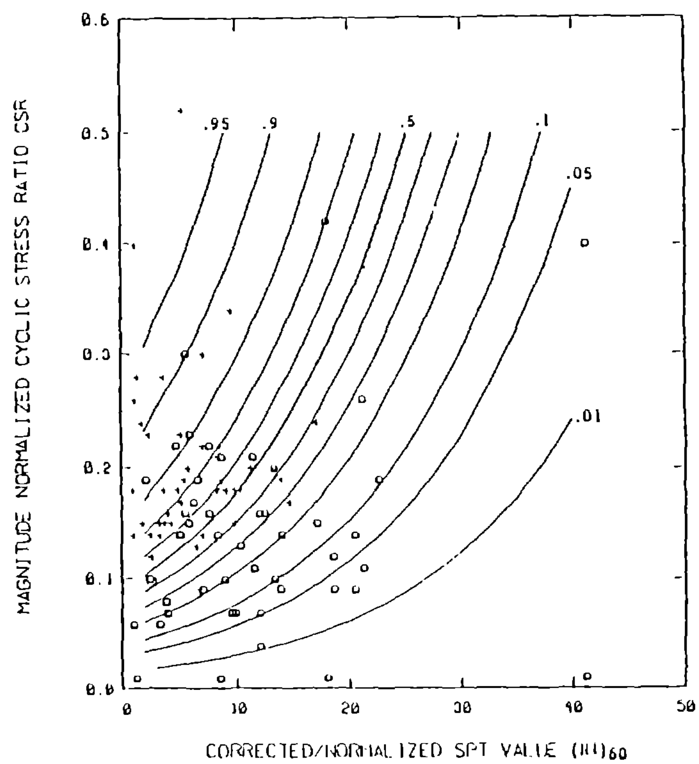

FIGURE 3-2b Liao's $(N1)_{60}$, CSR Relationship Indicating Probability of Liquefaction - Silty Sands - Fines Content ≥ 12% (After Liao et al., 1988).

SECTION 4

METHODOLOGY USED FOR LIQUEFACTION POTENTIAL MAPPING

4.1 Data Collection

A literature search was implemented through the on-line computer databases, GEO-REF, GEOBASE, and GEOARCHIVE at the National Center for Earthquake Engineering Research Office of Information Services. Newspaper articles documenting the local effects of past earthquakes were extracted from the Buffalo Courier Express (1929) and the Buffalo Gazette (1812). These newspapers were found in the Buffalo Historical Society archives. Geologic and engineering reports, and approximately 2,000 drilling logs were collected from several agencies (in particular, the United States Army Corps of Engineers, Buffalo District; Geotechnical Section, New York State Department of Transportation; City of Buffalo Department of Public Works; Engineering and Survey Divisions, City of Buffalo Sewer Authority; Empire Soils/Thomsen Associates, Inc.) in the greater Buffalo area.

4.2 Representative Drilling Logs

Approximately 500 drilling logs were chosen as representative borings (see location in Figure 4-1) and incorporated into a database by the following criteria:

(1) Location with respect to the study area

(2) Clarity of geologic description by drillhole logging personnel

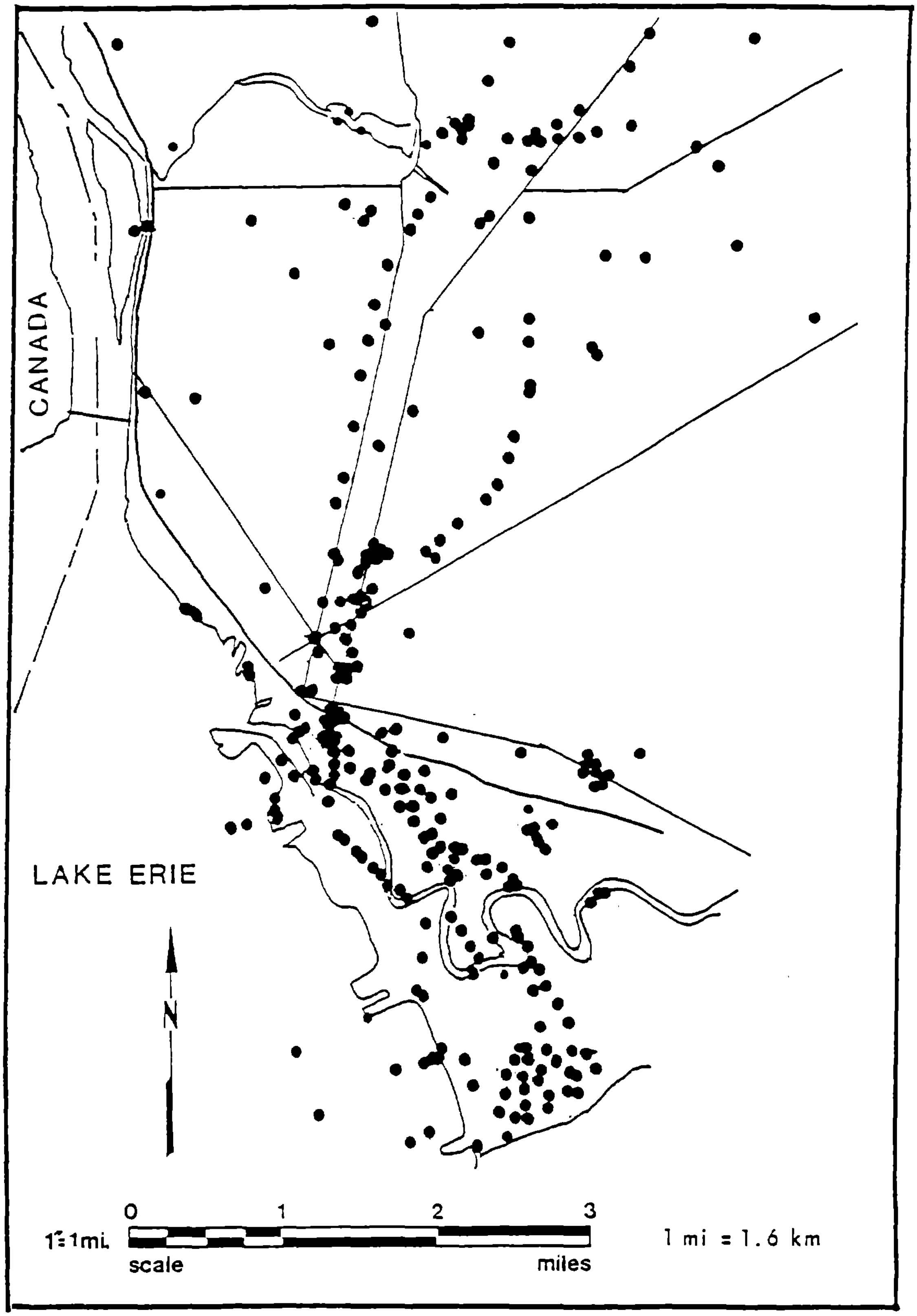

FIGURE 4-1 Test Boring Locations

(3) Similarity of stratification and of N-values with other nearby boreholes

Geographic coordinates were determined for each test boring using survey data and USGS quadrangle maps. Sediments were correlated by logged descriptions of textural composition and gradations, relative elevations, and mineralogic color ranges. Textural and sorting characteristics were determined from the Unified Soil Classification System and ASTM descriptions that were recorded on the drilling logs.

4.3 Determination of Liquefaction Potential

Potentially liquefiable sand deposits at depths of 50 feet or less and with N-values of 15 or less were extracted from the database. Soil layers with thicknesses less than one foot were not considered due to conventions of the SPT test (the N-value being the average number of blows for the last 2 of 6 inches of a full penetration of 18 inches). N-values were standardized to represent a hammer energy ratio of 60% (N_{60}) and an effective overburden pressure of 1 ton/ft^2 (Seed et al., 1984). Cyclic shear stress ratios were calculated according to Seed et al. (1983) using a peak seismic acceleration value of 0.15g (Algermissen et al., 1982). Coordinates of $[N_{1(60)}, \tau_{av}/\sigma)]$ were compared to type curves according to Seed et al. (1984) to determine liquefiability. Liquefaction probability values were determined by the critical stress ratio method of Liao et al. (1988), using an assumed average bulk unit weight of 110 lbs./ft^3. A liquefaction potential probability map has been produced essentially using the methods established by Seed et al. (1983) and the probability curves of Liao et al. (1988). The liquefaction potential map is divided into zones corresponding to arbitrarily selected descriptions of high, moderate and low probability according to the following scheme.

H	high	probability of liquefaction	> 50%
M	moderate	probability of liquefaction	10 - 50%
L	low	probability of liquefaction	< 10%

SECTION 5

ASSESSMENT OF LIQUEFACTION POTENTIAL

Table 5-I presents a typical liquefaction potential and probability calculations for identified liquefaction susceptible locations. All of the susceptible sediments are of glaciofluvial origin with the exception of a pocket of loose sand north of the Buffalo Moraine. Figure 5-1 is the liquefaction potential map for the study area. Examination of geologic conditions in the City of Buffalo according to criteria proposed by Youd and Hoose (1977) shows possible liquefaction opportunity for areas along the Buffalo waterfront and Buffalo River. Local seismic conditions and activities near the Clarendon-Linden fault zone and the occurrences of moderate intensity earthquakes in western New York and Lake Ontario appear to provide sufficient opportunity for liquefaction induced ground failure. Unconsolidated deposits of western New York partly meet the criteria for liquefaction susceptibility:

1. The geologic age of unconsolidated sediments is Pleistocene or younger.
2. The deposits appear to be loose sediments that were deposited by fluvial and glaciofluvial processes.
3. The water table is generally very shallow near the waterfront and Buffalo River areas where liquefaction prone deposits are present.

Our computations of liquefaction potential from the geotechnical data did not reveal any areas of high liquefaction potential. Approximately 3 square miles of the identified susceptible sites have moderate liquefaction probability. Except for a shallow pocket of

Table 5-I. Liquefaction Probability Calculations. See the text for details of the calculations.

LAT. (N)	LONG. (W)	BORE HOLE ID	SURF. ELEV. (FT)	GW ELEV. (FT)	UNIT ELEV. (FT)	LAYER BASE (FT)	LAYER TKNS (FT)	SPT-N VALUE (FIELD)	USCS CLAS.	FINES %	RD	TOTAL STRESS (*)	EFF. STRESS (PSF)	HAMMER WEIGHT (LBS)	HAMMER FALL (IN)	SPOON OD (IN)	HAMMER RATIO RS	CORR. FOR SPT	STD. SPT N	Cn	N1(60)	CSR (**)	PROB. LIQ. (a)	CLASS. (b)
51.33	51.87	KI-27	581.3	573.3	566.3	24.0	9.0	4	SW	10	0.93	2640	2628.5	140	30	2.0	8.93E-06	1.00	3.99	0.87	3.48	0.091	40	M
51.67	51.78	KI-23	581.9	576.9	567.9	17.0	3.0	1	SM	50	0.93	1870	1859.5	140	30	2.0	8.93E-06	1.00	1.00	1.04	1.04	0.093	50	M
51.85	51.23	KI-28	578.7	574.2	562.7	19.0	3.0	25	SW	10	0.94	2090	2077.0	140	30	2.0	8.93E-06	1.00	24.96	0.98	24.49	0.093	1	L
51.88	50.70	NFB-22	582.3	559.3	559.3	28.0	5.0	19	SP	10	0.92	3080	3077.5	140	30	2.0	8.93E-06	1.00	18.97	0.81	15.29	0.089	7	L
52.10	51.35	KI-32	584.4	572.0	560.4	30.0	6.0	17	SW	10	0.91	3300	3285.4	140	30	2.0	8.93E-06	1.00	16.97	0.78	13.24	0.089	7.5	L
52.03	52.33	KI-16	581.3	574.3	566.3	18.0	3.0	3	SM	50	0.95	1980	1970.5	140	30	2.0	8.93E-06	1.00	2.99	1.01	3.02	0.093	38	M
52.39	51.51	NFB-2	583.7	570.0	559.7	28.0	4.0	10	SW	10	0.92	3080	3067.7	140	30	2.0	8.93E-06	1.00	9.98	0.81	8.06	0.090	10	M
52.40	51.32	NFB1-A	586.1	579.7	563.1	30.5	7.5	27	SW	10	0.91	3355	3334.7	140	30	2.0	8.93E-06	1.00	26.95	0.77	20.87	0.089	1	L
52.45	52.17	KI-14	580.7	567.7	567.7	19.0	6.0	7	SW	10	0.94	2090	2087.0	140	30	2.0	8.93E-06	1.00	6.99	0.98	6.84	0.092	30	M
52.45	51.58	NFB-3	581.2	574.0	557.7	28.0	4.5	18	SW	10	0.92	3080	3061.5	140	30	2.0	8.93E-06	1.00	17.97	0.81	14.52	0.090	1	L
52.47	51.50	NFB-12	583.6	565.6	560.6	28.0	5.0	10	SW	10	0.92	3080	3072.5	140	30	2.0	8.93E-06	1.00	9.98	0.81	8.05	0.090	10	M
52.48	52.25	KI-13	581.0	564.5	562.0	25.0	6.0	36	SW	10	0.93	2750	2744.5	140	30	2.0	8.93E-06	1.00	35.94	0.85	30.68	0.090	1	L
52.55	53.06	B08511388	579.5	576.5	566.5	25.5	12.5	4	SM	30	0.92	2805	2780.8	140	30	2.0	8.93E-06	1.00	3.99	0.85	3.38	0.091	38	M
52.55	51.45	NFB-13	579.7	572.7	572.7	13.0	6.0	3	SM	50	0.96	1430	1427.0	140	30	2.0	8.93E-06	1.00	2.99	1.18	3.55	0.094	39	M
52.62	52.32	KI-12	581.1	569.0	552.0	35.1	6.0	14	SW	50	0.89	3861	3841.0	140	30	2.0	8.93E-06	1.00	13.98	0.72	10.09	0.088	5	L
52.65	52.81	B08511382A	582.5	569.5	564.5	27.0	9.0	15	SW	0	0.92	2970	2960.5	140	30	2.0	8.93E-06	1.00	14.97	0.82	12.31	0.090	4	L
52.75	52.28	OOT-ONT-91	586.4	571.4	558.4	32.0	4.0	22	SW	10	0.90	3520	3505.0	250	18	2.0	8.93E-06	0.95	20.89	0.76	15.78	0.089	1	L
52.75	51.72	NFB-16	582.2	553.7	553.7	38.0	9.5	22	SW	10	0.89	4180	4175.3	140	30	2.0	8.93E-06	1.00	21.96	0.69	15.20	0.086	1	L
52.77	51.87	NFB-8	586.6	576.0	557.6	33.0	4.0	5	SP	10	0.90	3630	3609.6	140	30	2.0	8.93E-06	1.00	4.99	0.74	3.72	0.088	30	M
52.78	52.45	OOT-ONT-96	594.6	573.1	576.6	46.8	28.8	3	SM	50	0.86	5148	5137.1	250	18	2.0	8.93E-06	0.95	2.85	0.62	1.78	0.084	40	M
52.80	52.32	OOT-ONT-89	599.7	599.7	577.6	42.1	20.0	20	SM	50	0.87	4631	4598.9	250	18	2.0	8.93E-06	0.95	18.99	0.66	12.53	0.086	12	M
52.82	51.82	NFB-17	586.1	553.1	553.1	43.0	10.0	14	SW	10	0.87	4730	4725.0	140	30	2.0	8.93E-06	1.00	13.98	0.65	9.09	0.085	8	M
59.52	52.35	BEC-A3-C-11	621.0	601.0	597.0	45.0	21.0	15	SM	50	0.87	4950	4935.5	140	30	2.0	8.93E-06	1.00	14.97	0.64	9.53	0.085	14	M

(a) Liao et al. (1987)
(b) Budhu et al. (1987)
(*) Assumed unit weight = 110 pounds per cubic foot
(**) Design a(max) value = 0.15 g

LAT: 2 degrees)
LONG: 8 degrees)
SURF. ELEV. Ground surface elevation in feet (USGS datum)
GW ELEV Groundwater table elevation in feet
UNIT ELEV Elevation at top of depositional unit

LAYER BASE Depth to base of depositional unit
LAYER TKNS Thickness of suspected liquefiable layer
SPT-N VALU Field in-situ density value from SPT
USCS CLAS. Sediment description from Unified Soil Class. System

FINES Percentage of sediment < #200 sieve
EFF. STRESS ective stress
SPOON OD Outside diam. of spoon
COOR. FOR SPT n factor for penetration test apparatus

STD SPT N Corrected SPT N value
PROB. LIQ. Probability of liquefaction
CLASS H is > 50%
M is 10 to 50%
L is < 10%

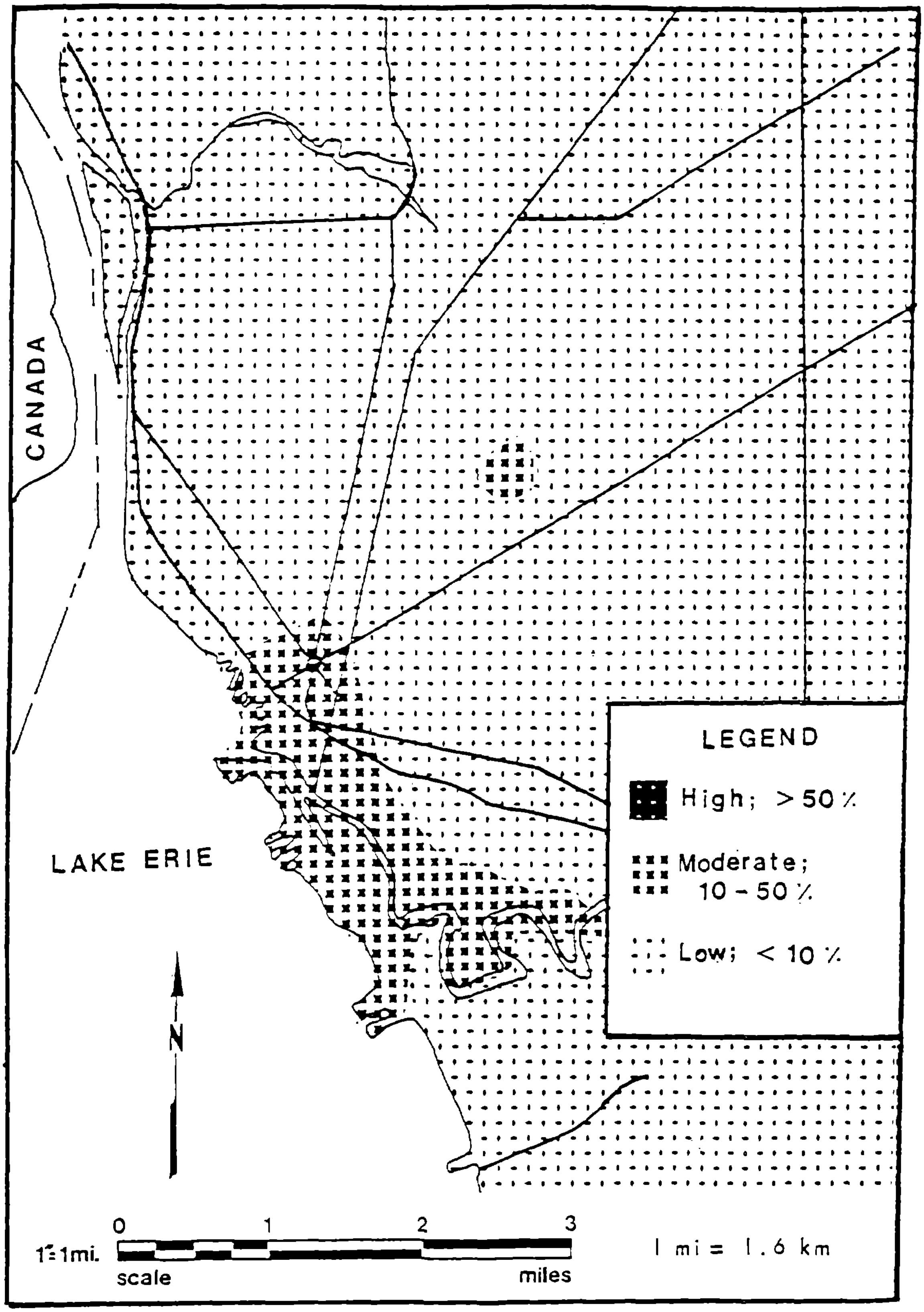

FIGURE 5-1 Liquefaction Potential Map. Shaded Zones Represent Categories of Liquefaction Potential Corresponding to Liquefaction Probability.

loose sand near the Buffalo Moraine which is susceptible to liquefaction, the sandy deposits are generally dense and are not susceptible to liquefaction. Probable liquefaction potential exists in areas of dumped fill along the Lake Erie shoreline and Buffalo River. This fill is in a loose condition and comprised of river and harbor dredgings, etc. SPT measurements in heterogeneous fills are of questionable value for use in liquefaction calculations and as such we suggest that caution be exercised in the interpretation of the moderate liquefaction potential obtained for the fill site between Lake Erie and the Buffalo River (compare Figure 3-2 with Figure 5-1). Much of the City has negligible liquefaction potential owing to the glaciolacustrine origin of surficial deposits and the preconsolidation of granular sediments by glaciation. Gravelly sands existing near the bedrock surface are not susceptible to liquefaction because of their high density, size (coarse) and high confining pressures due to the depth of burial. The ability of soft clays to amplify strong ground motions causing localized liquefaction of the seams and lenses of sand interbedded between the clay sediments was not considered.

SECTION 6

CONCLUSIONS

Although an examination of local seismicity shows sufficient seismic opportunity for earthquake-induced liquefaction in Buffalo, the potential for liquefaction of the cohesionless sediments is low. An area about 2 square miles of moderate liquefaction potential (probability between 10% and 50%) exists between Lake Erie and the Buffalo River. This part of Buffalo consists of loose waterfront fills, and we have doubts about the applicability of current liquefaction-potential methodology to these deposits.

SECTION 7

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APPENDIX A
A LISTING OF HISTORICAL EARTHQUAKES LOCATED IN NEW YORK STATE (FROM STOVER ET AL, 1981) WHICH OCCURRED BETWEEN 1737 AND 1977

Year	Month	Day	Time	Lat.	Long.	Depth	Mag.	Note	Scale
1977	12	15	8:55	43.03	77.44	5	2.6	1	
1977	9	28	17:21	44.39	73.89	3	3.1	2	III
1976	10	20	23:42	44.69	73.89	1	2.8	2	
1976	8	20	22:08	41.11	73.75	6	2.5	2	
1976	5	11	13:18	40.48	73.8	1	2.8	2	
1976	4	28	21:32	44.58	74.63	1	2.8	2	
1975	11	3	20:54	43.91	74.65	5	3.9	2	IV
1975	10	28	21:45	41.57	73.93				II
1975	10	24	7:43	41.59	73.93	3	2.2	2	II
1975	10	24	7:08	41.62	73.98	5	2	2	II
1975	10	8	9:00	43.48	78.5	5	2.6	2	III
1975	7	19	20:59	41.43	73.79	5	2.3	2	III
1975	7	11	1:44	44.32	73.87	2	2.8	2	VI
1975	6	9	18:39	44.87	73.65	11	4.2	2	
1975	5	14	00:08	43.4	78.6		2.9	1	
1975	2	20	08:06	40.3	73.2		2.9	2	
1975	1	28	00:15	45	73.8		2.6	1	IV
1975	1	15	19:16	44.9	74.56	0	2.6	2	
1975	1	4	20:40	44.89	74.55	0	2.7	2	
1975	1	4	20:40	44.89	74.55	0	2.8	2	
1974	11	27	10:28	43.33	79.11	0	3.3	1	
1974	9	18	6:23	43.4	73.8	5	2.5	1	
1974	6	7	19:45	41.6	73.95	3	3.3	1	VI
1974	6	2	14:42	44.7	74.6		2.5	1	
1974	3	18	16:05	44.5	74.9		2.7	1	
1973	6	16	8:41	43.76	74.47	1	3.3	2	
1973	6	15	10:32	43.92	74.4	3	3.2	2	
1973	6	15	8:20	43.89	74.43	1	3.4	2	
1973	6	11	10:08	44	74		2.8	1	
1973	2	9	4:46	42.8	78.3		2.7	1	
1973	2	2	23:09	44.4	74.7		2.8	2	
1972	11	2	5:15	44.8	74.6		3	1	
1972	3	15	12:10	43.7	74.7		2.6	1	
1972	2	15	23:53	43.3	73.6		2.6	1	
1971	7	10	8:15	43.91	74.44	2	3.7	1	
1971	6	21	2:48	43.9	74.48	2	3.6	1	
1971	5	23	9:29	43.93	74.47	1	3.4	1	
1971	5	23	6:24	43.9	74.48	9	3.9	1	
1969	8	13	2:42	42.9	78.2		2.5	2	
1967	11	22	21:10	41.2	73.8				
1967	6	13	19:08	42.83	78.23	1	4.4	2	
1966	6	30	.. ..	44.4	73.7				
1966	5	21	7:30	41.2	74				
1966	1	1	13:23	42.84	78.25	0	4.6	2	
1966	1	1	11:29	42.8	78.3		3	1	
1966	1	1	10:30	42.8	78.2				
1965	9	29	20:57	41.4	74.4				
1965	8	28	1:55	43	78.1		3.1	1	
1965	7	16	11:06	43.2	78.5		3.5	1	
1964	11	30	10:47	41.3	73.9				
1964	11	30	00:34	42.8	74.9		2.6	1	
1964	11	17	17:08	41.2	73.7				

Year	Month	Day	Time	Lat.	Long.	Depth	Mag.	Note	Scale
1964	9	29	00:16	41.2	73.7				
1964	6	16	13:00	45	74.2		2.7	1	
1964	6	4	23:40	44.7	75.3		2.8	1	
1964	3	29	9:16	44.9	74.9				
1963	7	1	19:59	42.6	73.8		3.3	1	
1963	5	19	19:14	43.5	75.2		3.5	1	
1963	5	19		43.2	73.3				
1963	2	16	8:00	44.9	73.7		2.6	1	
1963	1	30	14:15	44	75.9		3	1	
1962	11	27	4:14	41.5	73.8		1.7	1	
1962	10	2	23:45	44.8	74.3				
1962	5	6		39.9	75.5				
1961	9	29	6:30	44.9	74.9				
1961	4	20	13:00	45	74.8		2	1	
1958	8	22	14:25	43	79		3.6	1	
1958	5	6	19:00	42.7	73.8				
1958	2	12	13:29	44.8	75.3		2.6	1	
1958	1	11	16:36	44.9	74.9				
1957	11	30	6:27	45	74.8				
1957	2	20	15:45	44.9	74.9				
1956	7	27	1:34	44.7	73.8		3.4	1	
1955	8	16	7:35	42.9	78.3				
1955	1	21	12:20	42.9	73.8				
1955	1	21	8:40	42.9	73.8				
1954	12	15	17:35	44.8	74.7				
1954	12	13	3:53	44.6	74.6	12	3.6	1	
1954	9	29	3:50	44	75.9				
1954	5	20	22:01	45	74.2	20	2.7	1	
1954	4	21	15:45	44.7	73.5				
1954	2	1	00:37	43	76.7		3.3	1	
1954	1	31	12:30	42.9	77.2				
1953	4	26	1:17	44.7	73.5		2.6	1	
1952	12	21	12:00	44.9	74.9				
1952	11	20	.. ..	42.9	76.6				
1952	10	8	21:40	41.7	74				
1952	8	25	00:07	43	74.5				
1951	12	8	4:37	41.7	73.9				
1951	11	6	17:37	44.92	73.55	31	3.7	1	
1951	9	3	21:26	41.3	74.3		4.4	1	
1949	2	7	6:17	44.9	74.9				
1948	11	22	23:32	44.4	74.3		2.9	1	
1948	8	7	.. ..	44	74				
1948	7	7	7:15	44.7	75				
1948	4	4	2:44	44.2	73.8		2.5	1	
1947	10	29	15:45	45	74.9				
1946	12	25	4:48	45	74.9		3	1	
1946	11	28	22:00	43.9	73.8				
1946	11	11	10:20	45	74.9		3	1	
1946	11	10	11:41	42.9	77.5		3.1	1	
1946	9	4	19:29	45	74.9		2.3	1	
1946	6	27	21:06	44.6	74.5		3	1	
1946	6	20	23:09	44.4	74.2				

Year	Month	Day	Time	Lat.	Long.	Depth	Mag.	Note	Scale
1946	3	20	3:02	44.3	75.9				
1946	3	20	2:29	44.3	75.9				
1946	3	20	2:01	44.3	75.9				
1946	3	16	4:20	45	74.9				
1946	2	13	15:10	45	74.9				II
1945	12	2	15:22	45	74.9		3	1	
1945	6	24	1:56	45	74.9		2.7	1	
1945	4	15	15:30	43	76.4				III
1945	4	15	14:20	43	76.4				III
1945	4	15	13:15	43	76.4				III
1945	1	2	23:00	45	74.9				III
1945	1	1	10:00	45	74.9				III
1945	1	1	5:45	45	74.9				III
1944	12	31	5:30	45	74.9				III
1944	12	27	10:07	45	74.9				III
1944	12	5	12:00	45	74.9				III
1944	11	25	13:00	45	74.9				III
1944	11	23	7:00	45	74.9				III
1944	11	20	1:15	45	74.9				III
1944	11	17	10:15	45	74.9				III
1944	11	11	3:30	45	74.9				IV
1944	11	9	3:15	45	74.9				IV
1944	11	8	23:00	45	74.9				III
1944	10	31	8:42	45	74.9		4	1	IV
1944	10	26	00:57	45	74.9				III
1944	10	20	23:39	45	74.9				III
1944	10	17	13:00	45	74.9				III
1944	10	13	10:00	45	74.9				III
1944	10	13	2:33	45	74.9		2.7	1	
1944	10	10	00:00	45	74.9				III
1944	10	9	7:00	45	74.9				III
1944	10	9	1:45	45	74.9		2.3	1	
1944	10	9	1:00	45	74.9				III
1944	10	8	13:50	45	74.9				III
1944	10	6	13:00	45	74.9				III
1944	10	5	21:00	45	74.9				III
1944	10	5	11:30	45	74.9				III
1944	10	4	13:35	45	74.9				III
1944	10	4	00:30	45	74.9				III
1944	10	3	.. ..	45	74.9				III
1944	9	30	19:50	45	74.9				III
1944	9	24	19:00	45	74.9				III
1944	9	19	1:00	45	74.9				III
1944	9	18	4:55	45	74.9				III
1944	9	16	23:40	45	74.9				III
1944	9	16	4:05	45	74.9				III
1944	9	13	22:00	45	74.9		2.7	1	IV
1944	9	13	17:40	45	74.9				III
1944	9	13	2:45	45	74.9				III
1944	9	9	23:24	45	74.9		4.1	1	IV
1944	9	8	19:50	45	74.9				III
1944	9	8	19:35	45	74.9		2.8	1	

Year	Month	Day	Time	Lat.	Long.	Depth	Mag.	Note	Scale
1944	9	8	10:11	45	74.9		2.5	1	
1944	9	8	9:50	45	74.9				III
1944	9	7	13:55	45	74.9		2.5	1	
1944	9	7	2:47	45	74.9				III
1944	9	7	1:30	45	74.9				III
1944	9	7	.. ..	45	74.9				III
1944	9	6	13:30	45	74.9				III
1944	9	5	11:10	45	74.9		2.8	1	
1944	9	5	10:56	45	74.9		3.3	1	
1944	9	5	8:51	45	74.65	1	4.6	1	
1944	9	5	8:30	45	74.9		3.4	1	
1944	9	5	4:38	44.96	74.72	12	5.8	2	VIII
1944	5	29	23:03	44.7	73.8				II
1944	2	26	21:58	42.9	78.8				
1944	1	16	10:00	43.1	77.6				II
1943	10	15	23:00	44.4	74.2		2.5	1	
1943	6	11	22:51	41.1	71.8				II
1943	5	9	11:03	44.8	73.8		3.2	1	
1942	10	2	22:29	42.5	73.8		3	1	
1942	10	1	20:58	44	73.5		2.5	1	
1942	5	24	11:33	44.7	73.8		3.9	1	
1942	5	24	7:15	44.7	73.8		2.9	1	
1942	1	31	4:11	44.7	73.9		2.7	1	
1941	12	12	23:28	44.9	73.7		2.7	1	II
1941	10	21	6:10	44.8	74.8		3.3	1	
1941	10	21	5:23	44.8	74.8		2.2	1	
1941	10	20	21:29	44	75.9				II
1941	10	9	22:07	44	75.9				II
1941	7	29	00:24	41.1	73.8				III
1941	4	29	14:05	40.5	72.5		2.5	1	
1941	4	4	8:10	44.7	73.9		3.3	1	
1941	4	3	19:52	44.7	73.9		2.5	1	
1941	2	1	18:28	44.6	75.2				II
1940	9	27	.. ..	41.6	75.7				II
1940	9	26	23:30	44.7	73.4		2.9	1	III
1940	6	4	18:14	40	72				II
1940	6	4	18:13	40	72				II
1940	5	20	1:26	44.6	75.2				II
1940	5	10	19:23	40	72				II
1940	4	27	22:44	40	72				II
1940	4	27	22:37	40	72				II
1940	4	27	22:31	40	72				II
1940	4	13	8:23	44.8	74.9		2.6	1	
1940	4	12	1:58	42.8	74.6				II
1939	10	25	14:46	42.2	73.8				II
1939	10	21	8:59	43.3	73.3				II
1939	9	21	20:30	41.4	74.1				II
1939	6	1	3:36	44.6	75.2				III
1939	2	24	00:20	42.9	78.3				III
1939	2	21	..:..	44.8	74.3				II
1938	11	18	22:19	44.8	75.3				V
1938	10	21	7:18	41.2	73.7				II

Year	Month	Day	Time	Lat.	Long.	Depth	Mag.	Note	Scale
1938	8	23	7:11	41.2	73.7				III
1938	8	23	5:18	41.2	73.7				III
1938	7	29	7:44	41	73.7				III
1938	5	5	00:35	44.8	74.3				IV
1937	10	12	6:..	41.2	73.8				II
1937	10	12	3:..	41.2	73.8				II
1937	7	19	3:51	40.7	73.7				IV
1937	3	10	5:30	44.6	75.2				IV
1937	2	21	12:..	42.1	76.8				II
1936	6	21	4:40	44.7	74.2				IV
1936	6	21	4:..	44.7	74.2				IV
1936	6	21	4:..	44.7	74.2				II
1936	6	21	3:..	44.7	74.2				II
1936	6	21	3:40	44.7	74.2				III
1935	11	1	6:30	42.6	74.6				II
1935	1	28	9:01	44.8	74.3		3.2	1	III
1935	1	28	6:00	44.8	74.3				IV
1934	6	5	20:11	44.8	74.3				III
1934	4	15	18:05	44.8	74.3				III
1934	4	15	2:28	44.7	73.8		4.5	1	VI
1933	10	29	..:..	43	74.7				IV
1933	6	26	14:10	41	73.8				III
1933	5	20	19:57	44.8	74.7				III
1932	12	29	4:28	44	73.9				V
1932	12	7	16:45	44.4	74.1				III
1932	12	7	4:05	44.3	74.1				IV
1932	12	7	3:15	44.3	74.1				IV
1931	11	3	15:30	44.6	75.2				II
1931	6	7	2:30	43.2	77.6				II
1931	6	7	00.00	43.2	77.6				II
1931	5	4	18:43	44.8	74.3				III
1931	4	22	..:..	42.9	78.9				IV
1931	4	20	19:54	43.47	73.78	5	4.7	2	VII
1930	11	2	2:35	44.8	74.3				III
1930	1	17	..:..	42.8	78.3				II
1930	1	4	..:..	43.1	75.3				II
1929	12	3	12:50	42.8	78.3				IV
1929	12	2	22:14	42.8	78.3				IV
1929	8	12	11:24	42.91	78.4	9	5.2	2	VIII
1929	8	12	8:45	42.9	78.4				III
1929	8	12	6:..	42.2	77.2				III
1929	6	5	7:00	44.8	74.3				III
1928	3	19	3:20	44.5	74.3				III
1928	3	18	15:20	44.5	74.3		4.1	1	VI
1927	10	24	11:00	44.7	73.7				IV
1927	3	31	21:30	43	76.1				III
1927	3	31	21:00	43	76.1				III
1927	3	29	20:30	43	76.1				III
1927	3	14	14:15	44.6	75.4				IV
1927	3	12	22:14	44.6	75.2				IV
1926	5	22	..:..	41.7	73.9				II
1926	5	12	3:30	40.9	73.9				V

Year	Month	Day	Time	Lat.	Long.	Depth	Mag.	Note	Scale
1926	1	27	..:..	44.3	74.1				IV
1925	5	23	..:..	43.4	77.1				III
1925	4	7	20:18	43	76.1				III
1922	12	8	21:24	44.5	75.2				V
1921	1	27	..:..	43.3	73.7				IV
1921	1	19	10:00	43.3	73.7				IV
1917	10	2	2:14	43.3	73.7				III
1917	5	17	10:08	44.7	75.5				II
1917	1	26	..:..	44.4	74.1				II
1916	11	2	2:32	43.3	73.7				V
1916	10	30	..:..	43.3	73.7				III
1916	6	8	21:15	41	73.8				IV
1916	2	3	4:20	43	74				I
1916	2	2	16:26	42.9	74				I
1916	1	5	13:56	43.7	73.7				I
1915	2	21	23:41	44.7	73.4				IV
1913	8	10	15:15	44	74				IV
1911	1	29	7:..	44.7	75.5				II
1910	5	1	20:..	40.7	73.5				II
1910	3	3	11:15	44.3	74.2				III
1907	1	24	11:30	42.8	74				IV
1907	1	24	7:30	42.8	74				IV
1903	12	25	12:30	44.7	75.5				V
1897	5	28	3:16	44.5	73.5				VI
1896	5	20	..:..	43.2	75.2				II
1894	12	17	..:..	42.5	73.8				IV
1893	3	9	5:30	40.6	74				V
1889	8	10	..:..	43.4	73.7				IV
1886	9	9	..:..	42.5	73.4				II
1886	9	3	..:..	42.5	73.4				II
1886	1	25	00:04	41.6	73.8				IV
1885	1	31	10:05	41.3	73.8				III
1985	1	4	11:06	41.3	73.9				III
1884	8	11	..:..	40.6	74				V
1884	8	10	19:07	40.6	74				VII
1882	9	13	..:..	43	77.7				II
1882	4	2	..:..	42.9	74.2				II
1881	9	25	..:..	42.1	76.8				II
1881	4	21	16:30	40.9	73.1				III
1881	3	19	2:30	42.8	73.9				III
1880	9	6	7:00	45	74.8				III
1879	4	14	16:15	45	74.8				II
1878	12	29	2:32	42.7	74.3				III
1878	12	25	2:..	40.8	73.8				II
1878	10	4	7:30	41.5	74				V
1878	2	5	16:20	40.8	73.9				V
1877	11	14	14:40	45	74.8				III
1877	11	4	6:56	44.5	74				VII
1877	5	14	..:..	42.8	73.9				II
1877	5	11	..:..	42.8	73.7				II
1876	1	8	21:30	43.2	78.7				II
1874	12	13	4:..	41.4	73.9				II

Year	Month	Day	Time	Lat.	Long.	Depth	Mag.	Note	Scale
1874	12	11	3:25	40.9	73.8				V
1874	1	5	21:00	44.7	75.5				II
1873	4	25	19:00	44.8	74.2				V
1873	3	18	..:..	44.6	75.1				II
1872	7	11	10:25	40.9	73.8				V
1867	12	18	8:00	44.7	75.2				VI
1858	1	1	22:00	43.2	78.7				III
1857	10	23	20:15	43.2	78.6				VI
1855	12	17	19:00	43.3	73.7				IV
1855	2	7	4:30	42	74				VI
1855	1	17	..:..	40.8	73.6				II
1853	3	12	7:30	43.7	75.5				VI
1852	12	15	21:00	43.4	78.2				III
1847	9	29	..:..	40.5	70.4				V
1847	7	9	..:..	43.3	73.7				III
1847	1	12	4:30	42.6	73.7				II
1841	1	25	..:..	40.7	74				III
1840	1	16	20:00	43	75				VI
1804	5	18	..:..	40.7	74				III
1737	12	19	3:45	40.8	74				VII

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