Development of a Liquefaction Hazard Screening Tool for Caltrans Bridge Sites

K. L. Knudsen[1], J.D.J. Bott[1], M.O. Woods[2], and T.L. McGuire[2]

[1]California Geological Survey, Menlo Park, California, now at URS Corporation, Seismic Hazards Group, 1333 Broadway, Suite 800, Oakland, CA, 94612; Knudsen (510) 874-3120, Keith_Knudsen@URSCorp.com; Bott (510) 874-1761, Jacqueline_Bott@URSCorp.com
[2]California Geological Survey, 801 K Street, MS 12-31, Sacramento, CA 95814; Woods (916) 445-5519, mowoods@conservation.ca.gov; McGuire (916) 324-1247, tmcguire@conservation.ca.gov

ABSTRACT

We have developed a liquefaction hazard screening tool for the California Department of Transportation (Caltrans) that is being applied in evaluating liquefaction hazard to approximately 13,000 bridge sites in California. Because of the large number of bridge sites to be evaluated, we developed a tool that makes use of parameters not typically considered in site-specific investigations. We assessed geologic, topographic, seismologic, and subsurface conditions at about 100 sites of past liquefaction in California. Among the parameters we found common to many of these sites are: (a) low elevations, (b) proximity to a water body, and (c) presence of geologically youthful deposits or artificial fill materials. The nature of the study necessitated the use of readily available data, preferably datasets that are consistent across the state. The screening tool we provided to Caltrans makes use of the following parameters: (1) proximity to a water body, (2) whether the bridge crosses a water body, (3) the age of site geologic materials and the environment in which the materials were deposited, as discerned from available digital geologic maps, (4) probabilistic shaking estimates, (5) the site elevation, (6) information from available liquefaction hazard maps [covering the 9-county San Francisco Bay Area and Ventura County] and CGS Zones of Required Investigation. For bridge sites at which subsurface boring data were available (from CGS' existing database), we calculated Displacement Potential Index values using a methodology developed by Allison Faris and Jiaer Wu. The screening tool builds on unpublished work by Professor S. Kramer. Caltrans' staff are using this hazard-screening tool, along with other tools described in this session, to prioritize site-specific investigations.

INTRODUCTION

This paper describes a project whose goals were: (1) to develop a methodology for screening and prioritizing highway bridge sites for retrofit and/or site–specific field investigations based on exposure to liquefaction-induced ground failure hazard; and (2) to apply the methodology to screen those Caltrans bridge sites at highest risk from liquefaction-related damage. Caltrans plans to use the screening tool we have developed, in combination with other tools that address bridge structures, to evaluate the liquefaction hazard to the approximately 13,000 bridges for which it is responsible. Our focus has been on hazards at *bridge sites*, not on the bridge structures.

Development and demonstration of a cost-effective strategy to evaluate exposure of transportation structures to ground failure hazards has applicability elsewhere. Combining estimates of hazard exposure (this project) with information on structural vulnerability and importance (parallel project) can provide an estimate of risk that is a logical basis for prioritizing the expenditure of mitigation funds for earthquake and liquefaction retrofitting. Such an approach may be applicable to a variety of lifeline systems/organizations, not exclusively transportation systems. The results of this study will allow Caltrans to focus its resources on facilities that have been prioritized for future site-specific work using a sound and consistent approach that ranks bridge sites from across the entire state.

APPROACH

The goals of the project were accomplished through a phased approach. All of the phases made intensive use of Geographic Information System (GIS) software and analyses. The first phase of the project involved reviewing about 100 California liquefaction case histories (Table 1) to identify parameters that would be useful in predicting future liquefaction-related ground failures. Because the study region is so expansive (the state of California), it was necessary to identify parameters for which consistent, state-wide, digital (GIS) data layers are available. After the predictive parameters were identified, in the second phase of the project we developed a screening tool that is based on readily available geological, geographical and seismological information. The third phase of the project included intensive GIS analysis in which bridge locations were intersected with a number of regional databases and a master database of parameters for each bridge site was compiled. During this phase, we used geotechnical boring information in the vicinity of bridges that had been previously collected and entered into the CGS GIS database to develop preliminary quantitative estimates of liquefaction-related ground failure. We used the subsurface data, together with recently developed approaches to estimate magnitudes of liquefaction-related ground failure (Faris, 2004 and Wu, 2002), to quantify the liquefaction hazard and further screen the bridge sites for more detailed study or retrofit.

In the first phase of the project, we compiled information on about 100 California liquefaction case histories. Table 1 lists the eleven earthquakes and the number of case history sites for each earthquake that have been characterized. In developing and characterizing these sites, we relied on recent compilations of liquefaction sites by others that were developed primarily for refining liquefaction triggering relationships and lateral spread magnitude relationships (e.g. Bartlett and

Youd, 1992; Cetin et al., 2004; Faris, 2004; Moss, 2003; Rauch, 1997;Youd et al., 2002). Some of the sites we include liquefied in more than one of the earthquakes listed in Table 1. Because a digital compilation of San Francisco Bay Area liquefaction sites is available (Knudsen et al., 2000), the analysis is heavily weighted toward this area. In evaluating the potential success of different hazard indicators in predicting liquefaction, we tracked separately the relationships for native material and artificial fill sites. During the first phase of the project, we identified several "hazard indicators" that seem to be good predictors of hazard, which are typically not included in site-specific analyses. Among these parameters, are elevation and proximity of the site to a water body.

Table 1. Case History Sites and Earthquakes

Earthquake	Mw	Number of sites
1865 Santa Cruz Mountains	~6.5	2
1868 Hayward	~7	3
1906 San Francisco	~7.9	30
1957 Daly City	5.3	1
1971 San Fernando	6.6	2
1979 Imperial Valley	6.5	5
1981 Westmorland	6.0	4
1987 Superstition Hills	6.6	1
1989 Loma Prieta	6.9	67
1994 Northridge	6.7	8
2003 San Simeon	6.5	3

In the second phase of the project, we assembled data describing the approximately 13,000 bridge sites that are spread throughout California. Readily available information, which is reasonably consistent across the state, includes topographic information (e.g. elevation of bridge sites), geographic information (e.g. proximity of the site to a water body), digital geologic map information (from geologic maps at scales from 1:24,000 to 1:750,000) and the derivative NEHRP site class (from Wills and Clahan, 2006 and unpublished mapping by C. Wills), probabilistic ground motion estimates (we use 10% in 50 year exceedance values of PGA), and digital liquefaction hazard maps (that are available only for the San Francisco Bay Area and Ventura County). Additionally, we obtained geotechnical borings from within 200 meters of bridge sites for about 20% of the sites (from CGS files; these boring data are available online at http://gmw.consrv.ca.gov/shmp/MapProcessor.asp?Action=SHMP&Location=All). Lastly, based on the naming conventions Caltrans uses for its bridges, we were able to evaluate whether the bridge crosses a water body. One of the interesting and challenging aspects of this project is that for some bridge sites very detailed information is available, whereas for other sites little information is available.

In the third phase of the project, we developed and implemented the tool to rank bridge sites according to their susceptibility to liquefaction-related deformation.

The hazard susceptibility assessment makes use of and builds on a method proposed by Kramer (2008). Kramer defined a susceptibility rating factor (SRF) in which:

$$SRF = F_{\mathrm{hist}} \times F_{\mathrm{geology}} \times F_{\mathrm{comp}} \times F_{\mathrm{gw}}$$

where F_{hist} is a liquefaction history factor, F_{geology} is a geology factor, F_{comp} is a material composition factor, and F_{gw} is a groundwater factor. Each of Kramer's (2008) factors is composed of a combination of contributing factors; for example, the historical liquefaction factor is a function of past occurrences and past levels of seismicity, and the geology factor is a function of the age of the materials, the environment in which they were deposited, and the reliability of the geologic classification. Note that the relationship proposed by Kramer (2008) is multiplicative.

We have defined a site liquefaction hazard rating factor (SLHRF). Ideally this factor would be calculated making use of the kind and range of information Kramer (2008) proposed. However, given the scope of our project, we were not able to collect site-specific material composition information, site-specific groundwater information, or be sure that past shaking levels and liquefaction occurrences in the vicinity of bridge sites have been adequately noted. Thus, in our evaluation of case histories we searched for parameters that could be used as indicators of groundwater levels and material properties, but wouldn't require obtaining site-specific data. The tool is implemented in a Microsoft® Excel® workbook in which each row of the main page represents a single bridge site. Other worksheets in the workbook contain lookup tables that relate the parameter of interest to a numerical value that can be used, together with other numerical values representing other parameters, to rank bridge sites. Unlike Kramer's (2008) method, for every parameter we include a weighting coefficient that serves to emphasize the factors we believe to be best predictors of future liquefaction hazard and de-emphasize the factors that may not be as robust predictors. These weighting coefficients are included as a lookup table and thus can be altered based on one's confidence that different factors are reliable hazard predictors.

SITE LIQUEFACTION HAZARD RATING TOOL

For every bridge we were supplied with a single latitude/longitude pair. This unique site location was called the bridge site, and was used to query against spatial databases. A single latitude/longitude pair does not represent longer bridges very well. We considered adding a buffer about each point, but comparison of the coordinate pair locations with topographic maps showing bridges indicated that the coordinate pairs supplied were not consistently located along the bridges (i.e. the latitude/longitude pair for one bridge might lay at the north end of one bridge and the site coordinates might be in the middle of the next bridge).

For every bridge site we characterized: (1) the elevation (by querying against 1:100,000-scale DEMs), (2) the distance to the nearest water body (from 1:100,000-scale hydrology layers), (3) whether the bridge crosses a water body (using the Caltrans naming conventions), (4) the geology map unit shown by the best available map for the site (more than 30 geologic maps, of varying scales, were necessary) and from this the age of the deposits and the environment in which they were deposited, (5) the NEHRP site class soil type (using a map provided by Chris Wills of CGS), (6) the PGA (by querying against the 2006 statewide probabilistic map and then correcting the PGA value for the NEHRP site condition), (7) the de-aggregated mode magnitude (from the 2006 probabilistic map), (8) whether the site lies within a CGS Liquefaction Zone of Required Investigation (ZORI), (9) the liquefaction susceptibility as depicted by mapping available only for the nine-county San Francisco Bay Area (Witter et al., 2006) and Ventura County (William Lettis & Associates, 2004), and (10) from boring logs collected by the CGS Seismic Hazard Zoning Program, information about the nature of subsurface deposits, from which we estimated a minimum of two parameters (Displacement Potential Index, from Wu, 2002, and Faris, 2004, and Liquefaction Potential Index, from Iwasaki et al., 1978). At least one boring was available for about 20% of the bridge sites.

We used these data and the following equation and related lookup tables to assign "factors" to calculate a Site Liquefaction Hazard Rating Factor (SLHRF – rhymes with "turf") for each of the approximately 13,000 bridge sites. The factors were developed based on conclusions reached after analyses of the California liquefaction case histories described above. SLHRF is patterned after the Susceptibility Rating Factor originally proposed by Kramer (2008), but includes a wider range of parameters, some of which have not been used before to identify liquefaction hazards. Some of these factors, by themselves, probably have no physical connection to liquefaction hazard (e.g. low elevations), but they do seem to be reasonable predictors of liquefaction hazard for reasons to be explained later. SLHRF is defined here as:

$$SLHRF = F_{\mathrm{geol}} \times F_{\mathrm{PGA}} \times F_{\mathrm{Mw}} \times F_{\mathrm{cross\text{-}creek}} \times F_{\mathrm{elev}} \times F_{\mathrm{H20\text{-}dist}} \times F_{\mathrm{NEHRP}} \times F_{\mathrm{haz\text{-}map}} \times F_{\mathrm{ZORI}} \times F_{\mathrm{DPI}}$$

The larger the SLHRF value the greater the liquefaction hazard. Because this quantity is numerical, the bridges can be ranked based on the SLHRF, and bridges with the largest SLHRF values, we believe, should be prioritized for additional investigation. This rating factor also can be considered a screening tool, by which relatively hazard-free sites can be identified and not absorb the resources necessary for site-specific studies. In the following paragraphs we briefly describe the factors that are used to calculate the SLHRF.

The geology factor (F_{geol}) is a function of the age of the deposits and the environment in which they were deposited (Table 2), and the scale of the geologic map used to identify the site geology (Table 3), similar to an approach taken by Youd and Perkins (1987). The geology factor is defined as the product of these two "sub-factors." The geology scale factor increases as the scale of the map gets smaller (the mapping is less detailed). Thus, sites characterized with small scale mapping (e.g. 1:250,000) are treated more conservatively. Table 2 illustrates our belief that very geologically youthful deposits, including uncompacted artificial fill and late Holocene deposits, are much more susceptible to liquefaction than even early or middle Holocene deposits. This conclusion stems from our review of California case histories. More than 90% of the case histories we evaluate occurred in deposits that are historical or late Holocene; an alternative way of expressing this is less than 10% of the case histories occurred in deposits older than ~1,000 years.

The PGA factor (F_{PGA}) is shown in Table 4. Sites likely to experience PGAs of greater than 0.4 g are assigned a PGA factor of 1 and those that have a probabilistic (10% in 50 year exceedance) PGA of less than 0.4 are assigned factors less than 1. The mean PGA for the California case histories we reviewed was 0.34 g and the median PGA for these occurrences was 0.27 g. Thus, we assign a PGA factor of less than one for PGAs of less than 0.4 g (thereby lowering the SLHRF for those sites), essentially concluding that all or most hazardous sites will "trigger" at PGAs above 0.4 g.

The earthquake magnitude factor (F_{Mw}) is included to account for duration effects, as it is in liquefaction triggering relationships. If the deaggregated magnitude (probabilistic mode) is less than M_w 7, then a magnitude factor of less than 1 is assigned (Table 4). Sites forecasted to experience magnitudes greater than M_w 7 are assigned factor values greater than 1.

The cross-creek parameter is included based on the work of Dickenson et al. (2002), who reviewed liquefaction case histories prior to their study for the Oregon Department of Transportation. They concluded that bridges that cross a water body are generally more susceptible to liquefaction than bridges that do not. This conclusion seems reasonable because it is near water bodies that geologically youthful deposits are generally found and groundwater levels are likely to be near the surface. Our cross-creek factor has only three possible values: 0.8 for bridges known to not cross a water body, 1.3 for bridges that do cross a water body, and 1 for sites where it is not known if the bridge crosses a water body.

We have included an elevation factor (F_{elev}) because low elevations are common to many of the California liquefaction case histories we reviewed. Ninety of the 100 cases we reviewed occurred at sites where the ground-surface elevation is less than 50 m above sea level. The mean elevation for these 100 sites is 26.4 m and the median is 3.0 m. Similar to the cross-creek parameter, one would expect to find geologically youthful deposits and shallow ground water at low elevations, both characteristics of deposits that are susceptible to liquefaction. Table 5 shows our elevation factor. We assign a factor of 1.2 for elevations less than 100 m, a factor of 0.9 for sites at elevations greater than 200 m, and an elevation factor value of 1.0 to those sites between 100 and 200 m in elevation.

We include a factor $F_{H20\text{-}dist}$, which is the distance from the site to the nearest water body. About 60 % of the case history sites we reviewed were within 50 m of a water body. The reasons that proximity to a water body may be a good indicator of liquefaction hazard are similar to those for elevation and whether the bridge of interest crosses a creek. Geologically youthful, granular saturated deposits are more likely to be found near water bodies. The best available, consistent statewide maps of water bodies are at the scale of 1:100,000. We believe that the relationship between distance to water body and past occurrences would be even stronger were more detailed maps of water bodies available. Table 5 shows the values we use for the proximity to water body factor. These factor values are similar in magnitude and range to those for the "cross-creek" and elevation factors because they are similar in concept and likely connection to liquefaction hazard.

We include a parameter F_{NEHRP}, which we believe is related to liquefaction hazard in two ways: soils that are soft (D and E soils) may amplify ground motions, and softer soils are more likely to contain unconsolidated potentially liquefiable materials. The maps we use to assign a NEHRP soil type to each bridge site are small scale (1:250,000), and thus this parameter is not weighted heavily. The NEHRP soil type factor (F_{NEHRP}) is a product of the NERHP factor and the NEHRP soil-type quality factor, which is based on the scale of mapping. The values for these "sub-factors" are shown in Table 4.

Liquefaction hazard maps at 1:24,000 scale are available for the San Francisco Bay Area (Witter et al., 2006; Knudsen et al., in preparation) and for Ventura County (unpublished mapping by C. Hitchcock and colleagues at William Lettis & Associates). We have incorporated these maps into our analyses by including an $F_{\text{haz-map}}$ parameter (Table 3). We assign a factor value of greater than 1 for areas mapped as having high or very high liquefaction susceptibility and assign factors of less than 1 to areas mapped as low or very low liquefaction susceptibility.

The State's Seismic Hazard Zoning Program (SHZP) has mapped most of three counties in southern California (Los Angeles, Orange and Ventura) and has mapped parts of San Francisco, Alameda, Santa Clara and San Mateo counties in northern California (http://www.conservation.ca.gov/cgs/shzp/Pages/Index.aspx). Because these maps are generally considered to be conservative (i.e. large areas of relatively low hazard may get included in the Zones of Required Investigation), we assign a low F_{ZORI} to sites in areas that have been mapped by this program but are not included in the ZORI for liquefaction (Table 3). We don't place very much weight on those sites within the CGS ZORI areas – the F_{ZORI} for these sites is only given a value of 1.2.

The SHZP has collected numerous geotechnical borings in its liquefaction hazard zoning of flatlands in the areas mentioned above. For this project, we used the boring log records for all borings in the CGS database that are within 200 m of a Caltrans bridge site; approximately 20% of the bridge sites have at least one boring log for characterization of the site. For every boring log we calculate a number of liquefaction-related parameters, but primarily rely on Displacement Potential Index (DPI) in this study. DPI was developed by Wu (2002) and Faris (2004) as a way to predict limiting horizontal shear strains, and we consider it an index value rather than a prediction. The DPI factor is shown in Table 3. For the 80% of bridges that do not have associated subsurface information, we assign an F_{DPI} of 1.0, the median value where we do have borings.

Table 2. Geology Classification Factor: Based on Age and Environment of Deposition

Type of Deposit	Geology Classification Factor: Late Holocene-Historical	Holocene	Pleistocene	Quaternary	Pre-Quaternary	Comments
Artificial fill	7.5	7.5	7.5	7.5	7.5	when degree of compaction not known
Compacted artificial fill	0.6	0.6	0.6	0.6	0.6	
Stream channel	6	3	0.6	3	0.3	
Wash	6	3	0.6	3	0.3	
Delta	4.5	1.8	0.6	1.8	0.3	coastal and continental
Loess	1.8	1.2	1.2	1.2	0.3	
Flood plain	1.8	1.2	0.6	1.2	0.3	
Alluvial valley	1.8	1.2	0.6	1.2	0.3	includes "axial valley"
Nonmarine terrace	1.8	1.2	0.6	1.2	0.3	mainly stream terraces
Lacustrine	1.8	1.2	0.6	1.2	0.3	
Playa	1.8	1.2	0.6	1.2	0.3	
Basin	1.8	1.2	0.6	1.2	0.3	
Colluvium	1.8	1.2	0.6	1.2	0.3	
Dune	1.8	1.2	0.6	1.2	0.3	
Paralic	1.8	1.2	0.6	1.2	0.3	includes estuarine, paludal, bay and lagoon
Beach	1.8	1.2	0.6	1.2	0.3	
Foreshore	1.8	1.2	0.6	1.2	0.3	
Alluvial fan	1.2	0.6	0.6	0.6	0.3	
Alluvial plain	1.2	0.6	0.6	0.6	0.3	
Talus	0.6	0.6	0.3	0.6	0.3	
Glacial outwash	3	1.8	0.6	1.2	0.3	
Glacial till	0.6	0.6	0.3	0.6	0.3	
Tuff	0.6	0.6	0.3	0.6	0.3	includes lahar, pyroclastic and other volcanics
Marine terrace	1.2	0.6	0.6	0.6	0.3	
Landslide	0.6	0.3	0.3	0.3	0.3	
Undifferentiated surficial	1.8	1.2	0.6	1.2	0.3	
Marine, undifferentiated	1.8	1.2	0.6	1.2	0.3	
Alluvium, undifferentiated	1.8	1.2	0.6	1.2	0.3	
Pediment	0.6	0.3	0.3	0.3	0.3	deposits resting on a pediment surface
Rock	0.15	0.15	0.15	0.15	0.15	
Water	6	---	---	---	---	"water" based on query against most detailed geologic map

Table 3. Geologic map scale factor, Displacement Potential Index (DPI) factor, Liquefaction hazard map factor, and ZORI factor

Geologic map scale factor		DPI factor		Liquefaction hazard susceptibility map factor		CGS Zone of Required Investigation factor	
scale	*factor*	*DPI (ft)*	F_{DPI}	*Liquefaction susceptibility*	$F_{haz\text{-}map}$	*within ZORI?*	F_{ZORI}
site specific data	1	0 to 2	0.5	Very Low	0.8	Not In Zone	0.5
≤ 24,000	1.2	2 to 6	0.8	Low	0.9	Landslide zone	0.8
>24,000 to 100,000	1.35	6 to 12	1	Moderate	1	Not In Area Mapped	1
>100,000 to 500,000	1.5	12 to 18	1.6	High	1.1	Liquefaction zone	1.2
750,000	1.6	>18	1.8	Very High	1.2	---	1
		other	1	Water	1.15		
				not mapped	1		

Table 4. PGA factor, Earthquake magnitude factor, NEHRP soil type factor, and NEHRP soil type quality factor

PGA		Earthquake magnitude		NEHRP soil type		NEHRP soil-type quality	
Expected PGA (g)	F_{pga}	*Magnitude*	F_{Mw}	*soil type*	F_{NEHRP}	*NEHRP soil-type quality (scale)*	$F_{NEHRP\_quality}$
0 to 0.1	0.05	5 to 6	0.8	A	0.9	site specific data	1
0.1 to 0.2	0.25	6 to 7	0.9	AB	0.9	>= 1:24,000	1.1
0.2 to 0.3	0.5	7 to 8	1	B	0.9	< 1:24,000	1.2
0.3 to 0.4	0.75	8 to 9	1.1	BC	0.9		
0.4 to 0.5	1	9 to 10	1.2	C	0.95		
0.5 to 0.6	1			CD	0.95		
0.6 to 0.7	1			D	1		
0.7 to 0.8	1			DE	1.05		
0.8 to 0.9	1			E	1.1		
>0.9	1			F	1.2		

Note: the PGA used in SLHRF is corrected for NEHRP soil type.

Table 5. Distance-to-water-body factor, does bridge cross a water body factor, and elevation factor

H_2O Distance		Cross-Creek		Elevation	
Proximity to water body	F_{H2O_dist}	*Does bridge cross a water body?*	$F_{cross\text{-}creek}$	*Elevation (m)*	F_{elev}
0-50	1.2	no	0.8	-100 to 0	1.2
50-100	1.2	maybe	1	0 to 100	1.2
100-500	1	yes	1.3	100 to 200	1
>500	0.9			200 to 300	0.9
				>300	0.9

DISCUSSION AND CONCLUSIONS

We have implemented two different versions of the SLHRF, one where all factors are multiplied, and another where only similar quantities are multiplied and then these grouped quantities of hazard indicators are added. It is still unclear to us which is the preferred method. Either method allows for incorporation of the coefficients described above, which can be used to weight the different contributing hazard indicators according to the user' s insights about the relative reliability of the different indicators in predicting liquefaction hazard. In the second version of SLHRF, in which similar factors are multiplied, we have defined: (1) a "near water quantity" to be the product of the distance to water body factor and the does a bridge cross a creek factor: (2) a shaking quantity as the product of the PGA factor and the earthquake magnitude factor; (3) a geology-based map factor as the product of the geology factor (which depends on age and environment of mapped deposit along with map scale), the liquefaction hazard map factor, the NEHRP soil type factor and the CGS Zone of Required Investigation factor; (4) an elevation quantity that is the same as the elevation factor; and (5) the DPI factor.

There are several factors for which we have data for only a fraction of the bridges studied. For the 80% of the bridge sites that have no nearby borings from which to estimate DPI, the median F_{DPI} is applied. We also calculate the two versions of SHLRF with and without F_{DPI} so the user who is uncomfortable comparing bridges with some limited subsurface data against bridges with no available subsurface data has a choice. Two other parameters were incorporated into the analyses despite the availability of mapping of these parameters for a fraction of the bridges. As described above, digital liquefaction hazard maps are only available for the nine-county San Francisco Bay Area and Ventura County. The CGS liquefaction Zone of Required Investigation maps are only available in parts of Alameda, Los Angeles, Orange, San Francisco, San Mateo, Santa Clara and Ventura counties. For these two parameters, we structured the factor tables (Table 3) so that the factor ranges are centered on a value of 1.0, and we assign 1.0 when we do not have data for that parameter at a bridge site.

Preliminary review of California liquefaction case histories with respect to the size of watershed in which the liquefying material was deposited suggests that there may be a relationship between watershed size and liquefaction susceptibility. Such a comparison is not relevant for artificial fill deposits or marine deposits, whose deposits are not affected by watershed size. Conceptually, it seems reasonable that larger watersheds with larger, higher energy streams, will produce better sorted deposits that are more laterally continuous, and which present a greater liquefaction hazard. However, because we were not able to obtain a map of watersheds that is consistent in level of detail across the state, we did not include this parameter in our rating tool.

We would have preferred to have a more complete digital representation of each bridge than the single pair of latitude and longitude coordinates that we used to represent each bridge. By using just the single point to represent each bridge in queries against spatial datasets, we undoubtedly missed indicators of hazard. For example, if the coordinate pair representing a bridge site happened to map the end of a bridge founded in bedrock, while much of the rest of the bridge length spanned youthful geologic deposits, our query would have returned bedrock as the geologic map unit for the site and our results likely are unconservative for that bridge.

In conclusion, we believe the approach and tool we developed is useful for screening of networks or separated structures for liquefaction hazard. Although our specific application was for screening of bridge sites, the approach can be readily adapted to other kinds of distributed structures. If the region of interest is of manageable size (e.g. smaller than the state of California), more detailed information and analyses could be incorporated in the screening evaluation.

ACKNOWLEDGMENTS

This project was sponsored in part by the University of California at Berkeley's Pacific Earthquake Engineering Research Center's Program of Applied Earthquake Engineering Research of Lifeline Systems, supported by the California Department of Transportation. This work made use of the Earthquake Engineering Research Center's Shared Facilities, supported by the National Science Foundation. The authors wish to thank Tom Shantz of Caltrans for his guidance and support. A number of California Geological Survey personnel contributed, and we wish to recognize, in particular, Charles Real for his support. John Tinsley and Michael Bennett of the USGS, who have investigated many of the case history sites, kindly discussed the case histories and their geologic interpretation with us. Geotechnical borings used in our analyses were obtained previously from many city and county agencies and private consultant files by the CGS Seismic Hazards Zoning Program. Unpublished geologic mapping was kindly provided by Don Elder of the U.S. Forest Service, and numerous published and unpublished digital geologic maps produced by CGS and the USGS were used in this analysis. The project benefited substantially from an EERI/FEMA Earthquake Hazards Reduction Professional Fellowship awarded to Keith Knudsen.

REFERENCES

Bartlett S. F., and T. L. Youd., 1992, Empirical Analysis of Horizontal Ground Displacement Generated by Liquefaction-Induced Lateral Spreads: *Technical Report NCEER-92-0021*, National Center for Earthquake Engineering Research, Buffalo, NY.

Cetin, K.O., Seed, R.B., Der Diureghian, A., Tokimatsu, K., Harder, L.F., Jr., Kayen, R.E., and Moss, R.E.S., 2004, Standard Penetration Test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. J. Geotech. & Geoenv. Engin., p. 1314-1340.

Dickenson, S.E., McCullough, N.J., Barkau, M.G., and Wavra, B.J., 2002, Assessment and Mitigation of Liquefaction Hazards to Bridge Approach Embankments: Final report to the Oregon Department of Transportation, 210 pages.

Iwasaki, T., Tatsuoka, F, Tokida, K., & Yasuda, S., 1978, A Practical method for assessing soil liquefaction potential based on case studies at various sites in Japan. Proc. of the 2nd International Conf. on Microzonation, Vol. 2, p. 885-896.

Faris, A.T., 2004, Probabilistic Models for Engineering Assessment of Liquefaction-Induced Lateral Spreading Displacements: Ph.D. Dissertation, University of California, Berkeley, California, 184 p.

Knudsen, K, Witter, R.C., Wentworth., C.M., and Sowers, J.M., in preparation, Maps of Quaternary deposits and liquefaction susceptibility in the nine-county San Francisco Bay Region, California: U.S. Geological Survey.

Kramer, S.L., 2008, Evaluation of liquefaction hazards in Washington State: Washington State Transportation Center, Seattle, Washington, 146 p.

Moss, R.E.S., 2003, CPT-based probabilistic assessment of seismic soils liquefaction initiation: Ph.D. Dissertation, University of California, Berkeley, California, 528 p.

National Earthquake Hazard Reduction Program, 1994, NEHRP Recommended Provisions for Seismic Regulations for New Buildings, Part 1, Provisions, 1994 Edition.

Rauch, A. F., 1997, EPOLLS: An empirical method for predicting surface displacement due to liquefaction –induced lateral spreading in earthquakes: Ph.D. dissertation, Virginia Polytechnic Institution, VA.

William Lettis & Associates, Inc., 2004, Unpublished Quaternary geology and liquefaction potential maps of the Ventura Basin, Digital Map Database: scale 1:24,000.

Wills, C.J., unpublished, Digital geologic map of California, scale 1:250,000.

Wills, C.J., and Clahan, K.B., 2006, Developing a map of geologically defined site-condition categories for California: Bulletin Seismological Society of America, vol. 96, pp. 1483-1501.

Witter, R.C, Knudsen, K.L., Sowers, J.M., Wentworth, C.M., Koehler, R.D., and Randolph, C.E., 2006, Maps of Quaternary deposits and liquefaction susceptibility in the central San Francisco Bay Region, California: U.S. Geological Survey Open-File Report 2006-1037, scale 1:24,000.

Wu, J., 2002, Liquefaction Triggering and Post Liquefaction Deformations of Monterey 0/30 Sand Under Uni-Directional Cyclic Simple Shear Loading: Ph.D. Dissertation, University of California, Berkeley, California.

William Lettis & Associates, Inc., 2004, Unpublished Quaternary geology and liquefaction potential maps of the Ventura Basin, Digital Map Database: scale 1:24,000.

Youd, T. L. and Perkins, D. M., 1978, Mapping liquefaction-induced ground failure potential: Journal of Geotechnical Engineering Division, Volume 104, p. 433-446.

Youd, T.L., Hansen, C.M., and Bartlett, S.F., 2002, Revised MLR equations for prediction of lateral spread displacement: Journal of Geotechnical and Geoenvironmental Engineering, 128(12), p. 1007-1017.