SEISMIC RISK CONSIDERATIONS FOR TRANSPORTATION SYSTEMS

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ABSTRACT

During the recent Loma Prieta Earthquake, major damage to certain key transportation elements greatly affected operations of major transportation systems within the San Francisco Bay Area. This experience has underscored the need to utilize seismic risk analysis concepts to optimize the planning and implementation of seismic risk reduction measures for transportation systems. Accordingly, this paper summarizes how seismic risk analysis can be applied to transportation system networks, and discusses the potential benefits of such analysis applications.

BACKGROUND

One of the most significant aspects of the Loma Prieta Earthquake of October 17, 1989 (Magnitude 7.1) was its severe impact on the transportation system of a major metropolitan area. Direct damage costs to the transportation system in the region of strong shaking totalled $1.8 billion, of which damage to state-owned viaducts totalled $200 million and damage to other state-owned bridges totalled $100 million (SCOPR, 1990). Indirect losses (i.e., costs associated with lost time and business productivity in the affected areas) have

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been estimated to be several times larger than these direct dollar loss levels. A significant portion of these damage costs occurred in the San Francisco-Oakland area and was associated with collapse of a 1.25-mile segment of the Cypress Street Viaduct along the Nimitz Freeway in Oakland, collapse of a single span of the Bay Bridge, and severe damage and prolonged closure of six elevated viaducts along major freeways in San Francisco. Travel between the East Bay area and San Francisco was severely hampered during the 6-week time period required to replace the collapsed span of the Bay Bridge. During this time, the Bay Area Rapid Transit (BART) system and emergency trans-bay ferry service provided the only direct transportation links between San Francisco and the Oakland section of the East Bay area. The San Mateo Bridge -- another major trans-bay transportation link to the south -- also sustained damage during the Loma Prieta Earthquake (failed steel rocker bearings) which could have been much more severe if the shaking had been longer or stronger.

The above experience from the Loma Prieta Earthquake has demonstrated how damage to a few major links within an extended transportation system can cause significant disruption of the overall system. This clearly underscores the importance of identifying critical links within such systems that may be particularly vulnerable to seismic effects, in order to prioritize the implementation of seismic risk reduction measures for the system. System-wide seismic risk analysis (SRA) procedures can perform this important function. Although not yet widely applied to transportation systems, such SRA procedures have been used to guide seismic risk reduction planning for a variety of utility lifeline systems. For example, network seismic risk analyses have been applied to culinary water, sewage, electric power, and natural gas systems for a variety of purposes including financial planning, assessments of system reliability and seismic risk reduction alternatives, and development of government public policy recommendations (e.g., Khater et al., 1988; Ostrom and Gould, 1966; McDonough, 1990; Dames & Moore, 1988; Taylor et al., 1988a). In addition, two committees of the ASCE Technical Council of Lifeline Earthquake Engineering (TCLEE) -- The Seismic Risk and Water and Sewage Committees -- are completing a four-year effort to demonstrate how losses may be estimated for a hypothetical water system (Moghtaderi-Zadeh, 1990; Taylor et al., 1988b). Another demonstration project on seismic risk analysis -- for a highway transportation system -- has been initiated by the Transportation and Seismic Risk Committees of TCLEE.

OBJECTIVE AND SCOPE OF PAPER

With this as background, the objective of this paper is to describe how SRAs of transportation systems can be implemented and interpreted. To accomplish this objective, the remainder of this paper is organized into two main sections. The first of these sections describes the basic SRA methodology and concepts, and how they may be applied to transportation systems. In this description, particular emphasis is placed on basic considerations associated with the development of vulnerability models for selected transportation system components. The final section of the paper discusses potential benefits of the application of system-wide SRA's to transportation systems.

SEISMIC RISK ANALYSIS METHODOLOGY

The basic SRA methodology consists of the four steps shown in Figure 1. The application of each of these steps to transportation systems is described in the paragraphs that follow.

Definition of System Exposure

The definition of key characteristics and potential seismic exposure of the overall transportation system and its elements are defined under this first step in the SRA methodology. This includes:

- Location -- mapping of key facilities and routes.

- Replacement Costs -- estimation of potential costs associated with replacement of critical elements of the transportation system.

- Regional Hazard Characteristics -- review of geologic and seismologic data to estimate potential earthquake activity within the region that may damage system components.

- Local Hazard Characteristics -- review of geologic and geotechnical engineering reports for the system and its elements. This review should be used to identify system components that: (1) may undergo surface fault displacement; (2) may be subject to strong shaking due to their close proximity to active faults and/or the presence of soft underlying soils; (3) may be prone to liquefaction or landslides; or (4) may be prone to flooding from a tsunami, from a seiche, or from damage to nearby dams or levees.

- Vulnerability Characteristics -- review of structural drawings, calculations, and reports together with inspection and maintenance records for the transportation system elements. This review should be directed toward identifying any characteristics of the geometry, the structural design, and the current condition of these elements that may increase their potential vulnerability to earthquake hazards.

- Traffic Conditions -- review of traffic data for the transportation system. This review should be used to identify critical traffic links within the system, as well as potential alternative links that may be used in the event of seismic damage to the critical links. For economic analysis of secondary losses, marginal costs of earthquake damage to a transportation system (in terms of lost time or productivity) must consider such factors as traffic volume and the length and capacity of each transportation link, as a function of the time of day and available alternative routes.

Identification of Hazards

The potential seismic hazards along a transportation system route include ground shaking, geologic hazards (surface fault rupture, liquefaction, landslide, settlement, etc.), and hydrologic hazards (seiche, tsunami, or flooding from damage to dams or levees in the area). When defining these seismic hazards for use in a system-wide seismic risk analysis, it is particularly important to account for the fact that each possible earthquake will cause a variety of different hazards along the extent of the transportation system network. Consideration of these correlated earthquake effects can be accomplished by developing earthquake scenarios using probabilistic methods that incorporate the seismotectonic characteristics of the region.

Ground Shaking -- The most widespread and potentially important hazard to a transportation system is earthquake ground shaking. The representation of potential system-wide ground shaking hazards through the above-indicated earthquake scenarios should incorporate effects of attenuation of the seismic waves with increasing distance from the earthquake source, and potential effects of seismic wave amplification due to local soil conditions.

Geologic Hazards -- Regions within the system network that may be susceptible to earthquake-induced geologic hazards can be identified by developing geologic hazard susceptibility maps for the system. Such maps are established from geologic data for the region and from geotechnical engineering reports for sites along the transportation system routes. Surface fault rupture commonly occurs in regions of shallow-focus earthquakes and, in such regions (e.g., California), the potential amount of movement along a fault can be estimated from empirical correlations with earthquake magnitude (e.g., Slemmons, 1982) or from dating of prehistoric fault movements (e.g., Sieh and Jahns, 1984). Zones of earthquake-induced liquefaction, landslide, settlement, etc., can be established through evaluation of subsurface soil and topographic conditions along the system routes.

Hydrologic Hazards -- Zones along the transportation system network that may be susceptible to earthquake-induced flooding from a tsunami, from a seiche, or from failure of dams or levees can also be mapped along the system routes. In California, tsunami maps for coastal regions have been established (e.g., Houston and Garcia, 1974). The potential for flooding from a seiche is greatest near relatively low shorelines of reservoirs or lakes. Inundation maps are available for major dam structures, and can be used to assess whether any segment of the transportation system is in a potential inundation zone that would result from damage to the dam.

Development of Component Vulnerabilities

The third element of a system-wide SRA consists of the development of a component vulnerability model for each major component of the transportation system. Component vulnerability models take the form of plots relating loss[3] to the magnitude of each potential seismic hazard that could be applied to the component (e.g., intensity of ground shaking, magnitude of fault displacement, magnitude of soil movement due to liquefaction or sliding, etc.). Such models may be developed from assessment of: (1) empirical data describing the performance of each type of component during past earthquakes; (2) past experimental investigations of the behavior of the component and/or its elements (e.g., bridge piers, cable restrainers across expansion joints, etc.); or (3) for major components, analytical investigations of the component's seismic response. Some considerations in the development of component vulnerability models for selected transportation system elements are outlined below.

Bridges and Elevated Viaducts -- Bridges and elevated viaducts may be prone to damage from ground motions and from ground movement due to earthquake-induced geologic hazards. Ground motions can lead to inertia forces from structural accelerations and to deformations of structural elements (e.g., drift in multi-level elevated viaducts). Geologic hazards can lead to severe structural deformations (e.g., from fault rupture, soil movement due to liquefaction and/or sliding of subsurface or abutment soils, etc.). Factors to consider in the development of component vulnerability models for bridges and elevated viaduct structures include: (1) the age of the structure; (2) the bridge type and materials of construction; (3) the design code and seismic design provisions used for the structure; (4) details of construction (e.g., beam-column connections, reinforcing details for concrete bridges, etc.); (5) the length of the structure, including its resulting flexibility and potential effects of traveling seismic waves; (6) the geometry of the structure (e.g., its curvature, skew, etc. and their potential effects on structural response); (7) subsurface soil conditions beneath the bridge and at its abutments; (8) foundation and abutment types; (9) current state of repair; and (10) the extent of any seismic retrofit measures that may have been incorporated into the bridge or viaduct.

Roadways and Railroads -- Paved roadway elements are key components of transportation systems for on-land travel (e.g., highways and streets), air travel (airport

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[3]In this, loss is often expressed as a percentage of the total replacement value of the component.

runways), and water travel (seaport access roads and open paved storage areas in ports). These roadway elements and railroad line components are susceptible to potential damage from earthquake-induced geologic hazards (i.e., surface fault rupture, settlement, soil movement from liquefaction of underlying soil materials, landslides, etc.) or hydrologic hazards (flooding from upstream dam or nearby levee damage, tsunami, seiche, etc). The susceptibility of such components to damage from these sources will depend to some extent on their age and current state of repair, and their materials of construction.

Underground Structures -- Key underground transportation system components include tunnels (for roadways and mass-transit subways) and subway station structures. These underground components are usually sufficiently flexible to enable them to deform with the surrounding soil or rock medium, (except at certain "hard points" where soil- or rock-structure interaction effects can be significant).[4] Therefore, the seismic response of these underground structures is most sensitive to the earthquake-induced deformations of the adjacent geologic medium, and the potential for significant movement of this medium due to fault rupture, liquefaction, sliding, etc. With this as background, factors to consider in the development of vulnerability models for these underground structures include: (1) the age and state of repair of the structure; (2) the seismic design procedures that were incorporated into their design; (3) the methods of construction (e.g., alternative cut-and-cover or tunnelling methods); (4) the configuration and geometry of the structure (i.e., its cross section, any sloping of the tunnel, tunnel intersections, points of curvature, etc. that exist along the length of the structure); (5) the materials of construction and the stiffness characteristics of structural liners and walls; (6) the nature of the surrounding soil or rock medium and their potential for significant movement during earthquakes; (7) any significant geologic discontinuities along the length of the tunnel; (8) the proximity of the underground structures to any major aboveground buildings or to adjacent underground structures for which through-soil coupling effects may influence their seismic

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[4]For example, hard points in underground subway systems may include end walls along station-tunnel junctions, station entrance structures, and tunnel intersections.

response; (9) the presence of any special flexible joints or other measures to accommodate deformation and localize damage at fault crossings; and (10) the depth of the structure below the ground surface.

Retaining Structures -- Retaining structures may be key elements of a variety of transportation systems including roadways or rail lines (wall elements at cut or fill sections) and seaports (dikes, bulkheads, etc.). The seismic performance and corresponding vulnerability modeling of a retaining structure depends primarily on the earthquake-induced deformations of the adjacent backfill, the stiffness, strength, and stability characteristics of these fills and the underlying soil materials, the lateral pressures applied to the structure through the backfill (including potential increases of these pressures due to pore water pressure buildup), and the retaining structure's configuration, mass, and stiffness characteristics.

Critical Buildings -- Buildings that are key elements of transportation systems include airport control towers and passenger terminals; central operation centers for urban mass transit systems, special port operations, or highway systems; and fire stations for major airports or seaports. Because such buildings must remain functional after a major earthquake, their seismic design provisions should be (but often are not) more stringent than those represented by current building codes -- which are intended to prevent collapse and loss of life after a major earthquake, but not necessarily to prevent major damage and loss of function. Factors to consider in developing vulnerability models for critical buildings include: (1) the age of the building and its corresponding seismic design and detailing procedures; (2) the building's materials of construction; (3) the nature of the lateral force resisting system for the building, whether it has sufficient ductility and strength, and whether it provides a continuous path for transmitting the building's lateral inertia forces from their points of application down to the foundation; (4) the extent of any horizontal or vertical irregularities in the building configuration; (5) the building's current condition and state of repair; (6) the building's foundation type and subsurface soil conditions; and (7) whether any special seismic retrofit measures have been incorporated into the building since its original design.

Calculation of Losses

The final step in the seismic risk analysis of a transportation system consists of the calculation of expected losses to each facility within the system network. These expected losses, which incorporate the correlated earthquake effects discussed earlier, can be exhibited probabilistically as illustrated in Figure 2 (e.g., Ballantyne, et al., 1990). Through consideration of the various loss levels and their estimated frequencies of occurrence, expected annual primary and/or secondary losses can be estimated. In addition, expected losses at specific selected probability levels can be estimated, and have been denoted by a variety of terms such as "maximum foreseeable loss" or "probable maximum loss."

Methods for loss calculation that account for correlated earthquake effects have been applied to a variety of utility lifeline systems (e.g., Taylor et al., 1988). For transportation systems, methodological developments at Carnegie-Mellon University have made it possible to see how such loss estimates, both primary and secondary, could be made for selected freeway systems (Oppenheim, 1979). However, further development of such methodologies for seismic risk analysis of transportation systems has been limited in recent years. The recently initiated TCLEE demonstration project for seismic risk analysis of a highway transportation system promises to renew these past methodological developments.

BENEFITS

The application of the foregoing SRA methodology to transportation systems can provide a variety of significant benefits. For example, they can be applied to a range of different transportation system configurations including the original system (with no seismic modification or strengthening) as well as modified systems (with various seismically strengthened components, alternative and/or redundant routes, etc). For each system configuration, SRAs will compute earthquake-induced dollar losses which, in turn, can be used by engineers, planners, and administrators for a variety of purposes including:

- identification of weak links in the system, and assessment of alternative strategies for seismically enhancing or strengthening these links and the overall system.

- justification of major expenditures for seismic enhancement and strengthening of the system.
- development of emergency response strategies.
- assessment of alternative routes for future expansion of the transportation system.
- evaluation of earthquake insurance needs for the system.
- assessment of whether the redundancy of the transportation system is adequate to accommodate post-earthquake response and recovery needs of the community served by the system.
- development of recommendations for state and federal public policy directions.

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