The REAL Dirt on Liquefaction

TECHNICAL APPENDICES
to the Guide to the Liquefaction Hazard in Future Earthquakes Affecting the San Francisco Bay Area

February 2001

ASSOCIATION OF BAY AREA GOVERNMENTS

CREDITS

Principal Report Author:

Jeanne B. Perkins – Earthquake Program Manager, Association of Bay Area Governments

Support:

DATABASE PROGRAMMING – Fred Parkinson – Systems Programmer
CARTOGRAPHY and COLOR LAYOUT – Kearey Smith and Vicki Rutherford
RESEARCH ASSISTANTS – Susannah Belding, Stuart Lowe, Michael Smith, and Robert Swierk

ABAG Management:

Eugene Y. Leong – Executive Director

Acknowledgments:

ABAG would like to specifically acknowledge Keith Knudsen for his extensive efforts to ensure the scientific accuracy of this report.

ABAG also would like to acknowledge the efforts of the following members of the ABAG Earthquake Hazard Mapping Review Committee for their thoughtful comments on the material that forms a basis for this document.

Earthquake Hazard Mapping Review Committee:

Bill Ward – Committee Chair – Councilmember, City of Hayward

Catherine Bauman – Planner, City Planning Department, City and County of San Francisco
Edward Bortugno / Scott McAfee – Calif. Office of Emergency Services – Coastal Region
Arrieta Chakos – Office of the City Manager, Berkeley
Tom Holzer / Mike Bennett – Geologists, U.S. Geological Survey
Stephan Kiefer – Building Official, City of Livermore
Keith Knudsen – Senior Engineering Geologist, California Division of Mines and Geology (CDMG)
William Lettis / John Baldwin – William Lettis & Associates
Dale Marcum / Bill Cotton – Geologist, Cotton, Shires and Associates
Carl Mortensen – Geophysicist, U.S. Geological Survey
Carol Prentice – Geologist, U.S. Geological Survey
Doug Sandy – Assistant Director – Disaster Services, American Red Cross – Bay Area
William ("Woody") Savage – Sr. Seismologist, Pacific Gas & Electric Company (PG&E)
Richard Scott – Principal Engineering Technician, City of Novato
William Schock – Building Official, Development Services, City of San Leandro
Michael Shimamoto – Geologist, Public Works Department, City of San José
Ted Smith – Supervising Geologist, California Division of Mines and Geology (CDMG)

The writing and production of this report was funded by Grant Nos. 1434-HQ-97-GR-03048 and 1434-HQ-97-GR-03121 from the U.S. Geological Survey (USGS), as well as by the Association of Bay Area Governments and William Lettis & Associates, Inc. Supplemental funding for additional analysis in Appendix C was funded by Grant. No. 99-HQ-GR-0005 from the U.S. Geological Survey. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

For information on ABAG's Earthquake Program, liquefaction hazard maps by city and other earthquake impacts, see our Internet site at: *http://quake.abag.ca.gov*

ABAG Publication Number: P01002EQK

APPENDIX A - LIQUEFACTION SUSCEPTIBILITY MAPPING APPROACH

What Is NEW About the Quaternary Mapping?

ABAG received funding from the U.S. Geological Survey (USGS) to work on liquefaction hazard mapping in a collaborative project with William Lettis & Associates, Inc. (WLA). As part of this collaborative effort, WLA received funding from USGS to develop new regionally consistent maps of Quaternary deposits (materials deposited in the last 1.6 million years) (Knudsen and others, 2000).

These maps are significantly different from the maps of Quaternary deposits ABAG and others have used in the past. (See, for example, Helley and Lajoie (1979) and Youd and Perkins (1987).) One of the principal differences is that the materials are mapped based more on the environment in which they have been deposited (basin, terrace, alluvial fan, etc.) and less on estimated grain size. Finally, much of the mapping is at a more detailed scale (including 1:24,000). The map is an interim product and will be revised as additional more detailed maps are prepared by WLA, the California Division of Mines and Geology (CDMG), and USGS.

The maps were digitized at USGS under the direction of Carl Wentworth. The maps are available in the form of a digital spatial database.

How Were the Liquefaction Susceptibility Maps Made?

Geologic map units in the digital Quaternary map were grouped into categories of similar susceptibility to liquefaction based on:

- typical ground water levels (for each map unit across all nine Bay Area counties),
- typical sediment properties; and
- liquefaction occurrences during past earthquakes.

A 1:1,000,000–scale version of the regional liquefaction susceptibility map is shown as a map plate on page 5 of ***The REAL Dirt on Liquefaction*** report. More detailed versions of this map appear on ABAG's Earthquake Program website at **http://quake.abag.ca.gov**.

Although the Quaternary geologic and liquefaction susceptibility maps are intended to provide baseline data for use in the preparation of the liquefaction zone maps developed by CDMG's Seismic Hazard Mapping Program, these maps are not intended to replace those zonation maps.

Where Is More Information Available?

The maps are in the form of a digital geographic information (GIS) database that may be accessed at the USGS web site – **http://geopubs.wr.usgs.gov/open-file/of00-444**/.

A 58-page report (Knudsen and others, 2000) containing the full documentation for the development of the file also can be accessed at that site.

References –

1. Helley, E.J., and Lajoie, K.R., 1979. ***Geologic Map of the Flatlands Deposits of the San Francisco Bay Region***: U.S. Geological Survey Professional Paper 944, 88 pp.
2. Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000. ***Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California***: U. S. Geological Survey Open-File Report 00-444. Digital Database (by Wentworth, C.M., Nicholson, R.S., Wright, H.M., and Brown, K.H.) Online Version 1.0.
3. Youd, T.L., and Perkins, J.B., 1987. ***Map Showing Liquefaction Susceptibility of San Mateo County, California***: USGS Miscellaneous Investigation Series Map I-1257-G.

APPENDIX B - THE PROCESS OF DEVELOPING LIQUEFACTION HAZARD MAPS

The Key Issue – Quantifying How Hard the Ground Must Shake to Trigger Liquefaction

A key component of mapping liquefaction hazard is estimating, in map form, the shaking needed to trigger liquefaction. The answer is based, in part, on just how susceptible the material is to liquefaction. Thus, in areas exposed to moderate shaking, a material that is highly susceptible to liquefaction may liquefy, but an adjacent material that is moderately susceptible may not. The tricky part is to quantify this relationship so that it can be used to develop maps estimating liquefaction hazard. The principal difficulty in quantification is that the process is based on making assumptions needed to convert general mapped units with variable properties to discrete units with specific properties.

Early Efforts Using Distance from Earthquake Source

In the 1970s and 1980s, shaking effects were estimated by relating earthquake magnitude to maximum distance from the earthquake source (or fault) for liquefaction effects. One formula, developed by Youd and Perkins (1978), relates distance to surface-wave magnitude as: $\mathbf{M = 5 + 1.15 \log d}$, where $\mathbf{M}$ = earthquake magnitude that will trigger liquefaction and $\mathbf{d}$ = distance from the fault source of the earthquake. In a later effort, Keefer (1984) plotted magnitude versus the maximum distance from the fault rupture zone to various types of earthquake-triggered ground failures (including lateral spreads and flows).

The problem with these early approaches is that, in the Bay Area, most artificial fills that are highly susceptible to liquefaction are on Bay mud, a material that significantly amplifies and lengthens shaking. These early approaches ignore variations in shaking amplification attributable to geologic materials. See Perkins and Boatwright (1995) for more information on the role of geologic materials in shaking amplification.

Efforts Correlating Triggering Shaking with Intensity

Other efforts to estimate levels of ground shaking needed to trigger liquefaction have used shaking intensity, a measure of the effect of an earthquake at a specific location. Most intensity maps use the modified Mercalli intensity scale to define shaking level in terms of damage. See the third column of Figure 1 in the main report for a summary description. See Richter (1958) for a more detailed description and definition of modified Mercalli intensity.

Richter (1958) includes liquefaction-related descriptions in his definitions for higher modified Mercalli intensities:
MMI VII – "small slides and caving in along sand or gravel banks"
MMI VIII – "cracks in wet ground"
MMI IX – "in alluvial areas sand and mud ejected,… sand craters"
MMI X – "sand and mud shifted horizontally on beaches and flat land"

Keefer (1984) notes that the "predominant minimum intensity" for lateral spreads and flows in his analysis was MMI VII.

The problem with using these types of intensity descriptions to estimate shaking levels needed to trigger liquefaction is that the information is not quantitative, and thus of minimal usefulness in modeling hazards in future earthquakes. To solve this problem, some efforts at combining shaking hazard with liquefaction susceptibility to create liquefaction hazard have used estimates of earthquake accelerations.

Use of Arias Intensity to Estimate Shaking Levels Needed to Trigger Liquefaction

Other research has been conducted using Arias intensity[1], an estimate of the energy delivered to structures on the earth's surface (see, for example, Kayen and Mitchell, 1997). From our perspective, using Arias intensity has an inherent advantage – the values (expressed in meters per second) can be directly correlated with various measures of shaking velocity. Because ABAG's shaking intensity maps also are based on average shaking velocity, rather than acceleration, this Arias intensity research allows us to make full use of ABAG's ground shaking maps. [See Perkins and Boatwright, (1995) and Perkins (1998) for information on these shaking hazard maps.]

To use Kayen and Mitchell (1997) work correlating liquefaction with Arias intensity, ABAG's maps of modified Mercalli intensity need to be correlated first with standard 1-component Arias intensity, and then to the 2-component Arias intensity at depth plotted by Kayen and Mitchell. These conversions are supplied in Table B1, below.

TABLE B1: Approximate Relationships Among Intensity Scales[2]

NOTE – These correlations apply to the ABAG maps because of the way the maps were generated. ***They do not work with other MMI maps.*** Therefore, this table should not be used to convert MMI maps generated by others to Arias intensity. ***All of the quantitative measurements of shaking strength used in this table have units of velocity, not acceleration.***

Modified Mercalli Intensity (as shown on ABAG maps)	Undamped Velocity Response Spectra (cm/sec)	Peak Velocity (cm/sec)	1-component Arias Intensity (m/sec)	2-component Arias Intensity (m/sec)	Approximate 2-component Arias Intensity at Depth (m/sec)
XII	(more than shaking)				
XI	(more than shaking)				
X	450	286	48.7	97.4	78
	300	191	21.6	43.2	35
IX	204	130	10.0	20.0	16
	141	90	4.8	9.7	7.8
VIII	96	61	2.2	4.3	3.5
	66	42	1.1	2.2	1.8
VII	45	30	0.5	1.0	0.8
	30	19	0.2	0.4	0.3
VI	21	13	0.1	0.2	0.16
	15	10	0.05	0.1	0.08
V	9	6	0.02	0.04	0.03

---

[1] Arias intensity is an estimate of the energy delivered to structures on the earth's surface. The actual formula is provided in Arias (1970):

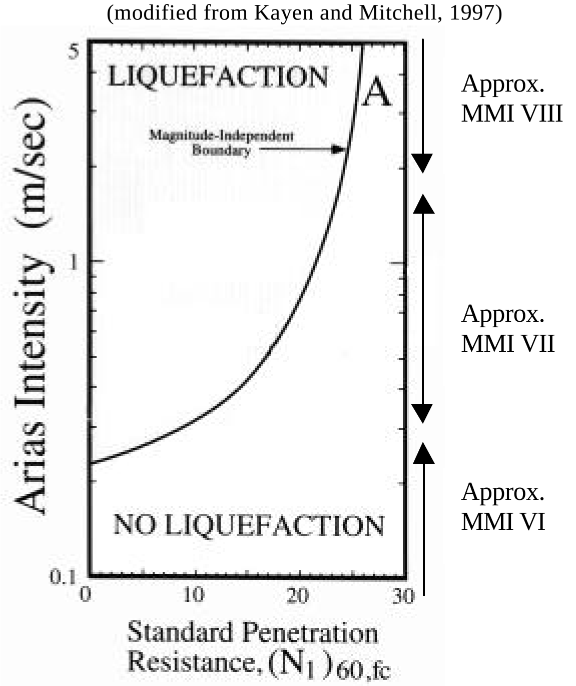
$$I_a = \frac{\pi}{2g}\int_0^{\infty}[a(t)]^2\,dt)$$

where I_a is Arias intensity, g is the acceleration due to gravity, and the remaining term is the integral of the square of acceleration over time.

[2] Kayen and Mitchell relate liquefaction to 2-component Arias intensity at depth – a variable removed for this simplified analysis by assuming most liquefaction will occur at approximately 5 m below the surface. The categories used on ABAG's MMI maps were converted to equivalent 1-component Arias intensity by J. Boatwright (personal comm., 1998). The 1-component Arias intensity values in Table B1 are the average of the two horizontal components, not the maximum of the two. Thus, the 2-component values are simply double the 1-component value. Finally, the Arias intensity at 5 meters is roughly 80% of the surface intensity for earthquakes of approximately moment magnitude = 7 (Kayen, and Mitchell, 1998, Kayen, personal comm., 2001).

FIGURE B1 – ESTIMATED TRIGGERING INTENSITY FOR LIQUEFACTION USING PENETRATION RESISTANCE DATA

(modified from Kayen and Mitchell, 1997)



The second conversion needed to use the Kayen and Mitchell (1997) work is between general liquefaction susceptibility categories mapped by Knudsen and others (2000) and the engineering property of soil materials used by Kayen and Mitchell – standard penetration test normalized blow counts with a fines content correction for "clean sand" or **SPT** $(N_{1,fc})$ **60**. No data are generally available to make estimates of the SPT values for the various susceptibility units. Part of the problem is the wide range of SPT values for each Quaternary geologic map unit. For example, fill over Bay mud can have SPT values ranging from 3 for non-engineered fill to over 35 for engineered fill. The other problem is that SPT data collected for individual development projects typically are not available for use in research. CDMG is beginning to collect SPT and other engineering data as part of their Seismic Hazard Mapping Program (Knudsen, personal comm., 2001).

Use of Pipeline Damage Statistics from the Loma Prieta Earthquake to Estimate Shaking Levels Needed to Trigger Liquefaction

Because of this lack of quantitative SPT information, we examined pipeline damage statistics from the Loma Prieta earthquake. The principal problem with the pipeline data is that there is no information for liquefaction effects in MMI IX and MMI X. In addition, not all of the pipeline leaks are related to liquefaction. However, these data show a clear increase in pipeline leaks per km of exposed pipeline above MMI VII for areas of very high liquefaction susceptibility. The triggering intensity for significant pipeline leaks in areas of high and moderate susceptibility appears to be MMI VIII. Interestingly, the statistics show that areas of high susceptibility in MMI VII and MMI VIII actually experienced fewer leaks/km than areas of moderate susceptibility, indicating the preliminary nature of our liquefaction hazard mapping efforts. See Appendix C for more information.

Estimates of Shaking Levels Needed to Trigger Liquefaction Used to Create Liquefaction Hazard Maps

We made qualitative assignments of the relative liquefaction hazard for various combinations of liquefaction susceptibility and shaking intensity. These assignments were based on a combination of Kayen and Mitchell (1997), Richter (1958), and Keefer (1984), together with the statistical information on pipeline and other damage described in Appendix C. This qualitative assessment is summarized in Figure B2, below.

As shown in Figure B2, we estimated that only some materials mapped as having very high liquefaction susceptibility will liquefy when exposed to strong shaking (modified Mercalli intensity (MMI) VII), while liquefaction of materials mapped as less susceptible will be triggered with very strong shaking (MMI VIII). The imprecise nature of the shaking model and the variability of the Quaternary deposits make liquefaction in areas shaken less than MMI VII, or in areas mapped as having a low to very low liquefaction susceptibility, a statistical possibility, but unlikely. See Technical Appendix C, ABAG's analysis of data on damage from the Loma Prieta earthquake, for additional statistical information.

Figure B2 – Liquefaction Hazard Based on Combinations of Modified Mercalli Intensity and Liquefaction Susceptibility Map Units

MMI Value	Description of Shaking Severity	Summary Damage Description Used on 1995 Maps	Liquefaction Susceptibility Category				
			Very Low	Low	Moderate	High	Very High
I							
II							
III							
IV							
V	Light	Pictures Move					
VI	Moderate	Objects Fall					
VII	Strong	Nonstructural Damage			Moderately Low	Moderately Low	Moderate
VIII	Very Strong	Moderate Damage			Moderate	Moderate	Moderate
IX	Violent	Heavy Damage			**High**	**High**	**High**
X	Very Violent	Extreme Damage			**High**	**High**	**High**

Need for Additional Research

There is a need for additional research on the shaking levels needed to trigger liquefaction for the different categories of Quaternary deposits. Such research will improve on the accuracy and reliability of the regional liquefaction hazard mapping.

The maps are only as accurate as the ground shaking, liquefaction susceptibility, and correlation table used to create them.

References –

1. Arias, A., 1970. "A Measure of Earthquake Intensity," in Hansen, R. J., ed., ***Seismic Design for Nuclear Power Plants***: MIT Press, Cambridge, Mass., p. 438-483.
2. Kayen, R.,E., and Mitchell, J.K., 1997. "Assessment of Liquefaction Potential During Earthquakes by Arias Intensity," in ***Journal of Geotechnical and Geoenvironmental Engineering***, Dec. 1997, pp. 1162-1174.
3. Kayen, R.,E., and Mitchell, J.K., 1998. "Variation of the Intensity of Earthquake Motion Beneath the Ground Surface," in ***Proceedings of the Sixth U.S. National Conference on Earthquake Engineering***, Earthquake Engineering Research Institute.
4. Keefer, D., 1984. "Landslides Caused by Earthquakes" in ***Geological Society of America Bulletin***, V.95, no.4, pp. 406-421.
5. Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000. ***Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California***: U. S. Geological Survey Open-File Report 00-444. Digital Database (by Wentworth, C.M., Nicholson, R.S., Wright, H.M., and Brown, K.H.) Online Version 1.0.
6. Perkins, J.B., 1998. ***On Shaky Ground – Supplement..*** ABAG: Oakland, CA, 28 pp.
7. Perkins, J.B., and Boatwright, J., 1995. ***The San Francisco Bay Area – On Shaky Ground***. ABAG: Oakland, CA, 56 pp.
8. Richter, C.F., 1958. ***Elementary Seismology***. W.H. Freeman and Company, San Francisco, pp. 135-149; 650-653.
9. Youd, T.L., and Perkins, D.M., 1978. "Mapping Liquefaction –Induced Ground Failure Potential" in ***American Society of Civil Engineers***, ***Journal of the Geotechnical Engineering Division:*** v. 104, no. GT4, pp. 433-446.

APPENDIX C - COLLECTION AND ANALYSIS OF LIQUEFACTION DATA FROM THE NORTHRIDGE AND LOMA PRIETA EARTHQUAKES

Loma Prieta Data Shows Damage Patterns

ABAG staff collected data on damage effects of two earthquakes – the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake.

The principal purpose of analyzing the Loma Prieta earthquake damage data was to look at damage patterns. The analysis provided several key findings related to disproportionate damage in areas mapped as having high liquefaction susceptibility, even when normalized to shaking intensity mapping. (See Perkins and Boatwright, 1995, and Perkins, 1998 for more information on ABAG's shaking intensity mapping.)

1. The damage to water pipelines in areas mapped as having high liquefaction susceptibility was 4-to-5 times greater than outside of these areas, given equivalent shaking intensities (velocities), and 3 times greater given equivalent shaking strains. These increases include large amounts of pipeline damage in areas with no surface expressions of liquefaction. Similarly, damage to natural gas pipelines was 3-to-11 times greater than outside of these areas given equivalent shaking intensities (ground velocities), and 3-to-9 times greater than outside of these areas, given equivalent shaking strains. (Predominantly older gas pipelines were damaged.)
2. The percentage of state and federal highway road surfaces repaired for MMI VIII was 1.3 times greater for areas mapped as very high liquefaction susceptibility than for outside those areas. In addition, the cost of repairing those areas was 25 times higher.
3. More surprisingly, the correlation between regional liquefaction susceptibility mapping and damage was highly mixed for the building types we examined. The fraction of pre-1940 single-family homes red-tagged in areas of high and very high liquefaction on the liquefaction susceptibility maps was about equivalent to two times less than outside of these areas, given equivalent shaking intensities. This apparent anomaly is consistent with damage patterns of four-story apartment buildings in the Marina District of San Francisco analyzed by Harris and Egan (1992): "The ground failure in the central part of the filled area appears to have mitigated much of the potential damage by dissipating seismic energy through liquefaction." The potential for dissipation of seismic energy through liquefaction also is consistent with the recording of the Loma Prieta main shock obtained at Treasure Island. Hanks and Brady (1991) note that the onset of liquefaction apparently significantly damped the ground shaking. Recordings of aftershocks do not show this damping effect, potentially due, in part, to shaking being insufficient to trigger liquefaction.
4. Last, we examined the correlation with hazmat incidents. There was a strong correlation between hazmat incidents / urban acre (excluding residential and urban open space) and shaking intensity. However, only a weak correlation existed with mapped liquefaction susceptibility, even

when looking at areas exposed to the same shaking intensities.

Data Collected

The following table summarizes the types of data ABAG collected, as well as any problems associated with these data.

TABLE C1: Damage Data Used to Analyze Liquefaction Effects in Past Earthquakes

Data Type	Data Obtained	Usable Data for Analysis
Loma Prieta Earthquake		
Water pipeline repairs	Data obtained for 508 leaks from water districts	Data finalized for 507 (1 has no location)
Gas pipeline repairs	Data on loan for 687 leaks from Pacific Gas and Electric (PG&E)	Data finalized for 487 (200 leaks not used, including 104 in Santa Cruz Co., 75 not earthquake related, and 21 with no location)
Sewer pipeline repairs	No leak data ever collected by cities or sewer districts	***No data available so no analysis***
San Francisco ***ground failure*** data and Bay Area data on residential ***building damage***	Ground failure data incomplete and only available for one city; statistical analysis only possible using residential tag data	Residential tagging of 301 single-family homes used for statistical analysis to isolate shaking vs. liquefaction
Caltrans and local government data on ***road surface repairs***	Data obtained from Caltrans on 39 repairs; local government data not generally available	Data finalized for 25 repairs (14 additional repairs in Santa Cruz Co. not analyzed)
ABAG data on hazmat incidents	Data obtained from ABAG on 190 incidents	Data finalized for 121 (69 total not analyzed, including 58 outside Bay Area and 11 with no location)
Northridge Earthquake		
Water pipeline repairs	Data obtained from D. Ponti on LA Dept. of Water & Power and Municipal Water District repairs	***ANALYSIS NOT BEING CONDUCTED AT THIS TIME***
Gas pipeline repairs	Data obtained from SoCal Gas	***ANALYSIS NOT BEING CONDUCTED AT THIS TIME***
Sewer pipeline repairs	Data obtained from D. Ponti on City of LA repairs	***ANALYSIS NOT BEING CONDUCTED AT THIS TIME***
City of LA ***ground failure*** data and southern California data on residential ***building damage***	Ground failure data not part of LA database; statistical analysis only possible using residential tag data	***ANALYSIS NOT BEING CONDUCTED AT THIS TIME***
Caltrans and local government data on ***road surface repairs***	LA repaired 510 streets; data also obtained from Caltrans	***ANALYSIS NOT BEING CONDUCTED AT THIS TIME***

Data Caveats

Note that the number of water and natural gas pipeline leaks resulting from the Loma Prieta earthquake listed in Table B1 is less than previously reported by other researchers. The principal reason for this apparent discrepancy is that the various utilities have since determined that many of these leaks were not earthquake related.

Use of Pipeline Damage Data to

Liquefaction ***susceptibility*** maps show areas with water-saturated sandy and silty materials. Liquefaction ***hazard*** maps show areas where the ground is

Confirm Hazard Mapping Categories

susceptible to liquefaction ***and*** that are likely to be shaken hard enough in a particular earthquake to trigger liquefaction. Technical Appendix B provides background information on the process of developing ABAG's liquefaction hazard maps. Note that, due to the lack of standard penetration test (SPT) data to use to assign liquefaction hazard levels to various combinations of liquefaction susceptibility and MMI, ABAG supplemented data from other sources with the combined natural gas and water pipeline leak data shown in Table C2, below.

TABLE C2 – PIPELINE LEAKS PER KILOMETER OF PIPELINE EXPOSED TO VARIOUS COMBINATIONS OF MODIFIED MERCALLI INTENSITY AND LIQUEFACTION SUSCEPTIBILITY IN THE LOMA PRIETA EARTHQUAKE

MMI Value	Description of Shaking Severity	Summary Damage Description Used on Perkins and Boatwright, 1995 Shaking Maps	Liquefaction Susceptibility Category				
			Very Low	Low	Moderate	High	Very High
V	Light	Pictures Move	0.001	0.002	0.002	0.000	0.004
VI	Moderate	Objects Fall	0.011	0.007	0.010	0.002	0.005
VII	Strong	Nonstructural Damage	0.032	0.011	0.036	0.008	0.086
VIII	Very Strong	Moderate Damage	0.028	0.063	0.182	0.019	0.278
IX	Violent	Heavy Damage	**No Data**	**No Data**	**No Data**	**No Data**	**No Data**
X	Very Violent	Extreme Damage	**No Data**	**No Data**	**No Data**	**No Data**	**No Data**

These data, together with the compelling information described in Appendix B for a relative lack of damage in MMI VI or lower and for an extensive amount of liquefaction hazard in MMI IX and X, form the basis for the liquefaction hazard assignments shown in Figure C1, below. This figure was used to create ABAG's liquefaction hazard maps, as explained in Appendix B.

FIGURE C1 – LIQUEFACTION HAZARD BASED ON COMBINATIONS OF MODIFIED MERCALLI INTENSITY AND LIQUEFACTION SUSCEPTIBILITY

MMI Value	Description of Shaking Severity	Summary Damage Description Used on Perkins and Boatwright, 1995 Shaking Maps	Liquefaction Susceptibility Category				
			Very Low	Low	Moderate	High	Very High
V	Light	Pictures Move					
VI	Moderate	Objects Fall					
VII	Strong	Nonstructural Damage			Moderately Low	Moderately Low	Moderate
VIII	Very Strong	Moderate Damage			Moderate	Moderate	Moderate
IX	Violent	Heavy Damage			**High**	**High**	**High**
X	Very Violent	Extreme Damage			**High**	**High**	**High**

There is a data discrepancy with the 2000 WLA/USGS mapping, for, using the data from the Loma Prieta earthquake, those areas mapped as having "moderate" liquefaction susceptibility had more pipeline problems than those mapped as having "high" liquefaction susceptibility. The reason or reasons for these inconsistencies are not fully understood at the present time. Possible partial explanations include:

- some categories of Quaternary materials assigned to "high" liquefaction susceptibility (including Bay mud) may have fewer ground failure problems than anticipated;

- the ABAG ground shaking methodology may be inaccurate;
- the Loma Prieta earthquake is only one event; future earthquakes may not experience the same problems.

Because of these unresolved issues, the categories of "moderate" and "high" liquefaction susceptibility have been assigned the same liquefaction hazard category in Figure C1.

Loma Prieta Damage Data Analysis and Accuracy of the 2000 WLA/USGS Mapping

A secondary purpose for analyzing the Loma Prieta earthquake damage data was to confirm that the 2000 WLA/USGS liquefaction susceptibility mapping (Knudsen and others, 2000) was as effective or better predictor of damage than the 1980 ABAG mapping (Perkins, 1980, and Youd and Perkins, 1987). The data showed that the areas mapped as "very high" liquefaction susceptibility on the 2000 WLA/USGS mapping were slightly more likely to have pipeline damage than the areas mapped as "high" and "very high" liquefaction susceptibility on the 1980 ABAG mapping.

More Can Be Learned

We hope to continue with this analysis effort by further examining the Loma Prieta data, as well as by examining the Northridge damage data. More can be learned.

First, the complex relationship between shaking intensity (ground velocity) and ground deformation (including ground failure) needs to be better understood, particularly in areas mapped as having moderate to very high liquefaction susceptibility. Our understanding of this relationship needs to be specifically improved in areas underlain by Bay mud. The areas mapped as high liquefaction susceptibility are also in particular need of additional analysis.

Second, we need to learn more about the actual causes of damage in earthquakes, although this determination can be extremely difficult to obtain. For example, although some damage to pipelines, buildings and other structures occurring in areas mapped as having high liquefaction susceptibility may be due to liquefaction, it can also be related to other factors in these mapped areas, including other earthquake-caused ground deformation.

We are convinced that this process of examining actual damage data has been, and will continue to be, valuable in generating useful information on liquefaction hazards. In particular, past damage data are useful in communicating the meaning and significance of the 2000 WLA/USGS liquefaction susceptibility mapping to the public and to non-engineering professionals. These data should also be useful in explaining the seismic hazard maps showing Zones of Required Investigation being published by the California Division of Mines and Geology.

ANALYSIS OF WATER PIPELINE LEAK DATA FROM THE LOMA PRIETA EARTHQUAKE

Data Collection Procedure

Data on 508 leaks in water pipelines were collected in a time-consuming process. A combination of phone calls, mailed questionnaires, and letters were used to obtain a 100% response rate from the hundreds of water supply agencies serving the nine Bay Area counties. However, data on one leak could not be included in the subsequent analysis due to insufficient information on precisely where the leak occurred. The following tables examine the remaining 507 leaks identified by water supply agencies following the Loma Prieta earthquake.

Analysis Procedure

Pipeline leaks were compared to kilometers of pipeline in general, and to kilometers of pipeline exposed to various mapped hazard levels, such as shaking intensities (ground velocities), shaking strain (proportional to ground velocities)[1], and liquefaction susceptibility. The kilometers of pipeline exposed to these mapped hazards in the Loma Prieta earthquake were estimated assuming that the exposure is roughly equivalent to the kilometers of local streets. ***The combined analysis of mapped shaking levels and liquefaction susceptibility was necessary to fully explore the underlying causes of damage to pipelines.***

Results

The initial analysis focused on examining shaking intensity and liquefaction susceptibility separately. This type of analysis has been typical with past researchers. The frequency of leaks (expressed as leaks / km of exposed pipe) is more clearly correlated with shaking level than with either liquefaction susceptibility map. This leak frequency is consistent with the ranges proposed by Eguchi (1991) in NSF-supported research at Dames and Moore. Eguchi's analysis examines shaking intensity alone and does not attempt to determine the potential role of ground materials mapped as having various levels of liquefaction susceptibility.

The highest frequency of leaks occurred in areas mapped as having very high liquefaction susceptibility on the WLA/USGS map, or high to very high on the ABAG map. The correlation with the new WLA/USGS mapping is only slightly stronger than with the older ABAG mapping, with approximately 36% of the water pipeline leaks occurring in those areas shown as very high on the WLA/USGS map and only 34% in the areas of high to very high on the ABAG map. There is no correlation with lower levels of liquefaction susceptibility given the shaking intensities experienced in the Loma Prieta earthquake. ***However, as stated earlier, only a combined analysis of mapped shaking intensity and liquefaction susceptibility can fully explore the underlying causes of damage to pipelines.***

In order to examine the joint effects of liquefaction susceptibility and shaking level (that is, liquefaction hazard), we examined the correlation of frequency of leaks to shaking level ***separately*** for those leaks in areas mapped as having very high liquefaction susceptibility (as shown on the WLA/USGS mapping) and those leaks outside of those areas. The correlation between frequency of leaks and shaking level remains strong for both subsets of leaks. The frequency of leaks for higher shaking intensities is far greater for areas mapped as having very high liquefaction susceptibility than for areas mapped as having lower liquefaction susceptibility:

[1] Maximum ground strain (tension and compression) in the direction of wave propagation = maximum horizontal ground velocity divided by the apparent horizontal propagation velocity (Newmark, 1967).

- 5.2 times higher for MMI VIII; and
- 3.9 times higher for MMI VII.

However, there is no significant difference in pipeline leak statistics as a function of liquefaction susceptibility in lower intensity areas (MMI VI and lower).

To confirm that the 2000 WLA/USGS mapping remained a more consistent predictor of pipeline leaks than the 1980 ABAG mapping, we performed the same analysis of the joint effects of liquefaction susceptibility and shaking level, using the high susceptibility areas as a cut-off for liquefaction susceptibility analysis. The correlation between frequency of leaks and shaking level remains strong for both subsets of leaks, although it is much stronger within those areas mapped as having high liquefaction susceptibility. Again, the frequency of leaks for higher shaking intensities is greater in areas mapped as having high liquefaction susceptibility than outside of those areas:

- 9.5 times higher for MMI VIII; and
- 2.0 times higher for MMI VII.

The 0.408 leaks / km pipe in areas mapped as having both a high liquefaction susceptibility (from 1980 ABAG mapping) and MMI VIII is slightly less than the 0.424 leaks / km pipe in areas mapped as having both a very high liquefaction susceptibility (from the 2000 WLA/USGS mapping) and MMI VIII. Thus, the WLA/USGS mapping is a slightly better indicator of water pipeline leaks.

Some researchers have suspected that ground strain[1], or the deflection of the ground due to the passing earthquake waves, is a better predictor of pipeline leak rates than ground shaking (ground velocity) (see, for example, O'Rourke, 1996). We modified the model for mapping shaking intensity (which depicts peak ground velocity) to obtain a model for mapping ground strain by doubling the correction for geology (that is, accounting for the variations among Bay mud, valley alluvium and rock by doubling the intensity increments). This modification presumes that the geology correction is proportional to the inverse of the shear wave velocity (personal communication, J. Boatwright, Feb. 1998). We then performed an analysis similar to that for shaking intensity.

In order to examine the joint effects of liquefaction susceptibility and ***strain*** level, we examined the correlation of frequency of leaks to ***strain*** level ***separately*** for those leaks in areas mapped as having very high liquefaction susceptibility (as shown on the WLA/USGS maps) and those leaks outside of those areas. The correlation between leaks / km and strain level remains very strong for both subsets of leaks. The leaks / km for each ***strain*** level is far greater for areas mapped as having very high liquefaction than for outside those areas:

- 3.1 times for very high strain levels,
- 3.3 times for high strain levels, and
- 3.2 times for moderately high strain levels.

These numbers for ***strain*** level are similar in magnitude to those determined for ***shaking*** intensity level (3.3 - 3.1 times higher versus 3.9 - 5.2 times higher for

[2] This percentage was calculated by applying the frequency of pipeline leaks in MMI VII and VIII in the areas ***excluding*** very high liquefaction susceptibility to the km of pipeline exposed to very high liquefaction susceptibility. These baseline leaks (20.0 + 19.7) were then subtracted from the actual number of leaks in those areas (77 + 102) to obtain the apparent increase in the number of leaks (57.0 + 82.3). A percentage was then calculated based on this total (139.4) divided by the total number of leaks that were analyzed (507).

shaking velocity/MMI). This conclusion is not surprising since ground strains are directly proportional to shaking velocity (mapped using MMI on ABAG's shaking maps). Note that these ground strains are relatively small, even in the higher strain hazard categories (about 1 cm/30 meters of pipeline or 3×10^{-4}) such as in the San Francisco Marina District. Thus, neither shaking intensity (ground velocity) nor ground strain alone are responsible for all of the pipeline leak damage observed.

These analyses point out that a minimum of 27% of the leaks caused by the Loma Prieta earthquake are limited to the areas mapped as having very high liquefaction susceptibility.[2] These observations also lead to two conclusions:

1. Significant pipeline failures initiate at some threshold of ground shaking, roughly defined as high MMI VI or the boundary between MMI VI and VII.
2. At roughly the same levels of shaking, and above the shaking threshold identified in (1) above, the presence of soils that have moderate or higher liquefaction susceptibility greatly increases the extent of pipeline damage.

See Appendix B for additional discussion of these relationships.

These conclusions are remarkable given the relative lack of observed surface features associated with liquefaction in the locations of these pipeline leaks. We suggest that there are at least three mechanisms for causing pipeline damage in liquefaction-susceptible soils.

1. Sufficient levels of shaking can cause limited liquefaction within the susceptible deposits. It is usually observed that when liquefaction occurs in a susceptible deposit, not all of the deposit liquefies. After liquefaction, the affected portions of the deposit may respond by decoupling from the adjacent layers, allowing the soil on top to oscillate back and forth and up and down in a different way than the surrounding ground. This type of failure may become a lateral spread if there is room for ground displacement, or displacing inertially due to continued ground shaking after the liquefaction has occurred to create a weak horizontal shear plane. The occurrence of liquefaction is not always apparent to the field observer, and it is possible for liquefaction to occur and to be accompanied by minor amounts of ground failure that can damage vulnerable pipelines without surface evidence of the ground failure.
2. Sufficient levels of shaking can also cause shear failure in soft clay beds or other relatively weak zones within or adjacent to the liquefaction-susceptible deposits, without liquefaction occurring. This kind of ground failure can produce minor-to-significant amounts of dynamic deformation (as the soil deposit slides back and forth on the weak zone) and occasionally permanent ground displacement. Similar effects of high shaking levels may also occur in young geologic deposits with low liquefaction susceptibility. The ground deformation may not leave visible evidence at the ground surface, but can damage vulnerable buried pipelines.
3. The propagation of seismic waves through a liquefaction-susceptible zone will produce elastic ground strains. Even for soft soil deposits, the ground strains associated with propagation of shear waves are quite small, and are not likely to be a typical cause of buried pipeline damage. In some unusual cases, however, large amplitude surface waves may be generated that can damage pipelines.

Water Pipeline Leaks - Loma Prieta Earthquake

COMPARISON OF LEAK DATA VERSUS THREE MAPS

507 Records		# Leaks	Rough %	Km Pipe Exposed	Leaks / Km Pipe	
2000	Very High - 5	182	35.9	1821	0.100	
WLA/USGS	High - 4	20	3.9	4022	0.005	
Liquefaction	Moderate - 3	159	31.4	9717	0.016	
Susceptibility	Low - 2	51	10.1	5839	0.009	
Map	Very Low - 1	95	18.7	15455	0.006	
	Sum	507	100.0	36854		
1980	High >14	172	33.9	1743	0.099	
ABAG	Moderate - 14	94	18.5	9563	0.010	
Liquefaction	Moderate - 13	71	14.0	2363	0.030	
Susceptibility	Low - 12	86	17.0	8697	0.010	
Map	Very Low - 11	84	16.6	14488	0.006	
	Sum	507	100.0	36854		
						Eguchi #s
1995	MMI X - 6	0	0.0	67	0.000	1.2
ABAG	MMI IX - 5	0	0.0	50	0.000	0.4
Shaking	MMI VIII - 4	135	26.6	645	0.209	0.3
Intensity	MMI VII - 3	282	55.6	9341	0.030	0.03
Map	MMI VI - 2	73	14.4	11050	0.007	0.003
	MMI V - 1	17	3.4	15701	0.001	0
	Sum	507	100.0	36854		

Water Pipeline Leaks - Loma Prieta Earthquake

WLA/USGS LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING INTENSITY

Km of Pipe Exposed

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	263	488	829	241	0	0	1821
High - 4	1292	1224	1371	134	0	0	4022
Moderate - 3	2654	3182	3834	47	0	0	9717
Low - 2	2086	1981	1725	48	0	0	5839
Very Low - 1	9405	4175	1582	175	50	67	15455
TOTAL	15701	11050	9341	645	50	67	36854

Pipe Leaks

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	0	3	77	102	0	0	182
High - 4	0	5	10	5	0	0	20
Moderate - 3	1	33	109	16	0	0	159
Low - 2	2	9	34	6	0	0	51
Very Low - 1	14	23	52	6	0	0	95
TOTAL	17	73	282	135	0	0	507

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X
Very High - 5	0.000	0.006	0.093	0.424	n/a	n/a
High - 4	0.000	0.004	0.007	0.037	n/a	n/a
Moderate - 3	0.000	0.010	0.028	0.343	n/a	n/a
Low - 2	0.001	0.005	0.020	0.126	n/a	n/a
Very Low - 1	0.001	0.006	0.033	0.034	0.000	0.000

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X
Very High - 5	0.000	0.006	0.093	0.424	n/a	n/a
Not Very High	0.001	0.007	0.024	0.082	n/a	n/a

Water Pipeline Leaks - Loma Prieta Earthquake

ABAG 1980 LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING INTENSITY

Km of Pipe Exposed

Liquefaction	Shaking Intensity						
Susceptibility	V	VI	VII	VIII	IX	X	TOTAL
High >14	217	284	948	294	0	0	1743
Moderate - 14	2665	3386	3476	35	0	0	9563
Moderate - 13	244	493	1514	112	0	0	2363
Low - 12	3476	3137	2056	28	0	0	8697
Very Low - 11	9099	3750	1346	176	50	67	14488
TOTAL	15701	11050	9341	645	50	67	36854

Pipe Leaks

Liquefaction	Shaking Intensity						
Susceptibility	V	VI	VII	VIII	IX	X	TOTAL
High >14	0	1	51	120	0	0	172
Moderate - 14	0	17	75	2	0	0	94
Moderate - 13	0	3	65	3	0	0	71
Low - 12	5	30	45	6	0	0	86
Very Low - 11	12	22	46	4	0	0	84
TOTAL	17	73	282	135	0	0	507

Leaks/Km Exposed Pipe

Liquefaction	Shaking Intensity					
Susceptibility	V	VI	VII	VIII	IX	X
High >14	0.000	0.004	0.054	0.408	n/a	n/a
Moderate - 14	0.000	0.005	0.022	0.057	n/a	n/a
Moderate - 13	0.000	0.006	0.043	0.027	n/a	n/a
Low - 12	0.001	0.010	0.022	0.215	n/a	n/a
Very Low - 11	0.001	0.006	0.034	0.023	0.000	0.000

Leaks/Km Exposed Pipe

Liquefaction	Shaking Intensity					
Susceptibility	V	VI	VII	VIII	IX	X
High >14	0.000	0.004	0.054	0.408	n/a	n/a
Not High	0.001	0.007	0.028	0.043	n/a	n/a

Water Pipeline Leaks - Loma Prieta Earthquake

WLA/USGS LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING STRAIN

Km of Pipe Exposed

Liquefaction Susceptibility	Shaking Strain Low	Mod. Low	Moderate	Mod. High	High	Very High	TOTAL
Very High - 5	46	176	351	525	453	271	1822
High - 4	216	679	1086	954	1053	34	4022
Moderate - 3	657	1594	2986	3074	1391	15	9717
Low - 2	712	1061	2322	1588	149	7	5839
Very Low - 1	6921	3871	2643	1515	409	94	15453
TOTAL	8552	7381	9388	7656	3454	422	36854

Pipe Leaks

Liquefaction Susceptibility	Shaking Strain Low	Mod. Low	Moderate	Mod. High	High	Very High	TOTAL
Very High - 5	0	0	1	25	54	102	182
High - 4	0	0	2	7	11	0	20
Moderate - 3	0	2	27	33	83	14	159
Low - 2	0	2	11	32	6	0	51
Very Low - 1	12	12	24	33	10	4	95
TOTAL	12	16	65	130	164	120	507

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Strain Low	Mod. Low	Moderate	Mod. High	High	Very High
Very High - 5	0.000	0.000	0.003	0.048	0.119	0.376
High - 4	0.000	0.000	0.002	0.007	0.010	0.000
Moderate - 3	0.000	0.001	0.009	0.011	0.060	0.955
Low - 2	0.000	0.002	0.005	0.020	0.040	0.000
Very Low - 1	0.002	0.003	0.009	0.022	0.024	0.042

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Strain Low	Mod. Low	Moderate	Mod. High	High	Very High
Very High - 5	0.000	0.000	0.003	0.048	0.119	0.376
Not Very High	0.001	0.002	0.007	0.015	0.037	0.120

ANALYSIS OF NATURAL GAS PIPELINE LEAK DATA FROM THE LOMA PRIETA EARTHQUAKE

Data Collection Procedure

ABAG collected data on 687 leaks and analyzed data on 487 leaks in natural gas pipelines identified by Pacific Gas and Electric Company in the two weeks following the Loma Prieta earthquake. Information was obtained on the location of each leak, the type of pipe that leaked, and the type of leak.

Special Data Limitations

Although any data on damage collected following an earthquake are inherently problematic due to the emergency situation, it is important to understand several additional caveats related to these data included in a report prepared by PG&E describing the leaks (Phillips and Virostek, 1990):

- The number of the recorded leaks specifically attributable to the earthquake is unknown.
- Not all leaks found were necessarily reported because of the nature of the emergency.
- Leaks may continue to develop or existing leaks may continue to be discovered due to post-earthquake settling of the soil.
- The earthquake found weak points in the system. Some of the leaks found may have been inevitable; the earthquake just accelerated the process.
- The leak causes were not always clear and the documentation of the causes was not always consistent. For instance, a potential corrosion leak accelerated by the earthquake may have been given a leak cause code of "corrosion" or "damage by outside forces" or "other."
- Leak surveys were not performed on the San Francisco Marina District and Watsonville low-pressure systems that were shut-in and replaced."

The Phillips and Virostek report notes that a total of ***1,094*** leaks were found and recorded during the first two weeks following the Loma Prieta earthquake (from October 17 to October 31, 1989) (Phillips and Virostek, 1990). Their breakdown of leak location is:

- 207 - East Bay Region (approximately Alameda and Contra Costa Counties)
- 562 - Golden Gate Region (approximately San Francisco and San Mateo Counties)
- 325 - Mission Trail Region (approximately Monterey, San Benito, Santa Cruz, and Santa Clara Counties)

Note that the file ABAG obtained from PG&E for this analysis is significantly smaller than the one described by Phillips and Virostek (687 leaks versus 1094 leaks). The principal reason for this apparent discrepancy is PG&E has since determined that many of these leaks were not earthquake related. In addition, in the course of working with PG&E in further identifying the location and cause of these leaks, 75 additional leaks were deleted from the 687 leaks because they are not earthquake related. For example, some leaks were caused by "a dig in," that is, the pipe being broken by a back hoe in the course of routine construction during this two week observation period. Some leaks that remain in this file may have been present prior to the earthquake, but were discovered after the earthquake in the course of the sophisticated leak detection program initiated following that earthquake.

Finally, these leak frequency data are not suitable for predicting the number and locations of pipeline leaks in future earthquakes. Beginning in 1985, PG&E undertook a 25-year, $2.5 billion program, known as the Gas Pipeline Replacement Program (GPRP). This program has specifically focused on types of pipes (such as cast iron and older welded steel) that are more prone to leaking due to their condition or location, and that are much more susceptible to earthquake damage compared to modern steel and polyethylene pipe. As a result of the GPRP, many pipeline upgrades have been installed both prior to and following the Loma Prieta earthquake. These upgrades are continuing. The newer pipelines are significantly less vulnerable to earthquake effects, including liquefaction, differential settlement, violent shaking, and ground strain.

In spite of these limitations, ABAG has examined these leak data closely to see if the distribution of the leaks could help define the role of liquefaction versus ground shaking in pipeline leaks. To make it consistent with the shaking information and water pipeline data, 104 leaks in Santa Cruz County were not examined. Finally, 21 leaks with insufficient locational information have been excluded from the analysis.

Analysis Procedure

As with the water pipeline data, natural gas pipeline leaks were compared to kilometers of pipeline in general, and to kilometers of pipeline exposed to various mapped hazard levels, such as shaking intensities (ground velocities), shaking strain (proportional to ground velocities)[3], and liquefaction susceptibility. The kilometers of pipeline exposed to these mapped hazards in the Loma Prieta earthquake were estimated assuming that the exposure is roughly equivalent to the kilometers of local streets. ***As with the water pipeline leak analysis, the combined analysis of mapped shaking levels and liquefaction susceptibility was necessary to fully explore the underlying causes of damage to pipelines.***

Results

The initial analysis focused on examining shaking intensity and liquefaction susceptibility separately. The frequency of leaks (expressed as leaks / km of exposed pipe) is better correlated with shaking level than either liquefaction map. This leak frequency is most consistent with the values proposed by Eguchi (1991) in NSF-supported research at Dames and Moore for shaking levels equal to MMI VII. The leak rates are lower than Eguchi's for MMI VIII and higher for MMI VI. Eguchi's analysis examines shaking intensity alone and does not attempt to determine the potential role of ground materials mapped as having various levels of liquefaction susceptibility.

The highest frequency of leaks occurred in areas mapped as having very high liquefaction susceptibility on the 2000 WLA/USGS map, or high to very high on the 1980 ABAG map. The correlation with the newer WLA/USGS mapping is not as strong as with the older ABAG mapping, with 43% of the gas pipeline leaks occurring in those areas shown as high or very high on the ABAG map versus 21% in areas shown as very high on the WLA/USGS map. However, there is no correlation with lower levels of liquefaction susceptibility shown on either map given the shaking intensities experienced in the Loma Prieta

[3] Maximum ground strain (tension and compression) in the direction of wave propagation = maximum horizontal ground velocity divided by the apparent horizontal propagation velocity (Newmark, 1967).

earthquake. ***However, as stated earlier, only a combined analysis of mapped shaking intensity and liquefaction susceptibility can fully explore the underlying causes of damage to pipelines.***

In order to examine the joint effects of liquefaction susceptibility and shaking level (that is, liquefaction hazard), we examined the correlation of frequency of leaks to shaking level ***separately*** for those leaks in areas mapped as having very high liquefaction susceptibility (as shown on the WLA/USGS mapping) and those leaks outside of those areas. The correlation between frequency of leaks and shaking level is relatively high for areas mapped as having very high susceptibility, but not as strong for areas outside those areas. The frequency of leaks for higher shaking intensities is far greater for areas mapped as very high liquefaction susceptibility than for areas mapped as having lower liquefaction susceptibility:

- 10.7 times higher for MMI VIII; and
- 2.9 times higher for MMI VII.

To confirm that the 2000 WLA/USGS mapping remained a more consistent predictor of natural gas pipeline leaks in the Loma Prieta earthquake than the 1980 ABAG mapping, we performed the same analysis of the joint effects of liquefaction susceptibility and shaking level, using the high susceptibility areas as a cut-off for liquefaction susceptibility analysis. The correlation between frequency of leaks and shaking level is relatively high for areas mapped as having high liquefaction susceptibility, but not strong for outside those areas. Again, the frequency of leaks for higher shaking intensities is far greater for areas mapped as having very high liquefaction susceptibility than for outside those areas:

- 9.8 times higher for MMI VIII; and
- 12.5 times higher for MMI VII.

The 0.112 leaks / km pipe in areas mapped as having both a high liquefaction susceptibility (from 1980 ABAG mapping) and MMI VIII is less than the 0.133 leaks / km pipe in areas mapped as having both a very high liquefaction susceptibility (from the 2000 WLA/USGS mapping) and MMI VIII. Thus, the WLA/USGS mapping is again a slightly better indicator of pipeline leaks.

There is an apparent anomaly of high pipeline leak rates in areas mapped as having MMI VII and moderate liquefaction susceptibility. The principal reason for the anomaly is the high level of failures in areas mapped as MMI VII and moderate liquefaction susceptibility in San Francisco (150 of the 169 leaks in this subset of data). ***This apparent anomalous failure rate can be explained by either a problem with the intensity modeling or high leak rates in older pipelines that are being replaced in San Francisco. Thus, it is not likely a problem with the liquefaction susceptibility mapping.*** Of the 150 leaks in this subset of data in San Francisco, 14 were in old cast iron pipe, 90 were in steel pipe installed prior to 1931, and an additional 25 were in steel pipe installed between 1931 and 1960.

Some researchers have suspected that ground strain, or the deflection of the ground due to the passing earthquake waves, is a better predictor of pipeline leak rates than ground shaking (ground velocity) (see, for example, O'Rourke, 1996). We used the same ground strain maps developed to analyze water pipeline leaks and described in the previous section. (See page 5 for a definition of ground strain.) We then performed an analysis similar to that for shaking intensity.

In order to examine the joint effects of liquefaction susceptibility and ***strain*** level, we examined the correlation of frequency of leaks to ***strain*** level ***separately*** for those leaks in areas mapped as having very high liquefaction susceptibility (as shown on the WLA/USGS mapping) and those leaks outside those areas. The correlation between frequency of leaks and strain level remains very strong for both subsets of leaks. The frequency of leaks for each ***strain*** level is greater for areas mapped as having very high liquefaction susceptibility than for outside those areas:

- 8.9 times for very high strain levels,
- 3.2 times for high strain levels, and
- 2.6 times for moderately high strain levels.

These numbers for ***strain*** level are similar in magnitude to those determined for ***shaking*** intensity level (2.6 - 8.9 times higher versus 2.9 - 10.7 times higher for shaking velocity/MMI).

These analyses point out that a minimum of 15% of the leaks caused by the Loma Prieta earthquake are associated with by some type of problem limited to the areas mapped as having very high liquefaction susceptibility. This calculation is based on the apparent incremental increase in leak frequency in areas of very high liquefaction susceptibility exposed to MMI VIII and VII using the same technique described in the discussion of water pipeline leak data.

These conclusions are remarkable given the relative lack of observed surface features associated with liquefaction in the locations of these pipeline leaks. We speculate that there are at least three mechanisms for causing pipeline damage in liquefaction-susceptible soils. See the discussion at the end of the water pipeline section (page 7) for more information on these mechanisms.

However, the correlations in leak rates for natural gas pipelines with liquefaction susceptibility, shaking intensity (velocity), and ground strain are not nearly as strong as with water pipelines. The most likely explanation for this discrepancy is the relative importance of other factors, particularly pipeline age, material of construction, and type of pipe joint.

Gas Pipeline Leaks - Loma Prieta Earthquake

COMPARISON OF PG&E LEAK DATA VERSUS THREE MAPS

487 Records		# Leaks	Rough %	Km Pipe Exposed	Leaks / Km Pipe	
2000	Very High - 5	102	20.9	1821	0.056	
WLA/USGS	High - 4	15	3.1	4022	0.004	
Liquefaction	Moderate - 3	206	42.3	9717	0.021	
Susceptibility	Low - 2	29	6.0	5839	0.005	
Map	Very Low - 1	135	27.7	15455	0.009	
	Sum	487	100.0	36854		
1980	High >14	210	43.1	1743	0.120	
ABAG	Moderate - 14	61	12.5	9563	0.006	
Liquefaction	Moderate - 13	90	18.5	2363	0.038	
Susceptibility	Low - 12	57	11.7	8697	0.007	
Map	Very Low - 11	69	14.2	14488	0.005	
	Sum	487	100.0	36854		
						Eguchi #s
1995	MMI X - 6	0	0.0	67	0.000	1.2
ABAG	MMI IX - 5	0	0.0	50	0.000	0.4
Shaking	MMI VIII - 4	37	7.6	645	0.057	0.3
Intensity	MMI VII - 3	302	62.0	9341	0.032	0.03
Map	MMI VI - 2	122	25.1	11050	0.011	0.003
	MMI V - 1	26	5.3	15701	0.002	0
	Sum	487	100.0	36854		

Gas Pipeline Leaks - Loma Prieta Earthquake

WLA/USGS LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING INTENSITY

Km of Pipe Exposed

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	263	488	829	241	0	0	1821
High - 4	1292	1224	1371	134	0	0	4022
Moderate - 3	2654	3182	3834	47	0	0	9717
Low - 2	2086	1981	1725	48	0	0	5839
Very Low - 1	9405	4175	1582	175	50	67	15455
TOTAL	15701	11050	9341	645	50	67	36854

Pipe Leaks

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	2	2	66	32	0	0	102
High - 4	1	1	13	0	0	0	15
Moderate - 3	8	28	169	1	0	0	206
Low - 2	6	19	4	0	0	0	29
Very Low - 1	9	72	50	4	0	0	135
TOTAL	26	122	302	37	0	0	487

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X
Very High - 5	0.008	0.004	0.080	0.133	n/a	n/a
High - 4	0.001	0.001	0.009	0.000	n/a	n/a
Moderate - 3	0.003	0.009	0.044	0.021	n/a	n/a
Low - 2	0.003	0.010	0.002	0.000	n/a	n/a
Very Low - 1	0.001	0.017	0.032	0.023	0.000	0.000

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X
Very High - 5	0.008	0.004	0.080	0.133	n/a	n/a
Not Very High	0.002	0.011	0.028	0.012	n/a	n/a

Gas Pipeline Leaks - Loma Prieta Earthquake

ABAG 1980 LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING INTENSITY

Km of Pipe Exposed

Liquefaction	Shaking Intensity						
Susceptibility	V	VI	VII	VIII	IX	X	TOTAL
High >14	217	284	948	294	0	0	1743
Moderate - 14	2665	3386	3476	35	0	0	9563
Moderate - 13	244	493	1514	112	0	0	2363
Low - 12	3476	3137	2056	28	0	0	8697
Very Low - 11	9099	3750	1346	176	50	67	14488
TOTAL	15701	11050	9341	645	50	67	36854

Pipe Leaks

Liquefaction	Shaking Intensity						
Susceptibility	V	VI	VII	VIII	IX	X	TOTAL
High >14	0	0	177	33	0	0	210
Moderate - 14	4	32	25	0	0	0	61
Moderate - 13	0	1	85	4	0	0	90
Low - 12	15	40	2	0	0	0	57
Very Low - 11	7	49	13	0	0	0	69
TOTAL	26	122	302	37	0	0	487

Leaks/Km Exposed Pipe

Liquefaction	Shaking Intensity					
Susceptibility	V	VI	VII	VIII	IX	X
High >14	0.000	0.000	0.187	0.112	n/a	n/a
Moderate - 14	0.002	0.009	0.007	0.000	n/a	n/a
Moderate - 13	0.000	0.002	0.056	0.036	n/a	n/a
Low - 12	0.004	0.013	0.001	0.000	n/a	n/a
Very Low - 11	0.001	0.013	0.010	0.000	0.000	0.000

Leaks/Km Exposed Pipe

Liquefaction	Shaking Intensity					
Susceptibility	V	VI	VII	VIII	IX	X
High >14	0.000	0.000	0.187	0.112	n/a	n/a
Not High	0.002	0.011	0.015	0.011	n/a	n/a

Gas Pipeline Leaks - Loma Prieta Earthquake

WLA/USGS LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING STRAIN

Km of Pipe Exposed

Liquefaction Susceptibility	Shaking Strain						
	Low	Mod. Low	Moderate	Mod. High	High	Very High	TOTAL
Very High - 5	46	176	351	525	453	271	1822
High - 4	216	679	1086	954	1053	34	4022
Moderate - 3	657	1594	2986	3074	1391	15	9717
Low - 2	712	1061	2322	1588	149	7	5839
Very Low - 1	6921	3871	2643	1515	409	94	15453
TOTAL	8552	7381	9388	7656	3454	422	36854

Pipe Leaks

Liquefaction Susceptibility	Shaking Strain						
	Low	Mod. Low	Moderate	Mod. High	High	Very High	TOTAL
Very High - 5	0	2	1	35	32	32	102
High - 4	0	1	0	7	7	0	15
Moderate - 3	0	8	25	149	24	0	206
Low - 2	0	6	18	4	1	0	29
Very Low - 1	6	29	38	25	35	2	135
TOTAL	6	46	82	220	99	34	487

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Strain					
	Low	Mod. Low	Moderate	Mod. High	High	Very High
Very High - 5	0.000	0.011	0.003	0.067	0.071	0.118
High - 4	0.000	0.001	0.000	0.007	0.007	0.000
Moderate - 3	0.000	0.005	0.008	0.048	0.017	0.000
Low - 2	0.000	0.006	0.008	0.003	0.007	0.000
Very Low - 1	0.001	0.007	0.014	0.017	0.086	0.021

Leaks/Km Exposed Pipe

Liquefaction Susceptibility	Shaking Strain					
	Low	Mod. Low	Moderate	Mod. High	High	Very High
Very High - 5	0.000	0.011	0.003	0.067	0.071	0.118
Not Very High	0.001	0.006	0.009	0.026	0.022	0.013

DISCUSSION OF POTENTIAL USE OF SEWER PIPELINE LEAK DATA FROM THE LOMA PRIETA EARTHQUAKE

Procedure Used in Effort to Collect Data

Data on damage to sewer lines in the San Francisco Bay Area as a result of the 1989 Loma Prieta earthquake is very limited. Unlike water lines, the sewer system is not pressurized, so that leaks do not result in obvious "geysers."

In the East Bay, the East Bay Municipal Utility District (EBMUD) did not experience any damage on the large collector lines that it operates. The East Bay Discharges Authority did not experience any leaks, but did a subsequent study of potential seismic hazards. Individual municipalities operate the smaller lines, the vast majority of sewer system. Data on the status of this portion of the system was not systematically collected by the cities, so that any attempt to use data to perform a statistical analysis is not possible.

Damage occurred in San Francisco, particularly in the Marina District, but no comprehensive survey of the system apparently was conducted following the earthquake. Again, any attempt to use data to perform a statistical analysis is not possible.

Phone calls to selected cities in San Mateo and Santa Clara counties confirmed that no systematic data were collected on sewer problems. Thus, there is no practical way of using sewer damage data to aid in the assessment of liquefaction damage.

ANALYSIS OF RESIDENTIAL BUILDING DAMAGE DATA FROM THE LOMA PRIETA EARTHQUAKE

A Special Concern

Information on housing vulnerability in areas mapped as having moderate, high, or very high liquefaction susceptibility is of particular concern in the Bay Area because of the development patterns in the region. ***While these areas represent only 22.6% of the land, they underlie 46.3% of our urban areas and 48.9% of our housing units.***

Data Collection Procedure

The analysis of building damage patterns for various levels of mapped liquefaction susceptibility requires the comparison of areas of equivalent shaking severity, but different mapped liquefaction susceptibility. This analysis is problematic because housing in areas mapped as having very high liquefaction susceptibility and MMI VIII (occurring in San Francisco) tended to be tall older wood-frame multifamily residential), while housing in areas that are mapped as having lower liquefaction susceptibility and MMI VIII (that occur in Santa Clara County) tended to be newer single-family homes. The principal housing type that is comparable is pre-1940 single-family homes, of which there were 301 homes red-tagged in the Bay Area. Thus, this analysis focuses on the percentage of pre-1940 homes red-tagged as unsafe following the earthquake. These data had previously been collected by ABAG as part of its work on impacts of earthquakes on housing (see Perkins and others, 1996).

Results

As can be seen by examining the following tables:

- there is a very significant correlation between the percentage of pre-1940 single-family homes red-tagged and shaking intensity;
- there is no clear correlation between the percentage of pre-1940 single- family homes red-tagged and either the 1980 ABAG liquefaction susceptibility map or the 2000 WLA/USGS liquefaction susceptibility map.

In order to examine the joint effects of liquefaction susceptibility and shaking level, we examined the correlation between the fraction of pre-1940 single-family homes red-tagged to shaking level ***separately*** in areas mapped as having very high liquefaction susceptibility and outside those areas on 2000 WLA/USGS mapping. The correlation between the fraction of homes red-tagged and shaking level remains very strong for ***both*** homes within and outside of areas of very high liquefaction susceptibility. ***Surprisingly, there is virtually no difference between the percentage of pre-1940 single-family homes and the WLA/USGS maps for MMI VIII, while the areas subjected to MMI VII and lower show higher damage rates for areas outside of those with very high liquefaction susceptibility than for areas within the very high areas:***

- virtually the same for MMI VIII; and
- 2.1 times lower for MMI VII.

Again, we wanted to compare the 2000 WLA/USGS mapping with the 1980 ABAG mapping. Thus, we performed the same analysis of the joint effects of liquefaction susceptibility and shaking level using the high susceptibility areas on the ABAG mapping as a cut-off for liquefaction susceptibility. ***The reverse correlation is stronger for the 1980 ABAG map, with the percentage of homes red-tagged being greater for homes outside mapped high liquefaction susceptibility areas than inside those areas given the same shaking intensities:***

- 1.9 times lower for MMI VIII; and
- 2.4 times lower for MMI VII.

This apparent anomaly is consistent with damage patterns of four-story apartment buildings in the Marina District of San Francisco analyzed by Harris and Egan (1992): "The ground failure in the central part of the filled area appears to have mitigated much of the potential damage by dissipating seismic energy through liquefaction." The potential for dissipation of seismic energy through liquefaction also is consistent with the recording of the Loma Prieta main shock obtained at Treasure Island. Hanks and Brady (1991) note that the onset of liquefaction apparently significantly damped the ground shaking. Recordings of aftershocks do not show this damping effect, potentially due, in part, to shaking being insufficient to trigger liquefaction.

Analysis of Data Collected by Cities Not Feasible

Originally, we had hoped to supplement this analysis with an analysis of the San Francisco red- and yellow-tagged buildings database files, for these files also included a field related to "ground failure" as a contributing cause to building damage. Some inspectors of damaged buildings filled out this information. However, we determined that the file was inconsistent and incomplete. This same conclusion has been reached by staff of the City's Building Department (Zan Turner, personal communication, 2001). No other city even attempted to systematically include this type of information on the forms filled out for damaged buildings.

A Caveat

Although damage to residential buildings ***in the Loma Prieta earthquake*** appears to have been lessened due to the onset of liquefaction, the research on damage data in the Northridge earthquake emphasizes that buildings damaged by liquefaction were likely to have more extensive damage, and damage that was more costly to repair (see pages 32-34).

Residential Damage - Loma Prieta Earthquake

RED-TAG DATA FOR PRE-1940 SINGLE-FAMILY HOMES VERSUS THREE MAPS

		Dwelling Units Red-Tagged	Rough %	Dwelling Units Exposed	Fraction Tagged
2000	Very High - 5	24	8.0	5768	0.0042
WLA/USGS	High - 4	2	0.7	7965	0.0003
Liquefaction	Moderate - 3	67	22.3	61785	0.0011
Susceptibility	Low - 2	27	9.0	29426	0.0009
Map	Very Low - 1	181	60.1	79806	0.0023
	Sum	301	100.0	184750	
1980	High >14	35	11.6	21192	0.0017
ABAG	Moderate - 14	46	15.3	48851	0.0009
Liquefaction	Moderate - 13	5	1.7	9966	0.0005
Susceptibility	Low - 12	38	12.6	42198	0.0009
Map	Very Low - 11	177	58.8	62544	0.0028
	Sum	301	100.0	184750	
1995	MMI X - 6	65	21.6	196	0.3318
ABAG	MMI IX - 5	76	25.2	119	0.6392
Shaking	MMI VIII - 4	45	15.0	1846	0.0244
Intensity	MMI VII - 3	77	25.6	60372	0.0013
Map	MMI VI - 2	31	10.3	74172	0.0004
	MMI V - 1	7	2.3	48044	0.0001
	Sum	301	100.0	184749	

Data for Pre-1940 Single-Family Homes - Loma Prieta Earthquake

WLA/USGS LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING INTENSITY

Homes Exposed

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	962	786	3262	915	0	0	5925
Not Very High	47079	73417	57101	912	119	196	178824
TOTAL	48041	74204	60363	1827	119	196	184749

Homes Red-Tagged

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	0	0	2	22	0	0	24
Not Very High	7	31	75	23	76	65	277
TOTAL	7	31	77	45	76	65	301

Percentage Red Tagged

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X
Very High - 5	0.0000	0.0000	0.0006	0.0240	n/a	n/a
Very Low - 1	0.0001	0.0004	0.0013	0.0252	0.6392	0.3318

ABAG 1980 LIQUEFACTION SUSCEPTIBILITY MAP VERSUS SHAKING INTENSITY

Homes Exposed

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	661	601	18708	1223	0	0	21193
Not Very High	47380	73603	41655	605	119	196	163558
TOTAL	48041	74204	60363	1828	119	196	184751

Homes Red-Tagged

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X	TOTAL
Very High - 5	0	0	12	23	0	0	35
Not Very High	7	31	65	22	76	65	266
TOTAL	7	31	77	45	76	65	301

Percentage Red Tagged

Liquefaction Susceptibility	Shaking Intensity V	VI	VII	VIII	IX	X
Very High - 5	0.0000	0.0000	0.0006	0.0188	n/a	n/a
Very Low - 1	0.0001	0.0004	0.0016	0.0364	0.6387	0.3316

ANALYSIS OF ROAD SURFACE REPAIR DATA FROM THE LOMA PRIETA EARTHQUAKE

Data Collection Procedure

Caltrans made a total of 39 surface repairs – 25 in the Bay Area and 14 in Santa Cruz County following the Loma Prieta earthquake. No consistent data on local road repairs were collected. Thus, the following tables and analysis are limited to the road surface repairs in the Bay Area made by Caltrans.

Results

Although data could only be analyzed for 25 repairs, several key conclusions can be drawn by examining these data.

The correlation between frequency of road repairs (expressed as number of repairs / km road exposed – the first shaded column) is more consistent with mapped shaking intensity than with areas mapping as having very high liquefaction susceptibility on the WLA/USGS map (Knudsen and others, 2000) or with areas mapped as having high or very high liquefaction susceptibility on the ABAG map (Perkins, 1980).

The correlation between percent of road repaired (the second shaded column) remains consistent with shaking level, but is also much more consistent with mapped liquefaction susceptibility level. Most of the discrepancy occurs in areas with very low liquefaction susceptibility. These discrepancies are due to the occurrence of landslides.

The most striking correlation is between mapped liquefaction susceptibility level and cost of road repairs per kilometer of exposed road. ***The dollars spent per kilometer of exposed road were over 100 times larger for areas mapped as very high liquefaction susceptibility on the WLA/USGS map, or high to very high on the ABAG map, than the next highest category.***

In order to examine the joint effects of liquefaction susceptibility and shaking level, we examined the correlation of frequency of repairs to shaking level ***separately*** for those repairs in areas mapped as having very high liquefaction susceptibility (as shown on the WLA/USGS mapping) and outside those areas. Huge variations in repair costs per kilometer of exposed at MMI VIII for those areas within and outside of areas mapped as having very high liquefaction susceptibility may indicate that MMI VIII is a triggering intensity for liquefaction effects that affect roads.

Caltrans records confirmed that liquefaction was involved at three of the four sites of MMI VIII and very high liquefaction susceptibility. The percent of road repaired is over 40% for very high liquefaction areas and MMI VIII – a ***very large*** value.

The anomaly of $2.5 million for a road repair in an area that was only MMI V and was not a very high liquefaction area is apparent. According to Caltrans reports, this repair was due to a coastal landslide repair on Hwy. 1 in Marin County.

Road Surface Repairs - Loma Prieta Earthquake

CALTRANS DATA ON HIGHWAY SURFACE REPAIR EXPENDITURES

		# Repairs	Rough %	Km Road	Repairs/Km Caltrans Road Exposed	Km of Road Repaired	% of Road Repaired	$ Repairs	$/Km Rd Exposed
2000	Very High - 5	6	24.0	163	0.0369	14.0	8.615	5438000	33462
WLA	High - 4	1	4.0	316	0.0032	3.0	0.950	85000	269
Liquefaction	Moderate - 3	6	24.0	577	0.0104	1.4	0.243	263000	456
Susceptibility	Low - 2	0	0.0	385	0.0000	0.0	0.000	0	0
Map	Very Low - 1	12	48.0	1084	0.0111	21.2	1.955	8509000	7847
	Sum	25	100.0	2525		39.6		14295000	
1980	High >14	8	32.0	157	0.0510	17.4	11.084	5633000	35884
ABAG	Moderate - 14	3	12.0	653	0.0046	0.8	0.123	136000	208
Liquefaction	Moderate - 13	1	4.0	156	0.0064	0.1	0.064	32000	206
Susceptibility	Low - 12	3	12.0	547	0.0055	0.3	0.055	51000	93
Map	Very Low - 11	10	40.0	1012	0.0099	21	2.076	8443000	8345
	Sum	25	100.0	2524		39.6		14295000	
1995	MMI X - 6	1	4.0	3	0.3008	3.3	100.000	789400	237485
ABAG	MMI IX - 5	1	4.0	6	0.1628	6.1	100.000	4433700	721866
Shaking	MMI VIII - 4	8	32.0	72	0.1118	24.6	34.334	5613900	78480
Map	MMI VII - 3	11	44.0	541	0.0203	4.8	0.887	887000	1639
	MMI VI - 2	3	12.0	666	0.0045	0.7	0.105	71000	107
	MMI V - 1	1	4.0	1235	0.0008	0.1	0.008	2500000	2024
	Sum	25	100.0	2524		39.6		14295000	

Road Surface Repairs - Loma Prieta Earthquake

CALTRANS DATA ON HIGHWAY SURFACE REPAIR EXPENDITURES

		# Repairs	Rough %	Km Road	Repairs/Km Caltrans Road Exposed	Km of Road Repaired	% of Road Repaired	$ Repairs	$/Km Rd Exposed
ONLY	MMI X - 6	0	0.0	0	n/a	0.0	n/a	0	n/a
WLA/USGS	MMI IX - 5	0	0.0	0	n/a	0.0	n/a	0	n/a
Very High	MMI VIII - 4	4	66.7	33	0.1201	13.4	40.228	5377000	161423
Liquefaction	MMI VII - 3	1	16.7	71	0.0141	0.1	0.141	32000	453
Susceptibility	MMI VI - 2	1	16.7	29	0.0343	0.5	1.713	29000	994
	MMI V - 1	0	0.0	28	0.0000	0.0	0.000	0	0
	Sum	6	100.0	161		14.0		5438000	
EXCLUDING	MMI X - 6	1	5.3	3	0.3008	3.3	100.000	789400	237485
WLA/USGS	MMI IX - 5	1	5.3	6	0.1739	6.1	106.817	4433700	771078
Very High	MMI VIII - 4	4	21.1	37	0.1077	11.2	30.055	236900	6380
Liquefaction	MMI VII - 3	10	52.6	470	0.0213	4.7	1.000	855000	1820
Susceptibility	MMI VI - 2	2	10.5	637	0.0031	0.2	0.031	42000	66
	MMI V - 1	1	5.3	1207	0.0008	0.1	0.008	2500000	2071
	Sum	19	100.0	2360		25.6		8857000	
ONLY	MMI X - 6	0	0.0	0	n/a	0.0	n/a	0	n/a
ABAG High	MMI IX - 5	0	0.0	0	n/a	0.0	n/a	0	n/a
Liquefaction	MMI VIII - 4	4	50.0	43	0.0921	13.4	30.846	5377000	123777
Susceptibility	MMI VII - 3	4	50.0	56	0.0713	4.0	7.129	256000	4562
	MMI VI - 2	0	0.0	39	0.0000	0.0	0.000	0	0
	MMI V - 1	0	0.0	18	0.0000	0.0	0.000	0	0
	Sum	8	100.0	157		17.4		5633000	
EXCLUDING	MMI X - 6	1	5.9	3	0.3008	3.3	100.000	789400	237485
ABAG High	MMI IX - 5	1	5.9	6	0.1628	6.1	100.000	4433700	721866
Liquefaction	MMI VIII - 4	4	23.5	28	0.1424	11.2	39.727	236900	8433
Susceptibility	MMI VII - 3	7	41.2	485	0.0144	0.8	0.165	631000	1301
	MMI VI - 2	3	17.6	627	0.0048	0.7	0.112	71000	113
	MMI V - 1	1	5.9	1217	0.0008	0.1	0.008	2500000	2055
	Sum	17	100.0	2367		22.2		8662000	

ANALYSIS OF HAZARDOUS MATERIAL INCIDENT DATA FROM THE LOMA PRIETA EARTHQUAKE

Data Collection Procedure

The most complete database of hazardous materials releases for the Loma Prieta earthquake was previously compiled by ABAG (Perkins and Wyatt, 1994). Overall, 190 hazardous materials incidents are documented in that database. However, 58 incidents that occurred outside of the Bay Area and 11 incidents with insufficient locational information could not be included in this analysis, leaving 121 incidents. These spills did not occur randomly throughout the Bay Area. The challenge is to determine some simple correlations between number of spills and location without stretching the statistical limits of the data.

The analysis of hazmat incidents requires normalizing the incident rate against some measure of exposure. The exposure measure most realistic based on past work with these data is urban acres not including residential or urban open space (see Perkins and others, 1997).

Results

As can be seen by examining the following tables:

- there is a very significant correlation between the incidents per acre exposed and shaking intensity;
- there is a small correlation between the incidents per acre exposed and the 1980 ABAG liquefaction susceptibility map, but no significant correlation between incidents per acre exposed and the 2000 WLA/USGS liquefaction susceptibility map.

Thus, to determine if liquefaction mapping is useful in assessing or predicting hazmat incidents in earthquakes, the incident data need to be analyzed using a combination of liquefaction and intensity mapping.

In order to examine any potential joint effects of liquefaction susceptibility and shaking level, we examined the correlation between the incidents per acre exposed to shaking level ***separately*** in areas mapped as having very high liquefaction susceptibility and outside those areas as defined by the 2000 WLA/USGS mapping. Although there is still a general trend showing a correlation between the incidents per acre exposed and shaking level ***both*** areas within and outside of areas of very high liquefaction susceptibility, the data indicate inconsistencies. Thus, the data are mixed and stress that to the extent that these data are related to building damage, the correlation is weak.

Again, we wanted to compare the 2000 WLA/USGS mapping with the 1980 ABAG mapping. Thus, we performed the same analysis to examine the joint effects of liquefaction susceptibility and shaking level using the high susceptibility areas on the ABAG mapping as a cut-off for liquefaction. The results are similar to that for the WLA/USGS mapping.

Thus, liquefaction mapping is not useful in assessing or predicting most hazardous materials incidents.

Hazmat Problems - Loma Prieta Earthquake

INCIDENT DATA AND HAZARD MAPS VERSUS THREE MAPS

Map	Category	Number of Hazmat Incidents	Rough %	Select Acres Exposed	Incidents per Select Acre
2000 WLA/USGS Liquefaction Susceptibility Map	Very High - 5	29	24.0	35980	0.0008
	High - 4	15	12.4	41092	0.0004
	Moderate - 3	41	33.9	62545	0.0007
	Low - 2	14	11.6	39994	0.0004
	Very Low - 1	22	18.2	60715	0.0004
	Sum	121	100.0	240325	
1980 ABAG Liquefaction Susceptibility Map	High >14	28	23.1	31911	0.0009
	Moderate - 14	42	34.7	69986	0.0006
	Moderate - 13	26	21.5	30867	0.0008
	Low - 12	15	12.4	51271	0.0003
	Very Low - 11	10	8.3	56290	0.0002
	Sum	121	100.0	240326	
1995 ABAG Shaking Intensity Map	MMI X+IX - 6+5	1	0.8	255	0.0039
	MMI VIII - 4	18	14.9	11522	0.0016
	MMI VII - 3	75	62.0	75430	0.0010
	MMI VI - 2	24	19.8	71984	0.0003
	MMI V - 1	3	2.5	81135	0.0000
	Sum	121	100.0	240325	

Note:
Select acres includes urban land that is not urban open (largely parks) or residential.

Hazmat Problems - Loma Prieta Earthquake

COMPARISONS OF LIQUEFACTION DATA WITH INTENSITY EXPOSURE

		Number of Hazmat Incidents	Rough %	Select Acres Exposed	Incidents per Select Acre
ONLY	MMI X+IX - 6+5	0	0.0	0	n/a
WLA/USGS	MMI VIII - 4	16	55.2	9205	0.00174
Very High	MMI VII - 3	9	31.0	16623	0.00054
Liquefaction	MMI VI - 2	4	13.8	7645	0.00052
Susceptibility	MMI V - 1	0	0.0	2506	0.00000
	Sum	29	100.0	35980	

		Number of Hazmat Incidents	Rough %	Select Acres Exposed	Incidents per Select Acre
EXCLUDING	MMI X+IX - 6+5	1	1.1	255	0.00393
WLA/USGS	MMI VIII - 4	2	2.2	2316	0.00086
Very High	MMI VII - 3	66	71.7	58807	0.00112
Liquefaction	MMI VI - 2	20	21.7	64339	0.00031
Susceptibility	MMI V - 1	3	3.3	78629	0.00004
	Sum	92	100.0	204345	

		Number of Hazmat Incidents	Rough %	Select Acres Exposed	Incidents per Select Acre
ONLY	MMI X+IX - 6+5	0	0.0	0	n/a
ABAG High	MMI VIII - 4	18	64.3	10175	0.0018
Liquefaction	MMI VII - 3	10	35.7	12528	0.0008
Susceptibility	MMI VI - 2	0	0.0	7386	0.0000
	MMI V - 1	0	0.0	1822	0.0000
	Sum	28	100.0	31911	

		Number of Hazmat Incidents	Rough %	Select Acres Exposed	Incidents per Select Acre
EXCLUDING	MMI X+IX - 6+5	1	1.1	255	0.0039
ABAG High	MMI VIII - 4	0	0.0	1347	0.0000
Liquefaction	MMI VII - 3	65	69.9	62902	0.0010
Susceptibility	MMI VI - 2	24	25.8	64599	0.0004
	MMI V - 1	3	3.2	79312	0.0000
	Sum	93	100.0	208414	

Note:
Select acres includes urban land that is not urban open (largely parks) or residential.

THE NORTHRIDGE EARTHQUAKE

The following sections relate to damage data from the 1994 Northridge earthquake that are similar in type to that collected and analyzed for the Loma Prieta earthquake by ABAG staff. The analysis of these data is beyond the scope of the current research project. However, the data descriptions have been included in this appendix because we believe that further analysis of these data is warranted for it should shed additional light on the relationships among shaking, liquefaction, and damage. In addition, the data on the residential and building damage collected by Daniel Ponti (U.S. Geological Survey) and described in this section is particularly insightful.

COLLECTION OF WATER PIPELINE LEAK DATA FROM THE NORTHRIDGE EARTHQUAKE

Data on damage to water lines in southern California as a result of the 1994 Northridge earthquake was obtained from Daniel Ponti of the U.S. Geological Survey.

No analysis of these data has been conducted at this time.

COLLECTION OF NATURAL GAS PIPELINE LEAK DATA FROM THE NORTHRIDGE EARTHQUAKE

Data on damage to natural gas lines in southern California as a result of the 1994 Northridge earthquake was obtained for ABAG's use from Art Partridge of Southern California Gas Company. The database contains information on 576 gas line leaks that were probably related to the Northridge earthquake. Even these leaks were not necessarily unilaterally related to the earthquake, for SoCal Gas does not have the data necessary to make that determination. In addition, immediately following the earthquake, with the company's unprecedented effort to mitigate unsafe conditions, detailed recording of data collected in the field was not completely accurate or complete.

As with the PG&E data, researchers collecting data following the Northridge earthquake reported significantly more earthquake-related leaks than SoCal Gas experts currently think were earthquake-related. For example, EERI (1995) reported, as of approximately three months following the quake:

- 209 instances of damage to metallic distribution mains and services where no corrosion or construction-related damage was observed;
- 563 cases of damage to metallic distribution piping where corrosion, material, or construction-related defects were observed or where damage was of unknown origin;
- 27 instances of damage to polyethylene pipes, the majority of which occurred at coupling and transition fittings; and
- 35 non-corrosion-related repairs made to the transmission system, of which 27 were at cracked or ruptured oxyacetylene girth welds in pre-1932 pipelines.

The problems associated with this database are similar to those noted for the PG&E database of leaks following the Loma Prieta earthquake, so that the database is less reliable than that for water lines. In addition, these data may be harder to analyze than the PG&E data, due to small numbers and non-uniformity of the type of damage.

No analysis of these data has been conducted at this time.

ANALYSIS OF SEWER PIPELINE LEAK DATA

FROM THE NORTHRIDGE EARTHQUAKE

Data on damage to sewer lines in southern California as a result of the 1994 Northridge earthquake is much better than the equivalent data on damage to these lines in the Bay Area due to the Loma Prieta earthquake. Data are available on ***8,197 sewer segments*** based on a detailed evaluation of sewers conducted by the City of Los Angeles Collection Systems Division after the Northridge earthquake. Their survey focused on the areas that experienced the most intense damage, primarily the San Fernando Valley. The survey and associated replacement of damaged lines cost hundreds of thousands of dollars and was paid for, in large part, with funding from FEMA. Approximately 2,000 miles of lines were surveyed with remote video cameras. Survey work was concluded as of 6/97. Areas included in the survey were Northridge, Canoga Park, Reseda, and parts of Hollywood and Pacific Palisades. Surveyors did not spend very much time in areas of minimal damage; rather they sought to characterize the hardest hit areas. The survey was also limited by budget considerations and difficulty in obtaining access permission from residents in some areas, particularly Pacific Palisades.

Damage was graded by status down to the block level for the study area, with those areas graded A having virtually no damage, to those areas graded E having an obstruction. ABAG obtained a copy of the less detailed, but most extensive in aerial coverage, of two files from Daniel Ponti of the U.S. Geological Survey[4]. He notes that, having examined some of the original video camera footage:

- "codes A and B have only hairline cracks at joints, most likely shaking related;
- C grade contains both hairline joint cracks (although more frequent than A or B or may well contain more severe (but relatively minor) pipe damage that are likely ground failure induced; and
- D and E damage is significant and almost certainly due to ground failure."

No analysis of these data has been conducted at this time.

ANALYSIS OF RESIDENTIAL BUILDING DAMAGE DATA FROM THE NORTHRIDGE EARTHQUAKE

ABAG collected extensive data on red- and yellow-tagging of residential structures and units throughout the area impacted by the Northridge earthquake, not just the City of Los Angeles, as part of other research funded by the National Science Foundation (Perkins and others, 1996). These data have been extensively checked and reviewed for accuracy.

Ideally, data on the contribution of geology or ground failure to the damage would be available from the tagged databases developed by the cities and counties impacted. However, this information is not readily available without going back to the original hard copy" forms filled out by the inspectors and is inconsistent in its accuracy.

One other source of building damage data exists. Daniel Ponti of the U.S. Geological Survey worked with a volunteer student to examine the building permit files for almost 71,000 properties in the heavily impacted area. These properties represent roughly half of the parcels in the heavily impacted area. According to Dr. Ponti, "properties for which we have no data either suffered no reportable earthquake damage, were repaired without permits, or have not yet been

[4] A more detailed file showing the line-footage location of each sewer leak, together with a code on the type of damage shown, is available for the Granada Hills area. This file has 339,430 records. The file obtained by ABAG only has 8,325 records, with each record providing a description of the damage state of a sewer line segment from manhole to manhole.

repaired." Most of these properties were single-family homes. The resulting database contains information on the cost of the repair, as well as a general description of what was repaired. This database contains information on many parcels that were not tagged, many of which had extensive repair costs. In addition, interestingly, many parcels that had buildings that were tagged do not contain any permits for repairs. Dr. Ponti notes:

> For comparing the costs and types of damage within and outside ground failure zones, we have chosen to restrict our analysis to single-family residences situated on Holocene alluvium. We have done this in an attempt to reduce the effects of varying types of construction and local site geology. This reduced dataset consists of 4829 homes where some property loss occurred; the kinds of required repairs are known for 2983 of these. The building stock in this dataset is remarkably uniform. Over 98% of the houses are classified as being of mixed construction; typically they are stucco or partial stucco over wood frame, one or two stories in height. Most are built over slab-on-grade foundations, usually unreinforced. Most of the remaining 2% are either of steel-frame or reinforced concrete construction. All of the homes were built between 1906 and 1992, but 91% of them were constructed between 1946 and 1970, with a median age of 40 years (built in 1956). In the Balboa Blvd. area, where most ground failure occurred, construction type and home vintage are nearly identical to the study area as a whole. All of the homes in this area were built between 1956 and 1977, with 92% built between 1956 and 1963; the median age here is 39 years (built in 1957).
>
> For the purpose of our analysis, properties are considered to have been impacted by ground failure if: a) mapped ground cracks are contained within the property boundary or cross the property line, or b) the property is located within the zone of shallow ground water in the Balboa Blvd. Area inferred from our post-earthquake subsurface and associated studies. All properties not meeting these criteria are not considered to have been impacted by ground failure. Comparison of property loss inside and outside of ground failure zones are summarized in Figure GF3-D. Repair costs for all properties in the study area range from $200 to $381,000, averaging $12,193 per property. Average repair costs for the 315 properties impacted by ground failure, however, are found to be approximately 300% higher than for the 4514 properties located outside of ground failure zones ($32,578 vs. $10,771). This result is not surprising given the intensity of damage in the Balboa Blvd. area, but of real interest is that there is a much different distribution in the kinds of repairs performed in the two areas. Notably, over 6% of damaged homes affected by ground failure required demolition of both the structure and foundation, as opposed to only 0.2% of homes unaffected by ground failure. Likewise, foundation repairs needed to be performed on 27.5% of damaged structures in ground failure zones as opposed to only 5% of damaged structures outside these zones. Not only are foundation repairs more prevalent within the ground failure zones, but the average cost of repairing structures with foundation damage is twice as high ($48,870 vs. $24,865), indicating that foundation damage was likely more severe in ground failure zones as well. These data point to the importance of foundation damage in driving up property losses within ground failure zones. Foundation damage is also best attributable to the occurrence of ground failure itself, inasmuch as surface dislocations can directly cause cracking in foundation elements (Figure GF3-E). This relationship is further illustrated in Figures GF3-F and GF3-G, which show that properties that

suffered the greatest losses typically required foundation repair or replacement, and that these same structures are usually located on or near zones of mapped ground cracks.

In addition to foundation repairs, average costs of other types of repair were also somewhat higher for properties impacted by ground failure. However, with the exception of chimney repairs, the higher costs within ground failure zones are not statistically different. Nevertheless, this trend suggests that in addition to ground failure, ground motions were probably higher within the areas that exhibited ground cracking, as might be expected. However, the influence of this enhanced ground shaking on property loss, by itself, appears to be minimal. If we look only at structures within the ground failure zones that did not incur foundation damage, we find that their average repair cost is $14,418 - a value that probably is the exclusive result of shaking-related damage. This value is ~34% higher, and statistically greater than the $10,771 average repair cost outside the failure zones, with most of increase attributable to more expensive chimney repairs. However, the $14,418 figure is still less than one-half the average repair cost per property for ground failure zones as a whole. Thus, these data suggest that most property loss within areas impacted by ground failure are directly attributable to the ground failure itself, rather than to enhanced ground motions that may in part control the failures. In other words, had the Granada Hills and Mission Hills area not been subject to ground failure in the Northridge earthquake, the resulting damage to structures in that area would not have been a great deal greater, in terms of economic loss, than for the northern San Fernando Valley as a whole.

No analysis of either Dr. Ponti's database or of the residential tagging data has been conducted at this time.

ANALYSIS OF ROAD SURFACE REPAIR DATA FROM THE NORTHRIDGE EARTHQUAKE

Data on damage to road surfaces as a result of the Northridge earthquake was obtained from two sources:

- Caltrans; and
- the City of Los Angeles.

The data from the City of Los Angeles was compiled for the San Fernando Valley area and provided to the California Division of Mines and Geology (CDMG), who, in turn, provided the data to USGS (Daniel Ponti). We obtained the data from Dr. Ponti, with permission from Chuck Real from CDMG. The file contains the location of ***510*** surface street segments and the length of street repaired. In all, ***48.648*** km of street were repaired. At this time, this database does not contain any information on the repair costs or on repairs to streets outside of the heavily impacted portions of the San Fernando Valley.

Caltrans data was also obtained from Caltrans.

No analysis of these data has been conducted at this time.

References –

1. Earthquake Engineering Research Institute, 1995. “Northridge Earthquake Reconnaissance Report, Vol. 1” in ***Earthquake Spectra***: EERI Supplement C to v. 11 (April issue), Oakland, CA, pp. 176-180.
2. Eguchi, R.T., 1991. ***Early Post-Earthquake Damage Detection for Underground Lifelines***, Final Report to the National Science Foundation, Dames and Moore P.C., Los Angeles, CA.
3. Hanks, T.C., and Brady, G., 1991. "The Loma Prieta Earthquake - Damage and Ground Motions in Oakland, Treasure Island, and San Francisco" in ***Bulletin of the Seismological Society of America***: no. 81, El Cerrito, CA, pp. 2019-2047.
4. Harris, S.K, and Egan, J.A., 1992. “Effects of Ground Conditions on the Damage to Four-Story Corner Apartment Buildings” in ***The Loma Prieta, California, Earthquake of October 17, 1989 – Marina District***; U.S. Geological Survey Prof. Paper 1551-F: Reston, VA, pp. F181-F194.
5. Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000. ***Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California***: U. S. Geological Survey Open-File Report 00-444. Digital Database by Wentworth, C.M., Nicholson, R.S., Wright, H.M., and Brown, K.H. Online Version 1.0.
6. Newmark, N.M., 1967. "Problems in Wave Propagation in Soil and Rocks" in ***Proceedings of International Symposium on Wave Propagation and Dynamic Properties of Earth Materials***, Albuquerque, NM, pp. 7-26.
7. O'Rourke, M.J., 1996. "Response of Buried Pipelines to Wave Propagation" in ***MCEER Bulletin***: State University of New York at Buffalo, July issue, 9 pp.
8. Perkins, J.B., 1998. ***On Shaky Ground – Supplement..*** ABAG: Oakland, CA, 28 pp.
9. Perkins, J.B., 1980. ***Liquefaction Susceptibility – San Francisco Bay Region***: ABAG (out-of-print effective with the publication of this report).
10. Perkins, J.B., and Boatwright, J., 1995. ***The San Francisco Bay Area – On Shaky Ground***. ABAG: Oakland, CA, 56 pp.
11. Perkins, J.B., Chuaqui, B., Harrald, J., Jeong, D., 1996. ***Shaken Awake! Estimates of Uninhabitable Dwelling Units and Peak Shelter Populations in Future Earthquakes Affecting the San Francisco Bay Region.*** ABAG: Oakland, CA, 89 pp.
12. Perkins, J.B., Chuaqui, B., and Wyatt, E., 1997. ***Riding Out Future Quakes – Pre-Earthquake Planning for Post-Earthquake Transportation System Recovery in the San Francisco Bay Region.*** ABAG: Oakland, CA, 198 pp.
13. Perkins, J. B., and Wyatt, E., 1994. “Hazardous Materials Problems Due to the Earthquake” in ***The Loma Prieta, California, Earthquake of October 17, 1989 – Fire, Police, Transportation and Hazardous Materials***: U.S. Geological Survey Professional Paper 1553-C.
14. Philips, S.H., and Virostek, J.K., 1990**.** ***Natural Gas Disaster Planning and Recovery: The Loma Prieta Earthquake.*** PG&E: San Francisco, CA, 39 pp.
15. Youd, T.L., and Perkins, J.B., 1987. ***Map Showing Liquefaction Susceptibility of San Mateo County, California***: USGS Miscellaneous Investigation Series Map I-1257-G.