DEVELOPMENT OF HIGHWAY BRIDGE SEISMIC DESIGN CRITERIA FOR THE UNITED STATES

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SUMMARY

There has been a tendency in most parts of the United States to view earthquakes as primarily a California problem. However, more than 70 million people are subject to moderate or major earthquake risk. The paper presents preliminary criteria for the seismic design of highway bridges. The work was performed by Applied Technology Council (ATC) under contract with the Federal Highway Administration. The criteria have been developed by a Project Engineering Panel which was assembled by ATC and consists of university researchers, private practice consultants, and state highway representatives. A number of redesigns will be performed to determine the viability and economic impact of the preliminary criteria. The results of these designs will be incorporated as appropriate and the final provisions will be completed in mid-1980.

INTRODUCTION

Highway bridges are a vital part of the lifeline system in the United States. Portions of 39 states are subject to moderate or major earthquake risk. The development of seismic design guidelines for highway bridges and a summary of the preliminary guidelines are presented in the following text.

The 1971 San Fernando earthquake presented a major turning point in the development of seismic design criteria for bridges in the United States. Prior to 1971 the American Association of State Highway Transportation Officials (AASHTO) specifications for the seismic design of bridges were based in part of the lateral force requirements for buildings developed by the Structural Engineers Association of California. In 1973 the California Department of Transportation (CalTrans) introduced a new seismic design criteria for bridges that included the relationship of the site to active faults, the seismic response of the soil at the site, and the dynamic response characteristics of the bridge. In 1975 AASHTO adopted Interim Specifications which were a slightly modified version of the 1973 CalTrans provisions and made them applicable to all regions of the United States. In addition to these code changes the 1971 San Fernando earthquake also stimulated research activity on the seismic problems related to bridges. By 1977 the Federal Highway Administration (FHWA) felt it appropriate that an assessment be made of the 1971 AASHTO Interim Specifications and in June 1977 FHWA contracted with Applied Technology Council to:

- Evaluate current criteria used for seismic design of highway bridges.
- Review recent seismic research findings for design potential and use in new specifications.

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- Develop recommended new and improved seismic design guidelines for highway bridges.
- Evaluate the impact of these criteria and modify them as appropriate.

The status of the work is discussed and the preliminary guidelines are summarized in the following text. The Project Engineering Panel members listed in the acknowledgements should be considered co-authors of this paper. Unfortunately space does not permit listing them in the front of the paper.

PROJECT ORGANIZATION

The objectives of the work were to evaluate existing seismic design criteria and procedures for bridges and, using the latest research findings, develop comprehensive seismic design guidelines applicable to all regions of the United States with particular emphasis given to seismic risk. The guidelines are to consider life safety, protection of property and preservation of essential functions.

It was considered essential in the development of nationally applicable guidelines that representative segments of the bridge design and construction profession be involved. To ensure representative input and adequate consideration of the many factors involved, a Project Engineering Panel (PEP) was assembled composed of four AASHTO representatives, four representatives of design firms, three university researchers, two FHWA representatives, an ATC Board of Directors representative, and two ATC staff members.

BASIC CONCEPTS

Development of the design guidelines has been predicated on certain basic concepts including the following:

- Hazard to life be minimized.
- Bridges may suffer damage but have low probability of collapse due to earthquake motions.
- Function of essential bridges be maintained.
- Design ground motions have low probability of being exceeded during normal lifetime of bridge.
- Provisions be applicable to all of the United States.
- Ingenuity of design not be restricted.

APPLICABILITY OF GUIDELINES TO UNITED STATES

A basic premise in developing the bridge seismic design guidelines was that they be applicable to all parts of the United States. The seismic risk varies from very small to rather high across the country and the country was divided into seven areas of varying seismic risk. The Seismicity Index maps were prepared as part of another ATC project[1] and the coefficients corresponding to the map areas are given in Table 1. The seven map areas can best be shown in color and will be so included in the actual guidelines; reproduction of the color map was not feasible for this paper. For purposes of design, provisions were developed for four seismic performance categories to which bridges would be assigned based on the map area in which the site is located and the importance classification (IC). See Tables 1 and 2.

Differing degrees of complexity and sophistication of seismic analysis and design are specified for each Seismic Performance Category (SPC). SPC D Bridges include those designed for the highest level of seismic performance with particular attention to methods of analysis, design and quality assurance. SPC A bridges include those where no seismic analysis is required, but attention to certain design details for the superstructure is provided.

SEISMIC GROUND MOTION INTENSITIES

The selection of ground motion intensities to be used with the seismic design provisions was carefully reviewed. Fortunately, considerable study and effort have recently been made to develop seismic risk maps for the "Tentative Provisions for the Development of Seismic Regulations for Buildings", (ATC-3-06)[1]. The ATC-3-06 maps are based on (1) a realistic appraisal of expected ground motion intensities, (2) the probability of the design ground shaking being exceeded is approximately the same in all parts of the United States, and (3) the frequency of occurrence of earthquakes in various regions of the country. It is possible that the design earthquake ground shaking might be exceeded, although the probability of this happening is quite small.

SUPPORTING SOIL EFFECTS

It is generally recognized that the effects of local soil conditions on ground motion characteristics should be considered in structural design. Three fundamentally different approaches have been used in recent United States design provisions. One approach is based on the concept of potential resonance of a structure with the underlying soil. In the SEAOC requirements[2] the seismic site-structure resonance coefficient varies from 1.0 to 1.5 depending on the ratio of the fundamental building period to the characteristic site period.

In a second approach, CalTrans used the computer program SHAKE[3] to develop the soil amplification factor for the design criteria. For the third approach (ATC-3-06)[1], representative spectral shapes were modified to determine corresponding values of effective peak ground acceleration for three typical site conditions. These modifications were based on a study of ground motions recorded at locations with different site conditions and the exercise of experienced judgement in extrapolating these beyond the data base.

The ATC-3-06 approach for considering soil effects was used in this study.

DESIGN PHILOSOPHY

The primary basis for development of the seismic design guidelines for bridges is to minimize the hazard to life and provide the capability for bridges to survive during and after an earthquake with essential bridges to remain functional. To meet the above philsophy, certain principles were followed:

(1) Small to moderate earthquakes should be resisted within the elastic range of the structural components without damage.
(2) Realistic seismic ground motion intensities should be used in the design procedure.
(3) Exposure to shaking from large earthquakes should not cause collapse of part or all of the bridge. Damage that does occur should be readily detectable and accessible for inspection and repair.

Conceptually there are two different approaches currently in use to satisfy the above principles. These are the New Zealand and CalTrans approaches and are discussed in detail in references 3 and 4. In the New Zealand Code the bridge is designed elastically so that it can resist small to moderate earthquakes in the elastic range without damage. The New Zealand Code accepts the philosophy that it is uneconomic to design a bridge elastically against a large earthquake. For large earthquakes in the design of ductile bridges the philosophy is that, where possible, flexural plastic hinging in the columns is acceptable but significant damage to the foundation and other joints is not.

In the CalTrans approach the base shear and member forces are determined from an elastic design response spectra for a maximum credible earthquake. The design forces for each component of the bridge are then obtained by dividing these elastic forces by a Z factor. For hinge restrainers and shear keys, the Z factor is 1.0 and 0.8 respectively. These are therefore designed for the expected and greater-than-expected (in the case of shear keys) elastic forces resulting from a large earthquake. Well-confined ductile columns are designed for lower forces than expected from an elastic analysis as Z varies from 8 to 4. This assumes that the columns can deform plastically when the seismic forces exceed these lowered design forces. The end result is similar to the New Zealand approach although the procedures are quite different.

In assessing bridge failures of past earthquakes in Alaska, California, and Japan, many of the loss-of-span type failures are attributable in part to relative displacement effects. Relative displacements arise from out-of-phase motion of different parts of a bridge, from lateral displacement and/or rotation of the foundations and differential displacements of abutments. Therefore, in developing the draft guidelines the design displacements were considered to be just as important as design forces and, for SPC D bridges, requirements for ties between noncontinuous segments of a bridge are specified in addition to minimum support lengths at abutments, columns and hinge seats.

The methodology used in the draft guidelines is in part a combination of the CalTrans and New Zealand "force design" approaches but it also addresses the relative displacement problem. The methodology varies in complexity as the SPC increases from A to D. Three additional concepts are included in the draft guidelines that are not included in either the CalTrans or New Zealand approach. First, minimum requirements are specified for support lengths of girders at abutments, columns and hinge seats to account for some of the important relative displacement effects that cannot be calculated by current state-of-the-art methods. A somewhat similar requirement is included in the latest Japanese bridge code. Second, member design forces are calculated to account for the directional uncertainty of earthquake motions and the simultaneous occurrence of earthquake forces in two perpendicular horizontal directions. Third, design requirements and forces for foundations are intended to minimize damage because foundation damage that does occur will not be readily detectable.

PRELIMINARY GUIDELINES

The preliminary guidelines have been used to redesign twenty-two different bridges and will be finalized in mid-1980. A summary of some of the more important aspects follows:

Design Procedure

The first step in the design procedure is to determine the effective peak acceleration coefficient A_a and the effective peak velocity-related coeffcient A_v for the bridge site from Table 1. The site coefficient, S, is determined from the soil profile, Table 4.

The second step is to establish the importance classification (IC) and the Seismic Performance Category (SPC) for the bridge. The SPC is a function of the bridge site map area and the importance classification of the bridge as discussed previously and shown in Table 2. Selection of the SPC governs the complexitiy of the analysis procedures and design requirements that follow.

The third step in the design procedure is to select the required method of analysis which is a function of the SPC and the number of spans of the bridge. Next determine the elastic component forces and displacements using the required analysis procedure and the elastic design spectra or coefficient. The design forces for the components are obtained by dividing the elastic forces obtained by the appropriate component response modification factor R given in Table 3.

The displacements used in the design are those obtained either from the elastic analysis or the minimum support length requirement, whichever is greater. The bridge components are then designed for these design forces in combination with other prescribed dead and live loads. Special provisions are included for reinforced concrete column design for SPC C and D to ensure that the columns have reasonable ductility capacity.

The design of the foundations is performed with the lesser of the elastic forces obtained from the elastic analysis or the forces generated by the plastic mechanism of the column or bent.

Response Modification Factors

Response modification factors R are used to modify the component forces obtained from the elastic analysis. The values currently being considered are given in Table 3. Because considerable judgement is required in determining these values, they will be varied in the redesign phase of the project to determine their effect on the design of the various components.

Minimum Support Lengths

The length of support provided at abutments, piers and hinge seats has to accommodate displacements resulting from the overall inelastic response of the bridge structure, possible independent movement of the abutments, displacements resulting from out-of-phase motion of different parts of the substructure, and out-of-phase rotation of abutments and piers resulting from travelling surface wave motions.

In summary, the current state-of-the-art precludes a designer from making a reasonable estimate of the displacements to be expected when a bridge is subjected to an earthquake. As a result, the PEP believed it was necessary to specify minimum support lengths at the abutments, piers and hinge seats to account for the effects discussed above. Obviously a considerable amount of judgement is required and the proposed criteria will be subject to substantial refinement as the state-of-the-art progresses. In addition to these minimum requirements, consideration is being given to the use of the displacements resulting from the elastic analysis if these exceed the specified minimum.

Design Requirements for Reinforced Concrete Columns

A basic feature of the design philosophy and procedure is the capability of columns to respond to intense earthquake motions in a ductile manner. For small to moderate earthquakes the bridge is designed to respond elastically.

Compared to buildings, only a small amount of research has been performed on large bridge pier-type columns. Most of the experimental work performed has been done at the University of Canterbury in New Zealand.[4] The New Zealand Ministry of Works Design Brief[4] incorporates a slightly conservative methodology for estimating the ductility capacity of columns.

After carefully reviewing the New Zealand and SEAOC[2] approaches to column ductility capacity, the PEP decided to adopt the SEAOC approach used for buildings whereby design requirements are specified to ensure adequate ductility capacity. An estimate of the ductility provided is not required in the design process.

CONCLUSIONS

There has been a tendency in most parts of the U.S. to view earthquakes as primarily a California problem. However, more than 70 million people are subject to moderate or major earthquake risk. Therefore the need is evident for seismic design provisions for bridges that are applicable in all regions of the United States.

Review of the procedures in other countries have indicated a general similarity in the approadh to seismic design of bridges. However, the seismic design of bridges is relatively new and there are a number of areas where considerable additional work and study are needed.

The guidelines are being tested by making a number of comparative designs using the preliminary criteria. The results of these designs will be incorporated into the final guidelines as appropriate and the project will be completed in mid-1980.

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REFERENCES

1. Applied Technology Council, "Tentative Provisions for the Development of Seismic Regulations for Buildings", prepared for the National Bureau of Standards, ATC-3-06, Applied Technology Council, Palo Alto, California, June 1978.

2. "Recommended Lateral Force Requirements and Commentary", Structural Engineers Association of California, 1975 Edition.

3. Gates, J. H., "Factors Considered in the Development of the California Seismic Design Criteria for Bridges," Workshop on Earthquake Resistance of Highway Bridges, Applied Technology Council, Palo Alto, California January 1979.

4. Chapman, H., "An Overview of the State of Practice in Earthquake Resistant Design of Bridges in New Zealand," Workshop on Earthquake Resistance of Highway Bridges, Applied Technology Council, Palo Alto, California, January 1979.

TABLE 1
DETERMINATION OF COEFFICIENTS
A_a AND A_v

Map Area Number	Coefficient A_a	Coefficient A_v
7	0.40	0.40
6	0.30	0.30
5	0.20	0.20
4	0.15	0.15
3	0.10	0.10
2	0.05	0.05
1	0.05	0.05

TABLE 2
SEISMIC PERFORMANCE CATEGORY

A_v	Importance Classification II	I
>0.29	D	C
0.20–0.29	C	C
0.11–0.19	C	B
0.06–0.10	B	A
≤0.05	A	A

TABLE 3
RESPONSE MODIFICATIONS FACTORS

		Connection to/at		
	Columns or Piers	Abutments	Columns	Expansion Joints
Wall-type piers	2	0.8	1.0	0.8
Single columns	4	0.8	1.0	0.8
Multiple column bents	6	0.8	1.0	0.8

TABLE 4
SOIL PROFILE COEFFICIENT

	Soil Profile Type		
	S_1	S_2	S_3
S	1.0	1.2	1.5