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RECOMMENDED CRITERIA FOR DELINEATING SEISMIC HAZARD ZONES IN CALIFORNIA

[DRAFT]

May 1992
[~~Revised July 1999~~Revised April 2004]

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PREFACE

The Seismic Hazards Mapping Act (Chapter 7.8, Sections 2690 et seq., California Public Resources Code) requires the State Geologist, Chief of the Department of Conservation's ~~Division of Mines and Geology~~California Geological Survey (C~~DMG~~GS), to designate seismic hazard zones. These zones assist cities and counties in fulfilling their responsibilities for protecting the public health and safety from the effects of strong ground shaking, earthquake-induced landslides, liquefaction, or other ground failures. To assist the State Geologist in fulfilling this responsibility, the act directs the State Mining and Geology Board (SMGB), in consultation with an advisory board, to develop guidelines and criteria for the preparation of seismic hazard zones in the state. This report presents the recommendations of the Seismic Hazard Mapping Act Advisory Committee as accepted by the SMGB. It is expected that these criteria will continue to evolve as our understanding of seismic phenomena and the methods used to assess their likelihood and potential impacts on the built environment improve.

The Seismic Hazard Mapping Act Advisory Committee formed three working groups composed of acknowledged experts to address ground shaking, liquefaction, and landslide hazards in an attempt to gain a consensus on how to prepare the various maps (see Acknowledgments). A fourth working group on planning and implementation was formed to ensure that the resulting seismic zonation maps would be of practical use in the local planning and building department decision-making process. Recommendations from these working groups are principal components of this document.

Previous versions of this publication (May 1992; July 1999) presented criteria for delineating seismic hazard zones for liquefaction and earthquake-induced landslides. The revision reflects modifications to recommended criteria that relate to liquefaction zones only. Most notably, more specific recommended criteria are presented for determining anticipated depths to saturated soils in areas characterized by differencdt hydrologic conditions. Also, a general edit and update of the document was done for clarification purposes and to incorporate new developments in pertinent soil test technology and analyses.

PROBABILISTIC SEISMIC HAZARD MAP

Introduction

The California Department of Conservation, ~~Division of Mines and Geology~~California Geological Survey (C~~DMG~~GS) is charged with implementing requirements of the Seismic Hazards Mapping Act of 1990. Appropriate maps of expected ground shaking hazard are required and are an underpinning for mapping seismic hazard zones - amplified ground shaking, liquefaction and earthquake-induced landsliding. The following recommendations are provided to assist the C~~DMG~~GS in mapping ground shaking hazard on a regional scale throughout the state.

General Considerations For Mapping Expected Ground Shaking Hazard

The Advisory Committee recommends preparation of a suite of regional ground shaking hazard maps using Probabilistic Seismic Hazard Analysis (PSHA) techniques (NRC, 1988). The following maps should be produced at statewide scales:

1. Maps of peak ground acceleration, and spectral acceleration at 0.3 sec, 1.0 sec, and 3.0 sec., with exceedance probabilities of 10% in 50 years, 50% in 50 years, and 10% in 100 years.

2. Maps of peak ground acceleration, weighted with respect to a M7.5 earthquake, for evaluation of liquefaction potential and earthquake-induced landslide potential, with exceedance probabilities of 10% in 50 years, 50% in 50 years, and 10% in 100 years.

Existing probabilistic seismic hazard computational codes are acceptable, and no basic modeling developments nor substantive computational code changes are needed. The results should capture and display uncertainties on input parameters, including seismic sources, earthquake frequency, maximum magnitude, seismic wave attenuation, and site response. Input interpretations should be developed by an earth science team using consistent approaches throughout the state and formal uncertainty elicitation procedures (NRC, 1977).

PSHA mapping should extend to the near offshore regions, and use Uniform Building Code soft rock conditions as the base site condition and reference soil column. A companion report should be prepared that contains analysis of the key sources of uncertainty in enough depth and detail of presentation to permit users to factor uncertainty into their use of the maps. The analysis of uncertainty may require modest computational code development. Work should be coordinated with on-going PSHA efforts of the U.S. Geological Survey (USGS).

Seismic Source Modeling

Three general types of seismic sources are expected, 1) sources that model active faults, 2) sources that model "active" structures that may contain significant faults (i.e., active fold belts, such as those along the western edge of the Central Valley and within the LA Basin), and 3) sources that model distributed seismicity that cannot be assigned to specific geologic structures. All three types of sources can be readily modeled within existing computational programs. The details of fault geometry should not have a major impact on the results of a regional hazard study in terms of its effect on the density function for distance to rupture. (It may have a significant impact on parameters such as maximum magnitude and seismicity rate, if moment (slip) rate methods are used). Some special attention to details of geometry may be needed in the northwest to model the Cascadia subduction zone.

The seismic sources can be identified on the basis of existing extensive fault mapping and surface and/or subsurface mapping of actively deforming folds for California. Careful thought needs to be given to "background" sources to account for possible unidentified major sources. Uncertainty in sources can be modeled by providing weighted alternatives.

Maximum Magnitude

Maximum magnitudes for fault-specific sources should be based on interpretations of the potential maximum size of rupture and the well-developed empirical relationships between rupture dimensions and magnitude that are documented in the literature. Assessments of maximum magnitudes for tectonic structures may have to rely more on analogy than on specific dimensions of structures, although the general characteristics of the structure (e.g., long and continuous folds versus short and offset folds) may suggest trends in the maximum size that could be used to weight the various analogies. Assessments for seismicity zones and background zones most likely will have to rely on arguments based on analogy, largest observed events without surface rupture manifestations, and historical observations. Uncertainty on maximum magnitude should be modeled using a variable with a distribution rather than a single value.

Earthquake Frequency

The primary model for earthquake recurrence should be the Poisson model, because we know little more than average rates for the vast majority of seismic sources. Time-dependent models may be applicable in a few areas. This could be tested to assess how regional mapping results might be adjusted. For fault-specific sources, earthquake frequency (slip rate) should be based primarily on geologic information for those faults where data on paleoseismicity can be used to establish a rate. For other tectonic structures, other geologic information may have some use where rates of deformation can be established and where a fraction can be attributed to movement on faults. However, historical seismicity rates will likely be the primary source of recurrence information for these other structures, as it will be for distributed seismicity zones. Recurrence parameters should be modeled as variables with distributions.

Minimum Magnitude

It is recommended that the minimum magnitude of interest be set about magnitude 5. It may be desirable to compute results for a higher minimum magnitude to capture the level of hazard from major earthquakes compared to the hazard from moderate earthquakes.

Seismic Wave Attenuation

A new generation of seismic wave attenuation curves should be developed using an updated empirical database from recent strong-motion recordings. This work should be coordinated with ongoing seismic wave attenuation studies at the USGS. "Standard" attenuation curves should be developed for various UBC site soil conditions.

Magnitude dependence of attenuation dispersion should be confirmed and incorporated into the PSHA if appropriate.

A number of site/source/path conditions may influence seismic wave attenuation. Not all of these conditions are accommodated in the empirical curves when they are applied at a given site (e.g., long period ground motions in basins, faulting style, near-source effects at long periods, crustal structure, focal depth and topography). The PSHA should proceed with an awareness of these effects and they should be discussed in the commentary. In general, until more definitive procedures can be developed, the PSHA should treat these effects as part of the randomness in seismic wave attenuation.

AMPLIFIED SHAKING HAZARD ZONES

Building codes are currently the primary means of mitigating the effects of strong earthquake shaking on buildings. The effect of local surface geology on expected shaking is accounted for by seismic coefficients used in the lateral force formula, which correspond to the soil profile types defined in ~~the latest edition of the Uniform~~ the 2001 California Building Code, which is based on the 1997 Uniform Building Code (ICBO, 1997). This revision also contains a "near-source" factor that takes into consideration effects of the proximity to nearby earthquake source ruptures on shaking. Maps of known active fault near-source zones have been prepared for use with the 1997 UBC (ICBO, 1998). The advisory committee believes that, given the current understanding of the effects of geologic materials and structure on earthquake ground motions, there would be no benefit in establishing "amplified shaking hazard zones" for purposes of design and construction. The purpose of the Seismic Hazard Mapping Act is to identify where special provisions, beyond those contained in the UBC, are necessary to ensure public safety. This need has not been recognized for the hazard of ground shaking. Design provisions contained in the UBC are believed to be representative of current knowledge and capability in earthquake-resistant design.

Consideration should be given to preparation of "informational" maps that identify where soft-soil profiles (type S_E) are more likely to be found. Similarly, identifying areas where basin structure or topography may enhance ground shaking or where an aggregate of such adverse conditions within near-source zones might occur could be of value for land-use planning purposes. The development and utility of these options should be investigated.

LIQUEFACTION HAZARD ZONES

Introduction

The California Geological Survey (CGS) of the California Department of Conservation is the principal state agency charged with implementing the 1990 Seismic Hazard Mapping Act. The following are recommended criteria to assist CGS in mapping liquefaction zones of required investigation. The zones identify areas where site-specific geotechnical investigations must be conducted to assess liquefaction hazard before development and, if a hazard exists, provide a technical basis to mitigate the hazard.

Liquefaction Mapping Criteria

Liquefaction zones of required investigation are geographic areas meeting one or more of the following criteria:

1. Areas known to have experienced liquefaction during historical earthquakes.

Field studies following earthquakes indicate liquefaction tends to recur in certain areas (Youd, 1984). There are many published accounts of liquefaction and it is recommended that CGS include these sites in the liquefaction zones of required investigation.

2. Areas of uncompacted fills that are saturated, nearly saturated, or may be expected to become saturated.

In some areas there has been a practice of creating usable land by placing artificial fill on tidal flats or in ravines. Stratigraphic principles are of little use in characterizing soils within these fills, which can be less homogeneous than natural deposits. There is no reason to assume stratification in these fills and the validity of extrapolating subsurface data is questionable. CGS can search for evidence of uncompacted artificial fills by using maps showing old shorelines, comparing archival and modern topographic maps, studying logs of boreholes, and obtaining reports or original plans of projects involving reclaimed land.

3. Areas where analyses of existing data indicate that the soils are potentially liquefiable.

Four key types of information are generally available for producing liquefaction zones of required investigation:

(1) Geology maps that characterize depositional environments and relative ages of Quaternary sedimentary deposits.

(2) Ground-water data used to estimate depths to saturated soils.

(3) Geotechnical borehole data that describe the lithology and engineering properties of subsurface deposits.

(4) Seismic data that provide ground-motion parameters (liquefaction opportunity) used in quantitative liquefaction analyses.

Geology: The vast majority of liquefaction hazard areas are underlain by recently deposited sand and/or silty sand. These deposits are not randomly distributed, but occur within a narrow range of sedimentary and hydrologic environments. Investigators commonly use geologic criteria to establish boundaries of areas found to be susceptible to liquefaction through evaluation of other criteria, such as geotechnical analysis (Youd, 1991). CGS can obtain Quaternary geologic maps that show relative age estimates of depositional units based on ages reported in the literature, stratigraphic relationships, and soil profile descriptions. In addition to maps, analysis of historical aerial photographs and satellite imagery may reveal areas of flooding, recent sediment accumulation, or evidence of past liquefaction.

Ground Water: Saturation reduces the effective normal stress of near-surface sediment, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). CGS can compile and interpret ground-water data to identify areas characterized by, or anticipated to have in the future, near-surface saturated soils. For purposes of seismic hazard zonation, "near-surface" means at a depth less than 40 feet.

Natural hydrologic processes and human activities can cause ground-water levels to fluctuate over time. Therefore, it is impossible to predict depths to saturated soils during future earthquakes. One method of addressing time-variable depths to saturated soils is to establish an anticipated high ground-water level based on historical ground-water data. In areas where ground water is either currently near-surface or could return to near-surface within a land-use planning interval of 50 years, CGS can construct regional contour maps that depict these levels. In some areas with low precipitation, records may indicate that near-surface ground water existed during historical time, but large withdrawal and low recharge rates preclude a return to those conditions within 50 years. For these areas, the historically highest ground-water level is not used to establish the anticipated depth to saturated soil used for hazard evaluation. For these and all other areas, CGS can delineate present or anticipated near-surface saturated soils caused by locally perched water and seepage from surface-water bodies.

Future initiation of large-scale, artificial recharge programs could result in significant rises in ground-water levels over 50 years. When alerted of such plans, CGS can evaluate their impacts relative to liquefaction potential and revise official seismic hazard zone maps, if necessary.

Geotechnical Data: CGS should collect available geotechnical reports and compile information on the engineering properties of late Quaternary sediment. Information generated by standard penetration tests (SPT), cone penetration tests (CPT), shear wave velocity tests, and Becker hammer tests, along with laboratory textural analyses, is used in “simplified procedures” to evaluate the liquefaction resistance of soils (Youd and others, 2001).

For sandy and silty soils, SPT and CPT results are the data most commonly used to characterize soils for quantitative evaluation of resistance to liquefaction (Youd and others, 2001). To ensure consistency and quality data, these soil property tests should be conducted according to ASTM standards (for SPT: D1586-99 and D6066-96e1, and for CPT: D3441). "Standardized" penetration resistance values are used in simplified procedure when evaluating liquefaction resistance. Guidelines for performing SPT, and correlations for conversion of non-standard penetration test data to equivalent standardized penetration resistance $(N_1)_{60}$, are presented in Seed and others (1984; 1985), Seed and DeAlba (1986), Youd and Idriss (1997), Youd and others (2001) and Seed and others (2003). Standard CPT-based characterization of soil and evaluation of liquefaction resistance is done using measurements of the tip resistance (q_c) of the probe being pushed into a soil (*e.g.* Olsen, 1988; Moss, 2003). Evaluation of liquefaction resistance of gravelly soils can be based on in-situ penetration resistance measured using the large-scale Becker Hammer system (Harder, 1988; 1997). Characterization of soil properties with measurements of shear wave velocity is increasingly being used in evaluating a soil’s resistance to liquefaction (*e.g* Andruss and Stokoe, 2001).

Seismicity: Liquefaction opportunity is a measure of the potential for ground shaking strong enough to generate liquefaction. Analyses of in-situ liquefaction resistance require assessment of liquefaction opportunity. In accordance with requirements of the Seismic Hazards Mapping Act of 1990 and guidelines provided in Chapter 2 of these recommended criteria, CGS has prepared for use in seismic hazard zone mapping a suite of regional ground-shaking hazard maps using Probabilistic Seismic Hazard Analysis (PSHA) techniques (NRC, 1988). The minimum level of seismic excitation that CGS should use to develop liquefaction zones of required investigation is that level defined by M7.5-weighted peak ground surface acceleration (PGA) with a 10% probability of exceedance over a 50-year period.

4. Areas where existing subsurface data are not sufficient for quantitative evaluation of liquefaction hazard.

In areas of limited subsurface data, it is recommended that CGS generate liquefaction zones of required investigation through the application of geologic criteria as follows:

(a) Areas containing soil deposits of late Holocene age (current river channels and their historical floodplains, marshes and estuaries) where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 feet; or

(b) Areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 feet; or

(c) Areas containing soil deposits of latest Pleistocene age (between 11,000 years and 15,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 feet.

Application of these criteria allows compilation of liquefaction zones of required investigation which are useful for preliminary evaluations, general land-use planning and delineation of special studies zones (Youd, 1991).

Candidate Methods for Future Development

To further improve delineation of liquefaction zones and strengthen the justification for geotechnical site investigations, DMG should follow the development of methods based on quantifying ground deformation associated with the occurrence of liquefaction. Estimates of liquefaction potential based on simplified methods are known to be conservative with regard to damage potential. Surface manifestation of liquefaction, such as venting of sand, may not always correlate with structural damage, especially when only a small fraction of the soil column liquefies and is accompanied by little or no settlement. Total thickness of liquefiable material and related potential for significant vertical settlement or horizontal deformation are better indicators of damage potential. Improvements in generalized measures such as the Liquefaction Potential Index (Iwasaki et al, 1982), Liquefaction Severity Index (Youd and Perkins, 1987), and methods for evaluating anticipated liquefaction-induced deformations and displacements ~~from lateral spreading~~ (Bartlett and Youd, 1995; Seed et al., 2003), should be investigated for applicability in delineating seismic hazard zones in California.

~~LIQUEFACTION HAZARD ZONES~~

~~Introduction~~

~~California Department of Conservation, Division of Mines (CDMG) is the principal State agency charged with implementation of the provisions of the 1990 Seismic Hazard Mapping Act. These recommendations are developed to assist CDMG in mapping liquefaction hazard zones (LQ-Zones). The zones establish where site-specific geotechnical investigations must be conducted to assess liquefaction potential and, if required, provide a technical basis to mitigate the liquefaction hazard.~~

~~Liquefaction Mapping Criteria~~

~~Liquefaction hazard zones are geographic areas meeting one or more of the following criteria:~~

~~1. Areas known to have experienced liquefaction during historic earthquakes.~~

~~Field studies following past earthquakes indicate liquefaction tends to recur at many sites during successive earthquakes (Youd, 1984). There are many published accounts of liquefaction occurrences and the areas so delineated should be included in the liquefaction hazard zones.~~

~~2. All areas of uncompacted fills containing liquefaction susceptible material that are saturated, nearly saturated, or may be expected to become saturated.~~

~~In some areas there has been a practice of creating usable land by dumping artificial fill on tidal flats or in large deep ravines. Standard geologic criteria are of little use in characterizing soils within these fills, which are less homogeneous than natural deposits. There is no reason to assume lateral stratification in these fills and the validity of extrapolating subsurface data is questionable. Evidence for filling can be found using maps showing old shorelines, comparing old and modern topographic maps, by studying logs of boreholes, and by obtaining reports or original plans of specific projects involving reclaimed land.~~

~~3. Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable.~~

~~The vast majority of liquefaction hazard areas are underlain by recently deposited sand and/or silty sand. These deposits are not randomly distributed, but occur within a narrow range of sedimentary and hydrologic environments. Geologic criteria for assessing these environments are commonly used to delineate bounds of susceptibility zones evaluated from other criteria, such as geotechnical analysis (Youd, 1991). Ground water data should be compiled from well logs and geotechnical boreholes. Analysis of historical aerial photographs may delineate zones of flooding, sediment accumulation, or evidence of historic liquefaction. The Quaternary geology should be mapped and age estimates assigned based on ages reported in the literature, stratigraphic relationships and soil profile descriptions. In many areas of Holocene and Pleistocene deposition, geotechnical and hydrogeologic data are compiled. Geotechnical investigation reports with Standard Penetration Test (SPT) and/or Cone Penetration Test (CPT) and grain size distribution data can be used for liquefaction resistance evaluations.~~

~~For sand and silty sand, there are, at present, two accurate and reliable in-situ approaches available for quantitative evaluation of the soil's resistance to cyclic pore pressure generation and/or liquefaction. These are: (1) correlations and analyses based on in-situ Standard Penetration Test (SPT) (D1586 (ASTM, 1990); D6066-96e1 (ASTM, 1999)) data, and (2) correlations and analyses based on in-situ Cone Penetration Test (CPT) (ASTM D3441 ASTM, 1990) data.~~

~~Seed and others (1984; 1985), Seed and DeAlba (1986), and more recently Youd and Idriss (1997), provide guidelines for performing "standardized" SPT, and also provide correlations for conversion of penetration resistance obtained using most of the common alternate combinations of equipment and procedures in order to develop equivalent "standardized" penetration resistance~~ ~~$(N_1)_{60}$~~~~. This "standardized" penetration resistance can then be used as a basis for evaluation of liquefaction resistance.~~

~~Cone penetration test (CPT) tip resistance (~~~~q_c~~~~) may also be used as a basis for evaluation of liquefaction resistance. This is done either by empirical comparison between~~ ~~q_c~~ ~~data and case histories of seismic performance (Olsen, 1988) or by conversion of~~ ~~q_c~~~~-values to "equivalent" SPT resistance and use of correlations between~~ ~~$(N_1)_{60}$~~ ~~data and case histories of seismic performance (Robertson and Campanella, 1985; Seed and De Alba, 1986; Youd and Idriss, 1997).~~

~~In addition to sandy and silty soils, some gravelly soils are potentially vulnerable to liquefaction. At present, the best available technique for quantitative evaluation of the liquefaction resistance of this type of deposit involves correlation and anlysis based on in-situ penetration resistance measured using the very large scale Becker Hammer system (Harder, 1988; 1997).~~

~~The correlations of Seed and others (1985), as updated in Youd and Idriss (1997), and the~~ ~~$(N_1)_{60}$~~ ~~data can be used to assess liquefaction susceptibility. Since geotechnical analyses are usually made using limited available data, the susceptibly zones should be delineated by use of~~

~~geologic criteria. Geologic cross sections, tied to boreholes and/or trenches, should be constructed for correlation purposes. The units characterized by geotechnical analyses are correlated with surface and subsurface units and extrapolated for the mapping project.~~

~~Liquefaction opportunity is a measure, expressed in probabilistic terms, of the potential for ground shaking strong enough to generate liquefaction. Analyses of in-situ liquefaction resistance require assessment of liquefaction opportunity. The minimum level of seismic excitation to be used for such purposes with LQ-Zones will be that level defined by M7.5-weighted peak ground surface acceleration (PGA) for UBC S2 soil conditions with a 10% probability of exceedance over a 50-year period.~~

~~**4. Areas where existing geotechnical data are insufficient.**~~

~~In areas of limited or no geotechnical data, susceptibility zones may be identified by geologic criteria as follows:~~

~~(a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.10 g and the historic high water table is less than 40 feet below the ground surface; or~~

~~(b) Areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.20 g and the historic high water table is less than or equal to 30 feet below the ground surface; or~~

~~(c) Areas containing soil deposits of latest Pleistocene age (between 11,000 years and 15,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.30 g and the historic high water table is less than or equal to 20 feet below the ground surface.~~

~~The Quaternary geology may be taken from existing maps, where available, and hydrologic data should be compiled. Application of these criteria allows compilation of hazard maps which are useful for preliminary evaluations, general land-use planning and delineation of special studies zones where site-specific studies may be required before major development is approved (Youd, 1991).~~

EARTHQUAKE-INDUCED LANDSLIDE HAZARD ZONES

Introduction

The ~~California~~ Department of Conservation, ~~Division of Mines and Geology~~California Geological Survey (C~~DMG~~GS) is the principal State agency charged with implementation of the provisions of the 1990 Seismic Hazard Mapping Act. These recommendations are developed to assist C~~DMG~~GS in mapping earthquake-induced landslide hazard zones.

Landslide Hazard Zone Criteria

Earthquake-induced landslide hazard zones are areas meeting one or more of the following criteria:

1. Areas known to have experienced earthquake-induced slope failure during historic earthquakes.

It is very difficult, if not impossible, to distinguish earthquake-induced slope failures from landslides triggered by other mechanisms if the latest movement occurred prior to historic observations. Evidence of earthquake triggering for large pre-historic landslides tends to be circumstantial (for example, large dormant landslide complexes are often located near active faults), and the shallow disrupted landslides (debris or soil falls) found to be so common in historic earthquakes are not generally preserved in the geologic record. However, landslides caused by some historic earthquakes in California have been well documented (Lawson, 1908; Morton, 1975; Harp and others, 1984; Spittler and Harp, 1990; Harp and Jibson, 1995). Wherever possible, ~~CDMG~~ CGS should include documented earthquake-triggered landslides within zones of required investigation.

2. Areas identified as having past landslide movement, including both landslide deposits and source areas.

Steep scarps and toe areas of existing landslides often fail in moderate to large earthquakes. The entire mass of existing large rotational landslide deposits is not typically reactivated by earthquake shaking (Keefer, 1984). However, long-duration earthquakes, such as a magnitude 8+ earthquake on the San Andreas fault in southern or northern California, could reactivate existing landslides and result in significant damage to structures. Because of this possibility, existing landslide deposits and their source areas should be identified and included in zones of required investigation.

An inventory of all landslides should be prepared for each hazard zone map area. All existing landslides, including the source (scarp) and deposit, should be mapped and given a level of confidence of interpretation. Landslides identified as “definite” or “probable” should be added to the geologic strength map and should always be included in zones of required investigation. Landslides identified as “questionable”, that is, areas having geomorphic features that may be the result of other causes (e.g., stream terraces) and would require extensive exploration to verify a landslide origin, should be excluded from the earthquake-induced landslide zones.

3. Areas where C~~DMG~~GS’s analyses of geologic and geotechnical data indicate that the geologic materials are susceptible to earthquake-induced slope failure.

The recommended procedure for these analyses is the Newmark method as calibrated by McCrink and Real (1996), described below.

Newmark Method

Currently, the most advanced method for mapping regional earthquake-induced landslide hazards is based on the work of Newmark (1965). Newmark, recognizing the limitations of a factor of safety approach to dynamic slope stability analyses, devised a method of estimating the magnitude of ground displacement caused by a given earthquake ground motion. The U.S. Geological Survey tested Newmark’s method on a landslide triggered by the 1979 Coyote Lake earthquake (Wilson and Keefer, 1983), and pioneered the application of the Newmark analysis for mapping earthquake-induced landslide hazard potential in San Mateo County (Wieczorek and others, 1985).

McCrink and Real (1996) calibrated the San Mateo County mapping methodology using landslides and near-field strong-motion records from the 1989 Loma Prieta earthquake. They also developed specific procedures allowing the method to be run on a geographic information system (GIS). Because of the extensive calibration and validation of this technique, earthquake-induced landslide hazard zones should be based on a Newmark dynamic displacement analysis using the parameters and specific approaches that have been developed and documented by McCrink and Real (1996).

The following paragraphs provide a brief description of the recommended analytical procedure developed in this calibration study.

Assumptions to the model

In order to delineate the earthquake-induced landslide zones on a regional basis, the following assumptions and simplifications are reasonable:

- The failure should be assumed to be an infinite-slope type failure, that is, a relatively shallow failure that has a failure surface parallel to the ground surface.
- Only unsaturated slope conditions should be considered.
- The response of the geologic materials to earthquake shaking, in terms of landslide failure potential, should be characterized by the shear strength properties of the geologic materials.

Shear Strength Properties

In selecting representative shear strength properties to characterize geologic materials, C~~DMG~~GS should use the most appropriate combination of strength parameters available for the hazard map area. The calibration study (McCrink and Real, 1996) indicates that the internal angle of friction (ϕ) alone is adequate for regional mapping of earthquake-induced slope failure potential. Where appropriate, C~~DMG~~GS should identify adverse bedding conditions (out-of-slope bedding) and apply shear strength values representing the weaker materials (such as shale interbeds in a predominantly sandstone formation) of the mapped geologic unit. If geotechnical shear test data are insufficient or lacking for a mapped geologic unit, such a unit should be grouped with lithologically and stratigraphically similar units for which shear strength data are available. Published shear strength values can be used if necessary. The product of the shear strength characterizations should be a geologic material strength map, wherein the areas depicted on the map no longer represent “formations” but areas of similar shear strength.

Slope Stability Calculations

Slope stability calculations using the infinite-slope failure model should consist of first calculating a static factor of safety, followed by a calculation of the yield acceleration from Newmark’s equation:

$$a_y = (FS - 1)g \sin \alpha$$

where a_y is the yield acceleration (the horizontal ground acceleration required to cause the factor of safety to equal 1.0), FS is the **factor of safety** from the static stability analysis, g is the acceleration due to gravity, and α is the direction of movement of the slide mass, in degrees measured from the horizontal, when displacement is initiated (Newmark, 1965). For an infinite-slope failure model, α is the same as the slope angle.

Earthquake Ground Motion

Determination of anticipated earthquake shaking for the hazard map area should be made by selecting a representative strong-motion record or records, based on estimates of probabilistic ground motion parameters for levels of earthquake shaking having a 10 percent probability of being exceeded in 50 years (Petersen and others, 1996; Cramer and Petersen, 1996). The ground motion parameters used in the record selection should include mode magnitude, mode distance, and peak acceleration.

The currently accepted procedure calls for the selected strong-motion record to be integrated twice for a given yield acceleration to find the corresponding Newmark displacement. This process should be repeated for a number of yield accelerations to develop a mathematical relationship between the two parameters. The yield acceleration values calculated in the slope stability analyses should be correlated with Newmark displacements estimated from the strong-motion record to prepare a hazard potential map.

Slope Factors

C~~DMG~~GS should use the most accurate and up-to-date terrain data available to derive slope and aspect maps. Digital terrain data should have a minimum vertical accuracy of 7 meters, and a maximum horizontal resolution of 10 meters. Acceptable sources of terrain data include Level 2 digital elevation models (DEMs) prepared by the U.S. Geological Survey, terrain data derived from interferometric synthetic aperture radar, photogrammetrically produced terrain data, and ground survey data. The selected terrain data sources should meet or exceed the above accuracy and resolution requirements. Slope gradient and slope aspect maps prepared from the digital terrain data should be generated using algorithms most appropriate for the terrain data used.

Earthquake-Induced Landslide Potential

An earthquake-induced landslide potential map should be prepared by combining and comparing (overlay) the geologic-material strength map with a slope gradient map. Hazard potential criteria for the hazard maps should be based on the amount of calculated Newmark displacement and corresponding slope angle for each geologic unit caused by the selected strong-motion record: “Very Low” would correspond to displacements less than 5cm; “Low” potential has displacements of 5cm to less than 15cm; “Moderate” potential has displacements of 15cm to less than 30cm; and “High” potential has displacements of 30cm or greater. On the basis of the calibration study (McCrink and Real, 1996), High, Moderate and Low levels of hazard potential (all areas with calculated displacements greater than 5cm), should be included within the landslide zone of required investigation.

Hazards Not Addressed

Because of the many simplifying assumptions made when applying the Newmark analysis to regional hazard mapping, the current method does not capture all types of ground failures known to occur during earthquakes. Earthquake-generated ground failures that are not addressed by the Newmark method include those associated with ridge-top spreading and shattered ridges. Also, run-out areas of triggered landslides may extend beyond zone boundaries into areas outside the zone of required investigation. The potential for ground failure resulting from liquefaction-induced lateral spreading of alluvial materials, considered by some to be a form of landsliding, should not be specifically addressed by the earthquake-induced landslide hazard zone because such hazards are to be included in the LQ-zones.

Candidate Methods for Future Development

In order to improve the accuracy of the Newmark method in capturing all appropriate landslide-prone areas C~~DMG~~GS should continue to refine the method. From recent earthquakes it is known that ridge-top spreading typically occurs along strike-ridges, and that shattered ridges typically occur along the tops of high, narrow ridges. C~~DMG~~GS should use this knowledge to develop models to assess the potential for these ground failures in the future. Methods to identify rock fall and debris flow runout areas should also be investigated, if deemed adequate, and incorporated into future zone maps.

In addition to improving the current Newmark model, C~~DMG~~GS, in cooperation with USGS, should continue to investigate other analytical methods that might be useful in zoning. It is recommended that CGS investigate the applicability of two analytical methods as possible alternatives to the Newmark model:

1. The Multivariate Method

The multivariate method, described by Carrara and others (1991), uses a multivariate statistical procedure in conjunction with GIS techniques to model landslide hazards. In this method, the morphological, geological and vegetation characteristics for slopes are analyzed using a stepwise discriminant analysis, rating the characteristics in terms of their ability to discriminate between stable and unstable slopes. The method does not specifically address triggering mechanisms such as earthquakes or rainfall, but holds the potential to identify susceptible areas on the basis of past performance of the terrain and other characteristics.

2. The Probabilistic Slope Stability Method

The probabilistic slope stability method provides a systematic and quantitative way to deal with the uncertainties associated with soil and rock spatial variability, geotechnical sampling and testing, terrain models, and earthquake shaking. Vanmarcke (1976; 1980) has considered the basic 3-dimensional stability problem in a probabilistic framework for man-made embankments and natural slopes. The probabilistic approach has the advantage of being able to address the spatial variability of strength parameters and ground-water conditions, and may allow for the easy integration of probabilistic ground motion estimates. The USGS is evaluating a form of probabilistic earthquake slope stability in southern California using a Newmark displacement model and ground motion characterized by Arias intensity (Jibson and others, 1998).

The multivariate and probabilistic methods, used in full or in part, may prove suitable as possible alternative approaches to earthquake-induced landslide hazard mapping. These methods are not currently well developed for regional mapping purposes, and calibration studies will need to be conducted. However, some or all of the procedures could be applied to more accurately and cost-effectively delineate earthquake-induced landslide hazard zones.

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