Final Technical Report

SHAKE MAPS FOR EARTHQUAKES IN THE NORTHEASTERN UNITED STATES: COLLABORATIVE RESEARCH WITH COLUMBIA UNIVERSITY AND BOSTON COLLEGE

Award Number 06HQGR0019

John E. Ebel
Weston Observatory
Department of Geology and Geophysics
Boston College
Weston, MA 02493
Telephone: (617) 552-8300
Fax: (617) 552-8388
E-mail: ebel@bc.edu

Award Number 06HQGR0022

Won-Young Kim
Lamont-Doherty Earth Observatory
of Columbia University
Palisades, New York 10964

Telephone: (845) 365-8387
Fax: (845) 365-8150
E-mail: wykim@ldeo.columbia.edu

Program Element: Central and Eastern United States

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 06HQGR0019. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. government.

SHAKE MAPS FOR EARTHQUAKES IN THE NORTHEASTERN UNITED STATES: COLLABORATIVE RESEARCH WITH COLUMBIA UNIVERSITY AND BOSTON COLLEGE

Award Number 06HQGR0019

John E. Ebel
Weston Observatory
Department of Geology and Geophysics
Boston College
Weston, MA 02493
Telephone: (617) 552-8300
Fax: (617) 552-8388
E-mail: ebel@bc.edu

Award Number 06HQGR0022

Won-Young Kim
Lamont-Doherty Earth Observatory
of Columbia University
Palisades, New York 10964

Telephone: (845) 365-8387
Fax: (845) 365-8150
E-mail: wykim@ldeo.columbia.edu

Abstract

Weston Observatory of Boston College (WES) and Lamont-Doherty Earth Observatory of Columbia University (LDEO) are developing procedures necessary for generating ShakeMaps of Instrumental Intensity, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Peak Spectral Amplitudes (PSA) at various periods (e.g., 0.3, 1 and 3 sec) for earthquakes that occur in the northeastern United States. ShakeMaps are in great demand by the general public, rapid earthquake responders, emergency management agencies, and the earthquake engineering community. The routine generation of ShakeMaps in the northeastern U.S. will help promote earthquake loss mitigation measures in the region.

In this project, LDEO is implementing the ShakeMap software on one of their computers. When the software is fully implemented, LDEO will take incoming parametric data (PGA, PGV, and PSA at 0.3s, 1s and 3s) from WES, the USGS NEIC and other operators of seismic stations in the northeastern U.S., create the ShakeMaps, and post those maps online as soon as possible after an earthquake takes place. WES is providing LDEO with real-time feeds of its regional seismic network data via the internet using Earthworm import/export modules. WES also has procured a map of the soil conditions throughout the northeastern U.S. for use in the computation of estimated ground motions in areas where there are no seismic stations. The corrections for site soil conditions make use of published and unpublished correlations between surficial lithologies and seismic shear-wave velocities. Based on the shear velocity for the surficial materials at each site, the sites are assigned to one of the NEHRP soil classifications (A, B, C, D, or E), and the estimated strength of the bedrock ground motion at each site is modified based on the site classification. The application of these modification factors, which are a function of the strength of the bedrock ground shaking since non-linear effects occur in strong shaking, will serve to give estimates of the surface ground motions that take into account the site soil conditions.

Introduction

The aim of the work that was carried out in this project was to implement a system to generate ShakeMaps for earthquakes in the northeastern U.S. in a timely fashion. Immediately following an earthquake, emergency managers must make quick response decisions using limited information. Automatically and rapidly generated computer maps of the intensity of ground shaking (ShakeMaps) are now available for California within about 10 minutes after the occurrence of a significant earthquake. The quick, accurate, and important information from the ShakeMaps has proven in California to be an important aid in making the most effective use of emergency-response resources. This project report summarizes work to transport this important information system to the northeastern U.S.

Weston Observatory of Boston College (WES) and Lamont-Doherty Earth Observatory of Columbia University (LDEO) are working cooperatively to routinely generate ShakeMaps of Instrumental Intensity, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Peak Response Spectral Amplitudes at various periods (e.g., 0.3, 1 and 3 sec) for all significant earthquakes in the northeastern U.S. ShakeMaps are important products that the general public, rapid earthquake responders, emergency management agencies, and earthquake engineering community require for proper decision-making following the occurrence of a felt or damaging earthquake, and they represent a significant step forward in the development of real-time seismic information relevant to post-earthquake emergency management. ShakeMaps can be used by emergency managers to: 1) assess the geographic scope of an earthquake, 2) identify areas in which damage is likely, or unlikely, to have occurred, and 3) provide decision support for resource mobilization and prioritization of reconnaissance efforts.

In this project, LDEO is taking the lead to implement the ShakeMap software on one of their computers. When the software is fully implemented, LDEO will take incoming parametric data (PGA, PGV, PSA at 0.3s, 1s, 3s) from WES, the USGS NEIC and other operators of seismic stations stations in the northeastern U.S., create the ShakeMaps, and post those maps online as soon as possible after an earthquake takes place. WES has two responsibilities as part of this project. One responsibility is to provide LDEO with real-time feeds of its regional seismic network data (arrival times, PGA, PGV, PSA at 0.3s, 1s, 3s). This parametric data delivery is already in place and is being done via the internet using Earthworm import/export modules. The second WES responsibility is to produce maps of the soil conditions throughout the northeastern U.S. for use in the computation of estimated ground motions in areas where there are no seismic stations. The rest of this report describes the soil condition map that WES has obtained for incorporation into the ShakeMaps system for the northeastern U.S. and the use of this map for estimating the local amplification of ground motions throughout the region.

Surficial Geology Map

A survey of the geological surveys of the individual states in the northeastern U.S. revealed a wide divergence in the amount and availability of surficial geology data that could be used in the ShakeMaps project. Some states, such as Massachusetts and Connecticut, have complete digital surficial geology maps for their entire state. Other states, such as Vermont, only have digital surficial geology maps for a portion of their state. While the surficial geology maps

from the individual states should have the highest spatial resolution and greatest detail concerning the surficial geological materials, particularly their compositon and thickness, the incompleteness and non-uniformity of these data precluded their use for this project. Therefore, it was concluded that the use of a single surficial geology map that was compiled on a regional or national level would best serve the purposes of our ShakeMaps project.

After a survey of maps that were available, it was decided to use the Fullerton et al. (2003) map of surficial geologic materials east of the Rocky Mountains as the soil map basis for the amplitude corrections for the northeastern ShakeMaps. The advantages of this map is that it covers the entire region for which LDEO and WES intend to construct ShakeMaps, it has divided the region up over 150 different surficial geologic classifications, and it has good documentation concerning the surficial materials that it maps. The scale of the map base from which the digital map was created is 1:1,000,000. While this resolution is too coarse to properly represent the soil conditions on a site-specific basis, it is adequate to represent the variations of the surficial geologic materials, and therefore the potential for ground shaking amplification, on a regional basis. A subsection of the Fullerton et al. (2003) map that includes the northeastern U.S. area monitored by LDEO and WES is shown in Figure 1. Table 1 contains a listing of all of the geologic units contained on the Fullerton et al. (2003) map.

Ground-Shaking Amplification and Soil Classifications

The ShakeMaps program takes as one of its inputs observed ground motions from seismic stations (particularly accelerometers). Particularly in the northeastern U.S., most areas have little or no seismic instrumentation, and so the ground motions as these sites must be extrapolated based on the earthquake location and magnitude as well as on the observed ground motions that are obtained. For ground-motion interpolations between the locations with the ground-motion observations, a uniformly spaced grid of site conditions is required to generate the ShakeMaps. NEHRP classifications (types A through E, given as an associated average 30 m shear velocity) and corresponding amplification factors. A=Hard rock site, $V_{30m} > 1{,}500$ m/s through E=Soft clays, $V_{30m} < 180$ m/s (Borcherdt, 1994) are used to account for the effect of the surficial geology conditions on the ground motions.

There is a large amount of variation in the thickness of the surficial geologic layers in the Fullerton et al. (2003). In some places, the surficial layer might be 1 m or less thick, while in other places the thickness is greater than 30 m. The Borcherdt (1994) system of ground amplifications is based on the average shear-wave velocity in the top 30 m (about 100 feet) of soil at a site. For the purposes of this project, we assumed that all of the surficial units in the Fullerton et al. (2003) map are 30 m thick. Using this assumption, the amount of ground-shaking modification due to the surficial geologic layers is a function only of the shear-wave velocity of that layer. We examined several sources to estimate the shear-wave velocities for different kinds of surficial geologic materials for the region. As an example, Table 1 lists some correlations of shear-wave velocity and lithology for surficial materials in the central U.S. from Bob Bauer (personal communication, Illinois Geological Survey). Other correlations we examined are those of Redpath (1973) and Caldwell and Nottis (undated).

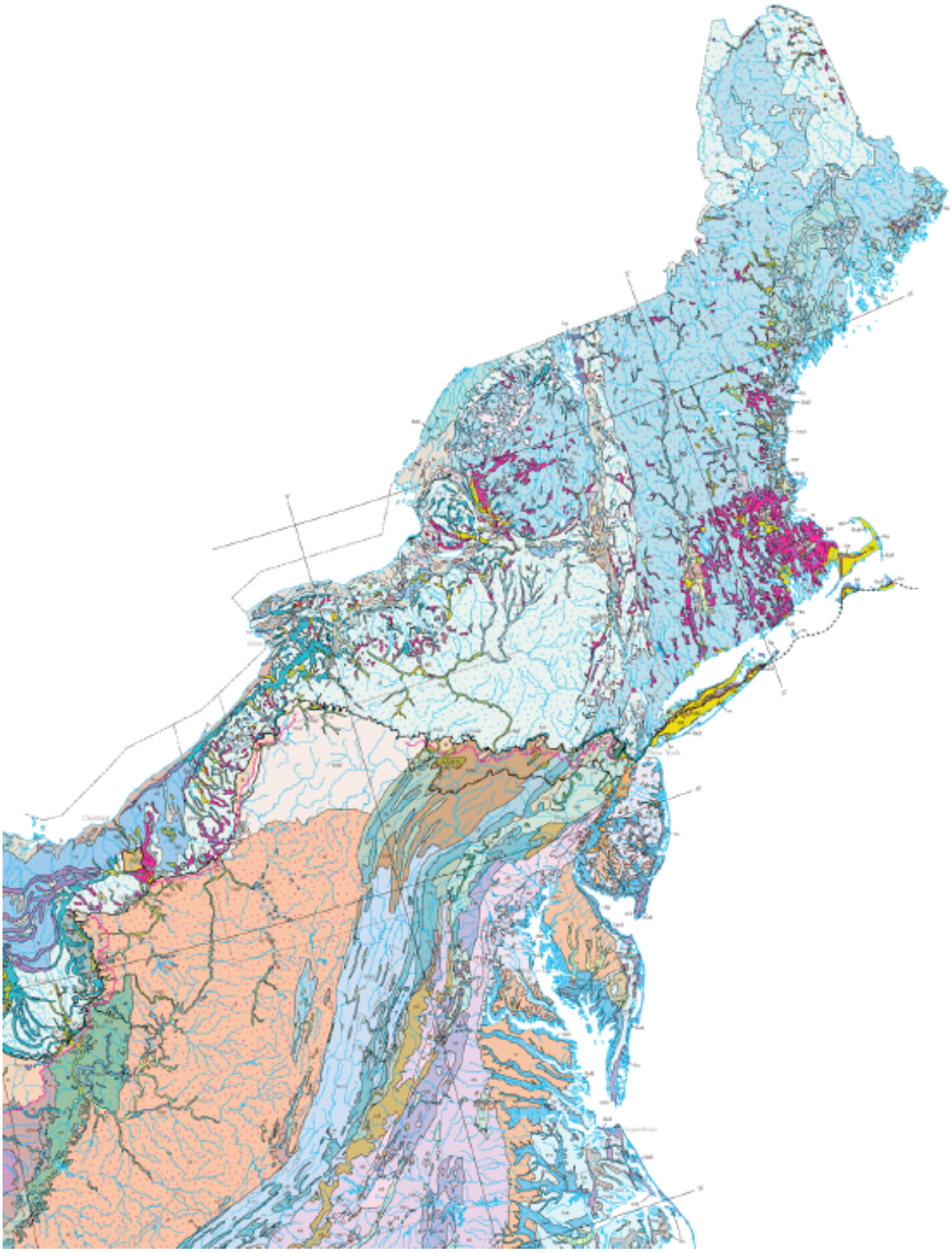


Figure 1. Map of surficial geologic materials for the northeastern U.S. from Fullerton et al. (2003).

Table 1 Estimated average shear-wave velocities in central North America for different soil types.

ID	Material	Vs(m/sec)
A	Cahokia Alluvium	230
D	Parkland Sand-dunes	330 calf
E	Carmi Member of Equality	170
P	Peoria Loess and Roxanna Silt	200 ?
G	Glasford Till	365
O	Sand and Gravel of Glasford	200 ?
M	Mounds Gravel	360
T	Teriary clay and sand	324
K	Cretaceous sand and gravel	280
C	Cherty residuum	200
S	Sandy residuum	200
R	Sandy cherty residuum	200
Z	Teriary, Cretaceous or Miss.	2000
1	Penn. Shale	1500
2	Penn. Sandstone	2000
3	Miss. Shale	2000
4	Miss. Limestone	2900
5	Devonian limestone	2900
6	Silurian limestone	2700
7	Devonian/Silurian dolomite/limestone	2900
8	Ordovician Shale	2000
9	Ordovician Sandstone, dolomite	2000
10	Ordovician dolomite	2900
11	Ordovician sandstone	2000
12	Ordovician limestone/dolomite	2900

Question marks are where a lack of data exists and values are best estimates.

The next step in this analysis was to relate each unit of the Fullerton et al. (2003) surficial geologic map for the region to a shear-wave velocity. This was done by comparing the description of each geologic unit in the Fullerton et al. (2003) map to relationships of lithology and seismic velocity from the sources mentioned in the previous paragraph and then assigning a shear-wave velocity to each geologic unit. The shear-wave velocity for each unit is used to assign each geologic unit into one of several NEHRP soil classifications (i.e., Martin and Dobry, 1994), as indicated in Table 2. For those sites that are not in site classification A (hard rock), the estimated hard rock ground motion at a site must be multiplied by the appropriate factor to estimate the ground motion amplitude on the surface of the soil. For example, surface PGA

values are computed by multiplying the rock PGA values by the NEHRP amplification factors in Table 3. Note that the amplification factors in Table 3 account for the non-linearity of strong ground motions. The stronger the ground shaking, the smaller the amplification factors for soil types D and E. In fact, deamplification occurs in soil type D for PGA at or exceeding 0.4g.

Table 2. Categories for NEHRP Soil Classification

SOIL CATEGORY	GENERAL DESCRIPTION	SOIL CATEGORY DEFINITION	SUSCEPTIBILITY RATING
A	Competent/hard rock	Vave > 750 m/s	Nil
B	Deep cohesionless soils, stiff cohesive soils or mix of cohesionless with stiff cohesive soils, not soft clay	360 m/s < Vave < 760 m/s	Low
C	Sands, silts and/or stiff/very stiff clays, some gravels; soft clay thickness < 3 m.	180 m/s < Vave < 360 m/s	Moderate
D1	Profile containing a small to moderate total thickness (Hc) of soft to medium stiff clay	Vave < 180 m/s, and/or 3 m < Hc < 15 m	High
E1	Peats or highly organic clays,	Hp > 3 m	Very High
E2	Very high plasticity clays	Hcp > 7 m and PI < 75%	Very High
E3	Very thick soft/medium stiff clays	Hc > 35 m	Very High

Table 3. Ground Motion Amplification Factors (from Finn, 1993)

SOIL CATEGORY	SHAKING INTENSITY				
	PGA=0.1g	PGA =0.2g	PGA =0.3g	PGA =0.4g	PGA =0.5g
A	1.0	1.0	1.0	1.0	1.0
B	1.2	1.2	1.1	1.0	1.0
C	1.6	1.4	1.2	1.1	1.0
D1	2.5	1.7	1.2	0.9	0.9
D2	2.0	1.6	1.2	0.9	0.9
E1-E3	1.2*D1	1.2*D1	1.2*D1	1.2*D1	1.2*D1

Table 4 lists all of the surficial geologic units in the Fullerton et al. (2003) map along with the value of shear-wave velocity that was assigned to each unit. For each site where the ground motion must be estimated by the ShakeMaps program, the shear-wave velocity in Table 4

for the corresponding surficial geologic unit is used to determine the soil category (in Table 2). The soil category is then used to determine the ground shaking modification factor (either amplification or deamplification depending on the soil class and strength of the rock ground shaking). The ground shaking modification factor is multiplied by the estimated hard rock ground shaking value to compute the surface ground shaking value that is to be displayed on the ShakeMap.

Table 4. Surficial Geologic Units (from Fullerton et al., 2003) and Assigned Shear-Wave Velocities

Geounit	Description	Shear Vel. m/sec
(ab)	Alluvial outwash ice-contact	230
(ae)	Alluvial deposits and estuarine marine deposits	230
(af)	Alluvial-fan and sheetwash-fan deposits	230
(ag)	Alluvial outwash, ice-contact, and glacial-lake deposits	230
(ai)	Alluvial deposits, lake deposits, and eolian deposits	230
(aj)	Alluvial deposits and lake deposits	230
(ak)	Flood deposits and flood-scoured till	230
(ao)	Cemented channel and flood-plain alluvium, fan alluvium, sheetwash alluvium, and pediment(?) alluvium	230
(bc)	Beach sand, dune sand, and delta deposits	330
(bd)	Beach sand and dune sand	330
(ca)	Colluvium and sheetwash alluvium	350
(cm)	Colluvium, decomposition residuum, and solution residuum	350
(cp)	Colluvium, sheetwash alluvium, and landslide deposits	350
(cr)	Colluvium and solution residuum	350
(ct)	Colluvium and alluvium	350
(cv)	Locally gypsiferous, clastic-clast colluvium and solution residuum	350
(cw)	Colluvium and decomposition residuum	350
(cx)	Colluvium and loess	350
(cz)	Colluvium, decomposition residuum, and solution residuum	350
(da)	Delta deposits	165
(db)	Delta deposits	165
(ea)	Loess, loessal alluvium, and loessal colluvium	200
(ec)	Sheet sand, loess, loessal alluvium, and loessal colluvium	200
(gc)	Outwash sand and gravel and till	200
(gd)	Outwash silt, outwash sand, and alluvium	200

(gk)	Outwash deposits, ice-contact deposits, and glacial-lake deposits	200
(gl)	Outwash deposits and ice-contact deposits	200
(gt)	Outwash deposits and till	200
(hd)	Swamp deposits and dune sand	230
(jb)	Landslide deposits, disintegration residuum, and sheetwash alluvium	350
(kd)	Glaciolacustrine kame-delta deposits	300
(kf)	Subaerial and submarine kame-fan deposits	300
(kl)	Ice-contact deposits and glacial-lake deposits	350
(km)	Marine kame-delta deposits	350
(kt)	Ice-contact deposits and till	350
(lk)	Beach sand and dune sand	330
(ln)	Slack-water lake deposits and alluvium	300
(lo)	Slack-water lake deposits and alluvium	300
(lp)	Slack-water lake deposits and alluvium	300
(mh)	Marine sand and alluvial sand	300
(mm)	Lagoon and beach deposits	300
(mt)	Glaciomarine deposits and till	350
(na)	Loamy solifluction deposits, colluvium, and decomposition residuum	350
(nb)	Loamy solifluction deposits	350
(qa)	Clinker and colluvium	350
(rg)	Plastic-clay solution residuum and cherty colluvium	200
(rh)	Solution residuum and decomposition residuum	200
(tg)	Till, ice-contact deposits, glaciofluvial deposits, and glaciolacustrine deposits	350
(tr)	Discontinuous till, discontinuous glaciofluvial deposits, and concentrations of erratic boulders and cobbles	350
(wc)	Sheetwash alluvium and lake deposits	300
(xe)	Silty clay disintegration residuum and gypsiferous solution residuum	300
(xh)	Silty clay loam disintegration residuum and sheetwash alluvium	200
(xi)	Loamy disintegration residuum and sheetwash alluvium on clayey shale	200
(xj)	Sandy disintegration residuum, sheetwash alluvium, and colluvium on soft sandstone, siltstone, and shale	200
(xk)	Loamy disintegration residuum, sheetwash alluvium, and colluvium on sandstone, siltstone, and shale	200
(xl)	Loamy disintegration residuum, sheetwash alluvium, and colluvium on soft sandstone, siltstone, mudstone, claystone, shale and lignite	200
(xm)	Smectitic disintegration residuum and sheetwash alluvium on bentonitic shale, micaceous shale, and soft clayey shale	200

(zd)	Decomposition residuum and colluvium on shale, siltstone, and sandstone	200
(zh)	Cherty decomposition residuum, solution residuum, and colluvium on limestone, shale, and sandstone	200
(zi)	Clayey to sandy decomposition residuum and solution residuum on sandstone, quartzite, shale, dolomite, and cherty limestone	200
(zm)	Loamy decomposition residuum and colluvium on sedimentary rocks of mixed compositions	200
(zo)	Clayey to sandy decomposition residuum and solution residuum	200
(zr)	Clayey to sandy decomposition residuum and solution residuum on clay, shale, coal, sandstone, and limestone	200
(zt)	Decomposition residuum and colluvium on arkose, sandstone, argillite, shale, and conglomerate	200
(zx)	Decomposition residuum and colluvium on igneous and metamorphic rocks	200
aa	Cemented alluvium	400
ac	Arkosic alluvium	230
ah	Flood deposits	230
al	Channel and flood-plain alluvium	230
an	Channel and flood-plain alluvium	230
ap	Alluvial delta deposits	230
at	Alluvium beneath terraces, in paleovalleys, and on upland surfaces	230
ba	Beach shell-fragment and shell sand	300
bb	Quartz beach sand	300
bm	Beach mud	300
cb	Resistant-block or resistant-boulder colluvium and rock waste	350
cc	Carbonate-boulder or carbonate-clast colluvium	350
cd	Crystalline-boulder colluvium	350
ce	Diabase- and basalt-clast colluvium	350
cf	Acid shale-chip colluvium	350
cg	Gravelly colluvium	350
ch	Sandy to clayey colluvium	350
ci	Calcrete-clast colluvium	350
cj	Clayey chert-clast colluvium	350
ck	Chert-clast colluvium	350
cl	Clastic-clast colluvium	350
co	Shale-clast, chalk-clast, and chalky limestone-clast colluvium	350
cq	Sandstone-block or sandstone-boulder colluvium	350
cs	Calcareous shale-chip and siltstone-clast colluvium	350
cu	Colluvium complex	350
eb	Loess	200
ed	Dune sand	330
ee	Clay dune deposits	330

el	Loess	200
es	Sheet sand	330
eu	Sand and silt	300
f	Man-made land	120
fa	Surficial deposits, surficial materials, and bedrock masses that were deformed and (or) transported intact by glacial ice	350
ga	Outwash silt, sand, and gravel	200
gb	Outwash sand and gravel	200
gg	Outwash sand and gravel	200
gs	Outwash sand	200
ha	Mangrove-swamp deposits	230
hb	Fresh-water coastal-marsh peat and clay	230
hc	Fresh-water, brackish-water, and (or) saline-marsh deposits	230
he	Algal-mat and carbonate deposits	230
hp	Peat and muck	230
hs	Fresh-water swamp deposits	230
ja	Slump-block, earthflow, and mudflow deposits	350
ka	Ice-contact sand and gravel	300
ke	Kame end-moraine or kame interlobate-moraine deposits	300
kg	Ice-contact sand and gravel	300
ks	Ice-contact silt and sand	300
la	Glacial-lake clay and silt	300
lb	Glacial-lake clay and silt	300
lc	Clay and silt	300
ld	Delta deposits	300
lf	Silt and sand	300
lg	Pluvial clay, silt, sand and dolomite	300
lh	Density-current underflow-fan deposits	300
lm	Marl	300
ls	Sand and gravel	300
lu	Clay, silt, sand and gravel	300
ma	Back-barrier and lagoon deposits	300
mb	Beach and near-shore deposits	300
mc	Clay and silt	300
md	Delta deposits	300
me	Sand and gravel	300
mk	Back-island-slope, wash-over-channel, lagoon, and wind-tidal-flat deposits	300
ml	Coralline limestone	300
mo	Oolitic limestone	300
ms	Sand	300
ra	Cherty, clayey to sandy solution residuum	300
rb	Solution residuum complex	300
rc	Chert-poor or chert-free, clayey to sandy solution residuum	300
rd	Cherty, quartz-sand solution residuum	300

re	Sandy solution residuum	300
sa	Clayey to sandy saprolite on granite, gneiss, schist and other felsic, mafic, and ultramafic igneous and metamorphic rocks	330
sb	Micaceous saprolite on felsic micaceous schist or rocks of mixed composition	330
sc	Clayey to sandy saprolite on phyllite, artillite, slate, marble, greenstone, serpentinite, metabasalt, metarhyolite and other felsic metavolcanic rocks	330
sd	Quartz-rich saprolite	330
se	Clayey saprolite on diabase and basalt	330
sf	Clayey saprolite on nephelene syenite	330
sg	Clayey to sandy saprolitized sand and gravel	330
ta	Clayey to loamy till	700
tb	Loamy till	700
tc	Clayey till--Ground-moraine deposits	700
td	Clayey till--End-moraine deposits	700
tf	Loamy till	700
th	Clayey to sandy till	700
tj	Loamy till--End-moraine deposits	700
tk	Loamy till--Ground-moraine deposits	700
tl	Loamy till--Ground-moraine deposits	700
tm	Loamy till--End-moraine deposits	700
tn	Loamy till--Stagnation-moraine deposits	700
to	Loamy till--Flood-scoured till	700
tp	Clayey to loamy till	700
ts	Sandy till--Ground-moraine deposits	700
tt	Sandy till--End-moraine deposits	700
tx	Clayey to sandy till	700
ua	Glaciated granitic grus	350
ub	Feldspathic sandy grus	350
wa	Sheetwash alluvium in badland terrain	230
wb	Sheetwash alluvium	230
xa	Disintegration residuum on clastic rocks	200
xb	Disintegration residuum on clastic rocks and carbonate rocks	200
xc	Quartz sand disintegration residuum	200
xd	Stony, gypsiferous disintegration residuum	200
xg	Cemented, gravelly disintegration residuum	200
za	Clayey to sandy decomposition residuum	200
zb	Decomposition residuum on sand and gravel beneath high stream terraces and in alluvial fans	200
zc	Decomposition residuum on sand or mixed-composition sand and gravel on upland surfaces	200
ze	Smectitic-clay decomposition residuum	200
zf	Ferruginous sand and clay decomposition residuum	200
zg	Crumbly quartz-clast decomposition residuum on sand and gravel	200
zj	Decomposition residuum complex	200

zk	Decomposition residuum on upland sand and gravel and on paleochannel fill deposits	200
zl	Quartz-pebble, chert-pebble, and quartzite-pebble decomposition residuum on sand and gravel on upland surfaces	200
zn	Chert-pebble decomposition residuum on channel gravel and sand	200
zp	Sand, silt, and smectitic-clay decomposition residuum	200
zs	Decomposition residuum on sandstone, siltstone, shale, limestone, and dolomite	200
zu	Gravel, sand, silt, and smectitic-clay decomposition residuum	200
zv	Decomposition residuum complex	200

Implementation of ShakeMap by ANSS-NE

Implementation of ShakeMap in the northeastern U.S. requires that the best methods for generating accurate ShakeMaps in the region be identified, tested and verified first. We acknowledge that for the foreseeable future, ShakeMaps for earthquakes in the northeastern U.S. will inevitably be heavily based on model computations rather than on strong-motion observations. However, we firmly believe that the usefulness of model-based ShakeMaps to the emergency management community as well as other stakeholders in the northeastern U.S. outweighs the shortcomings of those maps due to a paucity of strong ground-motion observations as inputs into their computation.

An Instrumental Intensity Map is generated for the Mw 4.0 October 3, 2006 Bar Harbor, Maine earthquake and is compared with the Community Internet Intensity Map (CIIM; see Figures 2 & 3). The ShakeMap shown in Figure 3 utilized ground motion values and a uniform site condition with shear velocity 1,500 m/s. The peak ground motion attenuation curves for eastern North America given by Atkinson & Boore (1995) are used, and the regression relationship between intensity and peak ground motions given in Wald et al. (1999) is employed.

Figure 2 shows the CIIM of Mw 4.0 Bar Harbor, Maine earthquake. Following the earthquake, 1,473 felt reports were filed on CIIM with the maximum Modified Mercalli Intensity (I_{mm}) of IV near the epicenter. Most felt reports were filed by residents in Bar Harbor (zip code 04609) near the epicenter (see Figure 2) and had 280 reports with an average intensity I_{mm} 4.4 (IV). 41 reports with an average intensity I_{mm} 3.9 were from Franklin, ME (zip code 04634) about 25 km north of the epicenter. 172 felt reports were from Ellsworth, ME (zip code 04605) about 25 km northwest of the epicenter with an average intensity I_{mm} 3.6, and an additional 58 reports were from Southwest Harbor on Mount Desert Island (MDI) about 15 km southwest of the epicenter with the same intensity. One felt report with I_{mm} 4.6 was from Lisbon Falls, ME near Lewiston, ME and two reports with I_{mm} 4.6 were from Canaan, ME located west of Bangor (see Figure 2). Hence, these few I_{mm} 4.6 (V) observations were likely less reliable because of their large distance from the epicenter of the event. From the CIIM data it appears that the observed I_{mm} IV (3.5-4.4) area is consistent with an approximately 125 km radius from the

epicenter north and west from the earthquake.

The Instrumental Intensity Map shown in Figure 3 for the Bar Harbor, Maine earthquake on October 03, 2006 is based on ground motion values at 45 stations in the distance ranges from 73 to 700 km. Although the earthquake is an Mw 4.0 event in the northeastern U.S., only a handful of regional seismic stations were within 300 km from the epicenter, and the majority of regional seismic stations (39 out of 45 stations) were in the distance range from 300 km to 700 km. Since there are not enough observed ground-motions to produce a ShakeMap that is well constrained by data, we used the attenuation relation of Atkinson and Boore (1995) to fill the data gaps between the seismic stations. Site corrections in terms of 30m average shear velocity as a function of position are not yet incorporated in the current calculation. This ShakeMap reproduces the observed Modified Mercalli Intensity (I_{mm}) IV area (Figure 2) close to the epicenter, but I_{mm} IV area west of the epicenter is not well reproduced due to a lack of observed strong-ground motion data. This example illustrates that we need to have better seismographic station coverage to generate more useful ShakeMaps for the earthquakes in the northeastern U.S.

Conclusions

This major result of this study is the correlation of the surficial geology units from the Fullerton et al. (2003) surficial geology map with shear-wave velocities (Table 4). This surficial geology map and corresponding surficial shear-wave velocities can be used to compute modification factors for the ground motions on surficial soils as part of the generation of ShakeMaps for the northeastern U.S. Because of the coarse scale of the surficial geology map of Fullerton et al. (2003), the ground motion values calculated for the northeastern U.S. ShakeMaps should not be used for site-specific estimates of ground motions, but they are appropriate for ShakeMaps generated on a regional scale.

References

Atkinson, G.M., and D. Boore (1995). New ground motion relations for eastern North America, *Bull. Seism. Soc. Am.*, **85**, 17-30.

Borcherdt, R. D. (1994). Estimates of site-dependent response spectra for design (methodology and justification), *Earthquake Spectra*, **10**, 617-654.

Caldwell, D.H., and G.N. Nottis (undated). Seismic Hazard Assessment, Onondaga County, New York, New York State Museum Report, available at www.nysm.nysed.gov/gis/geo_semo97.html.

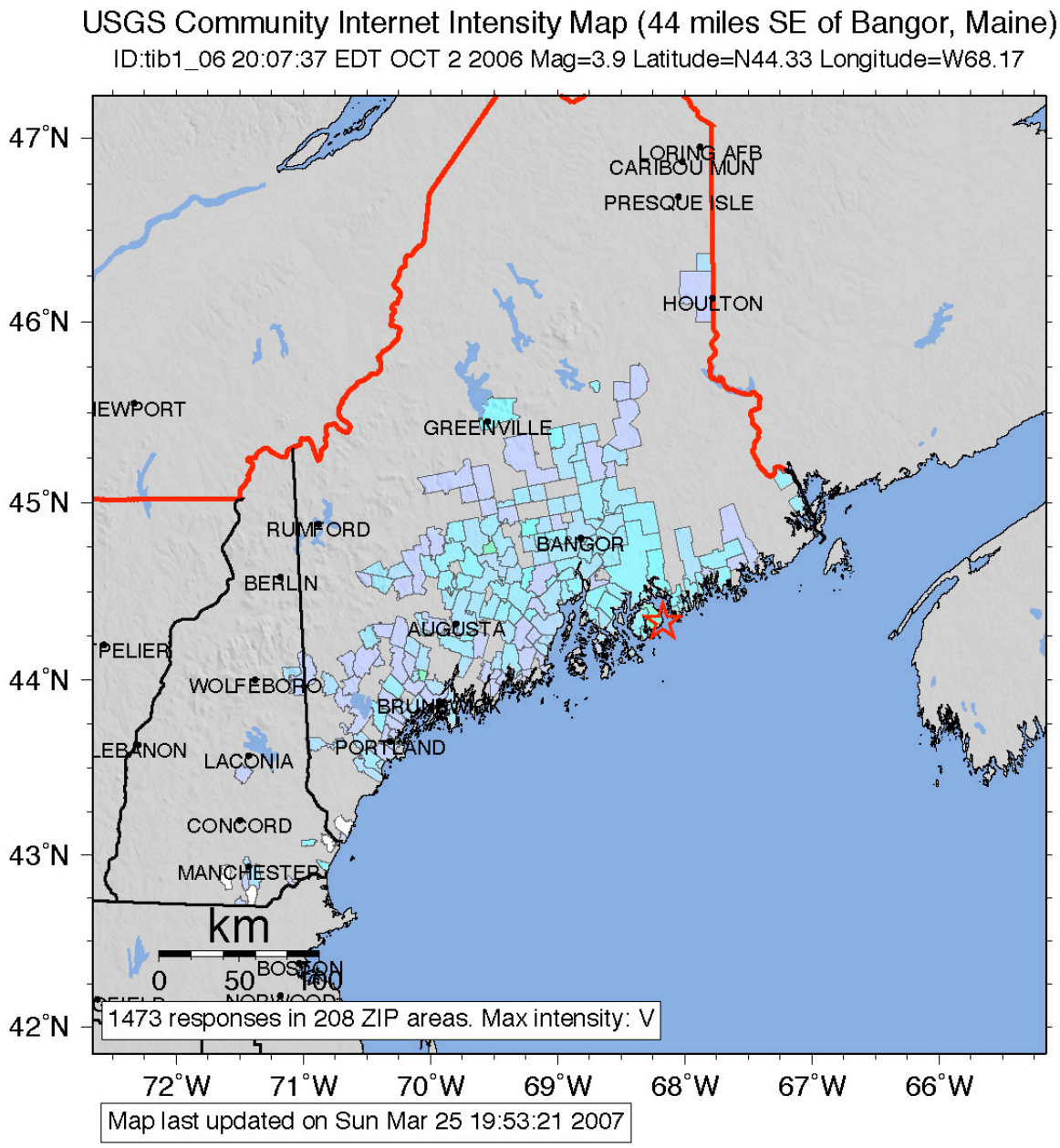
Finn, W.D. Liam (1993). "Characterization of Site Effects and Soil-Structure Interaction for Seismic Design Codes"; Seismic Soil/Structure Interaction Seminar, Vancouver, British Columbia, May 29.

Fullerton, D.S., C.A. Bush and J.N. Pennell (2003). Map of Surficial Deposits and Materials in the Eastern and Central United States (East of 102° West Longitude), *U.S. Geological Investigations Series I-2789*.

Martin, G.R., and R. Dobry (1994). Earthquake Site Response and Seismic Code Provisions, *NCCEER Bulletin*, **8(4)** 1-6.

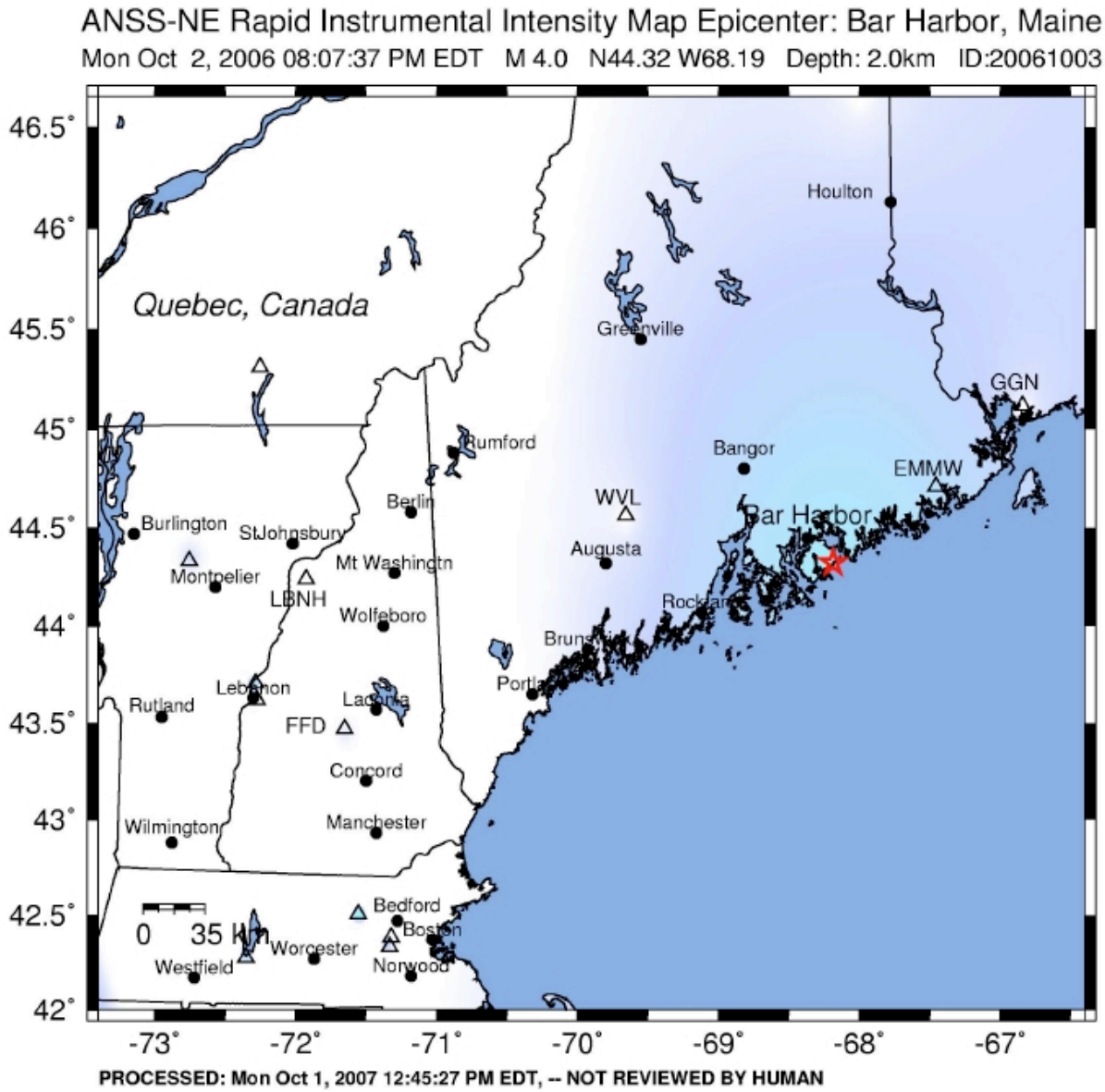
Redpath, B.B. (1973). Seismic Refraction Exploration for Engineering Site Investigations, *U.S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory Report TID-4500, UC-35*, Livermore, CA.

Wald, David J., Vincent. Quitoriano, Tom. H. Heaton, Hiroo. Kanamori, Craig. W. Scrivner, and C. Bruce Worden, (1999b). TriNet "ShakeMaps": Rapid Generation of Instrumental Ground Motion and Intensity Maps for Earthquakes in Southern California, *Earthquake Spectra*, **15**, 537-556.



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

Figure 2. Community Internet Intensity Map (CIIM) of Mw 4.0 Bar Harbor, Maine earthquake on October 03, 2006. The reported maximum Modified Mercalli Intensity (I_{mm}) is IV near the epicenter.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3. Instrumental Intensity Map generated for the Bar Harbor, Maine earthquake on October 03, 2006 (00:07 UTC). The Instrumental Intensity Map is based on ground motion values at 45 stations in the distance ranges from 73 to 700 km. This map reproduced observed Modified Mercalli Intensity (I_{mm}) IV area (Figure 2) near the epicenter, but the I_{mm} IV area west of the epicenter is not well reproduced due to a lack of observed strong-ground motion data.