



American Railway Engineering and
Maintenance-of-Way Association

CHAPTER 9

SEISMIC DESIGN FOR RAILWAY STRUCTURES¹

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¹ The material in this and other chapters in the AREMA Manual for Railway Engineering is published as recommended practice to railroads and others concerned with the engineering, design and construction of railroad fixed properties (except signals and communications), and allied services and facilities. For the purpose of this Manual, RECOMMENDED PRACTICE is defined as a material, device, design, plan, specification, principle or practice recommended to the railways for use as required, either exactly as presented or with such modifications as may be necessary or desirable to meet the needs of individual railways, but in either event, with a view to promoting efficiency and economy in the location, construction, operation or maintenance of railways. It is not intended to imply that other practices may not be equally acceptable.

INTRODUCTION

The Chapters of the AREMA Manual are divided into numbered Parts, each comprised of related documents (specifications, recommended practices, plans, etc.). Individual Parts are divided into Sections by centered headings set in capital letters and identified by a Section number. These Sections are subdivided into articles designated by numbered side headings.

Page Numbers – In the page numbering of the Manual (9-2-1, for example) the first numeral designates the Chapter number, the second denotes the Part number in the Chapter, and the third numeral designates the page number in the Part. Thus, 9-2-1 means Chapter 9, Part 2, page 1.

In the Glossary and References, the Part number is replaced by either a “G” for Glossary or “R” for References.

Document Dates – The bold type date (Document Date) at the beginning of each document (Part) applies to the document as a whole and designates the year in which revisions were last made somewhere in the document, unless an attached footnote indicates that the document was adopted, reapproved, or rewritten in that year.

Article Dates – Each Article shows the date (in parenthesis) of the last time that Article was modified.

Revision Marks – All current year revisions (changes and additions) which have been incorporated into the document are identified by a vertical line along the outside margin of the page, directly beside the modified information.

Proceedings Footnote – The Proceedings footnote on the first page of each document gives references to all Association action with respect to the document.

Annual Updates – New manuals, as well as revision sets, will be printed and issued yearly.





American Railway Engineering and
Maintenance-of-Way Association



Part 1

Seismic Design for Railway Structures¹

— 2007 —

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¹ References, Vol. 94, 1994, p.110; Vol. 96, p. 64, Vol. 97, p. 113.

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SECTION 1.1 INTRODUCTION (2004)



The railroad industry is vitally interested in maintaining reliability in its infrastructure to assure safety for its employees, passengers, customers' goods and the public at large.



These guidelines have been developed specifically for Railroad facilities to help reduce damage from earthquakes. While many structures, such as culverts, retaining walls and buildings, may not be substantially different because of use on railroads, North America's railroad bridges are functionally and behaviorally different from highway and other types of bridges.



This document provides a framework of considerations and methodologies for seismic design of new bridges, roadbed and other railroad facilities. This document also addresses retrofit and post-seismic event response and inspection considerations.



Railroad bridges historically have performed well in seismic events with little or no damage. Contributing to this ability are several factors, unique to railroad bridges, which are consistent throughout North America. First, bridges are traversed by track structure that functions as a restraint against longitudinal and lateral movement during earthquakes. Second, configurations of railroad bridges typically differ from other types of bridges. Third, the controlled operating environment permits different seismic performance requirements for railroad bridges compared to highway bridges.



SECTION 1.2 POST-SEISMIC EVENT OPERATION GUIDELINES

1.2.1 GENERAL (2001) R(2006)

The responses of track and structures to seismic events vary greatly with respect to each other and to the various types of construction, geotechnical conditions and other seismic parameters such as importance and risk factors, structural importance and value, etc.

1.2.2 GUIDELINES (2001) R(2006)

Unless more appropriate guidelines have been developed as a result of experience with significant earthquakes in the affected area and/or consideration of other local conditions, the following are recommended:

1.2.2.1 Operations¹

After an earthquake is reported to the Railroad, Train Dispatcher shall notify all trains and engines within a 100 mile radius of the reporting area to run at restricted speed until magnitude and epicenter have been determined by proper authority. Inspection of track, structures, signal and communication systems shall be initiated. Upon determination of the magnitude and epicenter, the following response levels will govern operations within the specified radius from the epicenter:

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

Table 9-1-1. Specified Response Radii

Earthquake (Richter)	Response Level	California and Baja California	Remainder of North America
0.0 - 4.99	I		
5.0 - 5.99	II	50 miles (80 km)	100 miles (160 km)
6.0 - 6.99	III II	100 miles (160 km) 150 miles (240 km)	200 miles (320 km) 300 miles (480 km)
7.0 or greater	III II	As directed, but not less than for 6.0 - 6.99. As directed, but not less than for 6.0 - 6.99.	

1.2.2.2 Response Levels

- I Resume maximum operating speed. The need for the continuation of inspections will be determined by proper Maintenance of Way authority.
- II All trains and engines will run at restricted speed within a specified radius of the epicenter until inspections have been made and appropriate speeds established by proper authority.
- III All trains and engines within the specified radius of the epicenter must stop and may not proceed until proper inspections have been performed and appropriate speed restrictions established by proper authority. For earthquakes of 7.0 (Richter) or greater, operations shall be as directed by proper authority, but the radius shall not be less than that specified for earthquakes between 6.0 and 6.99.

The associated damage philosophy with respect to the above operating procedures can be correlated with the damage criterion shown in [Table 9-1-2](#).

Table 9-1-2. Damage Criterion

Response Level	Ground Motion Level	Expected Damage to Track, Structure, Signal and Communications
I	0	Very low probability of damage or speed restrictions.
II	1	Moderate damage which may require temporary speed restrictions.
III	2	Heavy damage which can be economically repaired. Track or structures may be out of service for a short period of time.
III	3	Severe damage or failure requiring new construction or major rehabilitation. Track or structures may be out of service for an indefinite period of time.

The post-seismic event response will be affected by the individual Railroad's operating requirements based in part on the risk factor, return periods, required factor of safety, structural occupancy, signal and communication systems and appurtenances such as highways, building types and waterways.

1.2.2.3 Post Earthquake Inspection

Inspection procedures and modifications of facilities to expedite the inspection process should be established before the seismic event. The following list provides a general guideline that may be used for developing an inspection procedure:

1.2.2.3.1 Track and Roadbed

Line, surface and cross level irregularities caused by embankment slides or liquefaction, track buckling or pull aparts due to soil movement, offset across fault rupture, etc.

Disturbed ballast

Cracks or slope failures in embankments

Slides and/or potential slides in cuts, including loose rocks that could fall in an aftershock

Scour due to tsunami in coastal areas

Potential for scour or ponding against embankment due to changes in water courses

1.2.2.3.2 Drainage

Blockage of cut ditches or other changes in drainage patterns. (While these conditions will not usually prevent restoration of service, they will require correction.)

1.2.2.3.3 Bridges

NOTE: Following an earthquake, inspectors may need to travel by rail between bridges. The time required for bridge inspection will be critical and normally dry stream beds may be flooded when inspection is required. Therefore, provisions should be made beforehand to permit quick access to bearing areas and other critical points from the track rather than from the ground.

a. Steel

Displaced or damaged bearings

Stretched or broken anchor bolts

Distress in viaduct towers

Buckled columns or bracing

Tension distress in main members or bracing

Displaced substructure elements

b. Concrete

Displacement at bearings

Displaced substructure elements

Cracks in superstructure

Cracks in substructure

c. Timber Trestles

Line, surface and cross level of track. (Movements that do not affect line, surface or cross level are unlikely to be damaging, especially in open deck trestles).

Displaced timbers, particularly in framed bents

Broken bracing

Bent bolts or drift bolts

d. Movable Spans

Damage to counterweight guides

Open draw span shifted on pivot pier

Relative movement of piers that prevents opening or closing, including mis-alignment of track girders and segmental girders of rolling lift spans.

1.2.2.3.4 Culverts

Damage is unlikely if line and surface of track are good and no slides or embankment spreading are observed.

1.2.2.3.5 Retaining Walls

Increased tilt in walls which may be caused by footing rotation or cracking at base of stem. (Walls with surcharge above top of wall appear particularly vulnerable.)

1.2.2.3.6 Tunnels

Fallen material or loose material that may fall in an aftershock

New cracks or failures in lining

Offsets due to displacement across fault

Unusual flow of water within tunnel

1.2.2.3.7 Other Structures¹

Structural and/or non-structural damage to essential buildings that would prevent or inhibit use.

NOTE: Inspect promptly, with concurrence of local building authorities, to prevent outside inspectors from “red tagging” buildings that are damaged but not unsafe.

Leaks and/or structural damage to fueling facilities, including tanks and pipelines. Look for evidence of leaks in buried fuel lines.

Catenary support structures and tension-regulating systems of electrified lines.

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)



NOTE: Substations should be inspected by a qualified individual.

1.2.2.3.8 Structures That May Fall on Track

- a. Overpasses
 - Reduced support for span at bearings
 - Column damage
 - Damage to any span restraint system
- b. Adjacent Buildings
 - Structural damage affecting ability to resist aftershocks
 - Clearance infringements
 - Power lines that may be vulnerable to aftershocks

1.2.2.3.9 Signal and Communication Facilities

Signal and communications facilities must be inspected by qualified personnel. However, others involved in inspection should note damage to pole lines and other obvious damage to equipment. Signal masts, signal bridges or instrument housings observed to be out-of-plumb should be reported immediately.

SECTION 1.3 GENERAL REQUIREMENTS

1.3.1 APPROACH (2004)¹

Structures shall be designed to satisfy the specified performance criteria. The main objectives of the required performance criteria are to ensure the safety of trains and to minimize the costs of damage and loss of use caused by potential earthquakes.

In order to provide a framework for evaluating seismic effects on railroad structures, a three-level ground motion and performance criteria approach consistent with the railroad post-seismic event response procedures is employed. The ground motion levels, the structure performance requirements and the railroad response levels are as shown in [Table 9-1-3](#).

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

Table 9-1-3. Seismic Performance Criteria

Railroad Response Level	Ground Motion Level	Performance Criteria Limit State
II	1	Serviceability
III	2	Ultimate
III	3	Survivability

1.3.2 GROUND MOTION LEVELS (2004)

The ground motion levels reflect the seismic hazard at the site. They are defined in terms of peak ground acceleration levels associated with a given average return period.

The average return period for each ground motion level may be determined based on seismic risk considerations (see [Paragraph 1.3.2.1](#)) and structure importance classification (see [Paragraph 1.3.2.2](#)), using the range of average return periods shown in [Table 9-1-4](#).

Table 9-1-4. Ground Motion Levels

Ground Motion Level	Frequency	Average Return Period (Yrs.)
1	Occasional	50-100
2	Rare	200-500
3	Very Rare	1000-2400

Level 1 Ground Motion represents an occasional event with a reasonable probability of being exceeded during the life of the structure. Level 2 Ground Motion represents a rare event with a low probability of being exceeded during the life of the structure. Level 3 Ground Motion represents a very rare or maximum credible event with a very low probability of being exceeded during the life of the structure.

1.3.2.1 Risk Factors¹

Earthquakes are extreme events associated with a great amount of uncertainty and risk factors are an integral part of seismic design. To achieve a balance between seismic risk and costs associated with risk reduction, a certain amount of risk must be accepted. If there is a severe social penalty associated with structure failure, the acceptable level of risk will be greatly reduced.

The greatest amount of uncertainty is associated with the seismic hazard at the site. Therefore, the overall seismic risk of a bridge is strongly affected by the design ground motion used.

The acceptable risk criteria with respect to Level 1 Ground Motion shall consider the safety and continuing operation of trains with speed restrictions. For Ground Motion Levels 2 and 3, the acceptable risk criteria may be based mainly on economic considerations unless the bridge has a high passenger train occupancy rate. Train traffic is stopped per Railroad Response Level III for Ground Motions Levels 2 and 3 until bridge inspections are completed.

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

1.3.2.2 Structure Importance Classification¹



The purpose of the structure importance classification system is to assist the engineer in determining the appropriate average ground motion return period for each of the three limit states: serviceability, ultimate and survivability. The importance of a structure is determined by three measures: Immediate Safety, Immediate Value and Replacement Value. These three measures are combined in [Article 1.3.2.2.4](#) to determine the appropriate return period for each of the limit states.



1.3.2.2.1 Immediate Safety²

Immediate safety is a measure of the magnitude of earthquake a structure should be able to survive without any interruption of service. Factors to be considered are occupancy, hazardous material and community life lines. These factors should be summed to obtain the immediate safety factor. The immediate safety factor should not exceed 4.



a. Occupancy Factor

Freight Service only	1
Less Than 10 Passenger Trains per Day.	2
More than 10 Passenger Trains per Day.	4



b. Hazardous Material Factor

The value of the hazardous material factor should be determined by the engineer by considering the type of material being handled, the volume and the proximity of the structure to population. The hazardous material factor should be a value between 0 and 4.



c. Community Life Lines Factor

The community life line factor should reflect the danger to community if the structure fails during a seismic event. The community life line factor should be a value between 0 and 4. The nature of the structure should be taken into account when determining the community life line factor. If the structure is over a route that is critical for post seismic evacuation, a high community life line factor should be used. A high community life line factor should also be used when the structure is over a community's water supply. The potential disruption of telephone, electric, and water lines attached to the bridge and the importance of continued rail service should also be considered when determining the community life line factor.

1.3.2.2.2 Immediate Value³

Immediate Value is a measure of the magnitude of earthquake a structure should be able to survive with an interruption of service but with the ability to return to service after minor repairs. The factor is based on the railroad's utilization of the structure and the ability to detour around the structure. The utilization of the structure by others should also be taken into account.

a. Railroad Utilization Factor

Under 10 million gross tons annual traffic	1
Between 10 million and 50 million gross tons annual traffic	2
Over 50 million gross tons annual traffic	4

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)
² See [Part 2 Commentary to Seismic Design for Railway Structures](#)
³ See [Part 2 Commentary to Seismic Design for Railway Structures](#)



b. Detour Availability Factor

No Detour Available	1.00
Inconvenient Detour Route.	0.50
Detour Route Readily Available	0.25

The Immediate Value factor should be determined by multiplying the railroad utilization factor by the detour availability factor. Usage by outside parties should be taken into account after this railroad utilization and detour availability is taken into account.

1.3.2.2.3 Replacement Value¹

Replacement value is a measure of the magnitude of the ultimate earthquake the structure should be able to survive. The factor is determined by the difficulty of replacing the structure.

a. Span Length Factor

Span length less than 35 feet	1
Span length between 35 feet and 125 feet	2
Span length between 125 feet and 250 feet	3
Span length greater than 250 feet	4

b. Bridge Length Factor

Bridge length less than 100 feet	1.0
Bridge length between 100 feet and 1,000 feet	1.5
Bridge length greater than 1,000 feet	2.0

c. Bridge Height Factor

Bridge height less than 20 feet	0.75
Bridge height between 20 feet and 40 feet	1.00
Bridge height greater than 40 feet	1.25

The replacement value factor is determined by multiplying the span length, bridge length and bridge height factors, but should not exceed 4.0. The replacement value should be increased for conditions that would increase the difficulty of replacement such as multiple track, movable structures, difficult foundation and substructure reconstruction conditions, urban location and difficult access.

1.3.2.2.4 Conversion of Factors to Return Periods

The importance classification factor for each limit state is calculated using the following weighting factors. Individual railroads may decide to change the weighting factors to better represent the conditions that they operate under.

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

Table 9-1-5. Weighting Factors

Weighting Factors			Limit State
Immediate Safety	Immediate Value	Replacement Value	
0.80	0.20	0.00	Serviceability
0.10	0.80	0.10	Ultimate
0.00	0.20	0.80	Survivability

To calculate the importance classification factor for each limit state, add the Immediate Safety, Immediate Value and Replacement Value factors together after multiplying them by the appropriate weighting factor.

a. Return Periods

The return period for each limit state is calculated using a linear relationship between the appropriate average return period limits shown in Table 9-1-4. To calculate the return period, multiply the importance classification factor by the difference between the maximum and minimum return periods and divide by 4. Add this result to the minimum return period to get the final value.

1.3.2.3 Base Acceleration Coefficient Maps¹

Several base acceleration coefficient maps are provided in this Article to help define the earthquake hazard. Figures 9-1-1, 9-1-2 and 9-1-3 show base accelerations in the United States for return periods of 100 years, 475 years and 2400 years. Figures 9-1-4 and 9-1-5 illustrate base accelerations in Canada for return periods of 100 years and 475 years. Other maps or site-specific procedures may be used to define the base accelerations as long as they are based on accepted methods.

Base acceleration coefficients for locations in the United States with return periods other than those provided in Figures 9-1-1 through 9-1-3 may be determined based on the following formulas:

- Acceleration for return period, R , less than 475 years

$$A_R = A_{475} \left(\frac{R}{475} \right)^n$$

$$n = \frac{\ln \left(\frac{A_{100}}{A_{475}} \right)}{-1.558}$$

- Acceleration for return period, R , between 475 years and 2400 years

$$A_R = e^n$$

$$n = \ln(A_{475}) + [\ln(A_{2400}) - \ln(A_{475})] \times [0.606 \times \ln(R) - 3.73]$$

$$A_R = \text{Base acceleration coefficient for return period} = R$$

$$A_{100} = \text{Base acceleration coefficient for return period} = 100 \text{ years (Figure 9-1-1)}$$

$$A_{475} = \text{Base acceleration coefficient for return period} = 475 \text{ years (Figure 9-1-2)}$$

$$A_{2400} = \text{Base acceleration coefficient for return period} = 2400 \text{ years (Figure 9-1-3)}$$

¹ See Part 2 Commentary to Seismic Design for Railway Structures

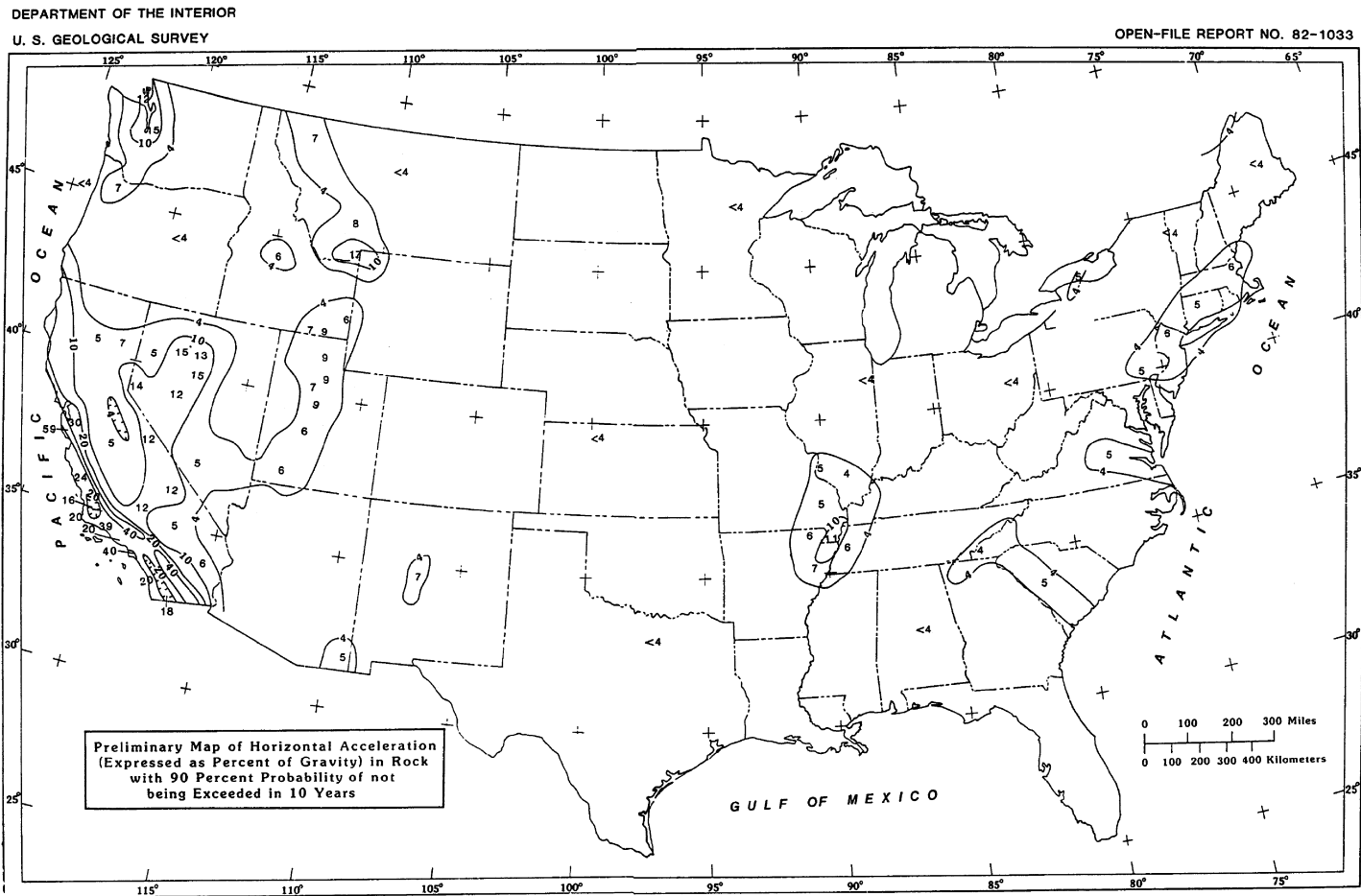


Figure 9-1-1. Plate 1 – 100-year Return Period – United States

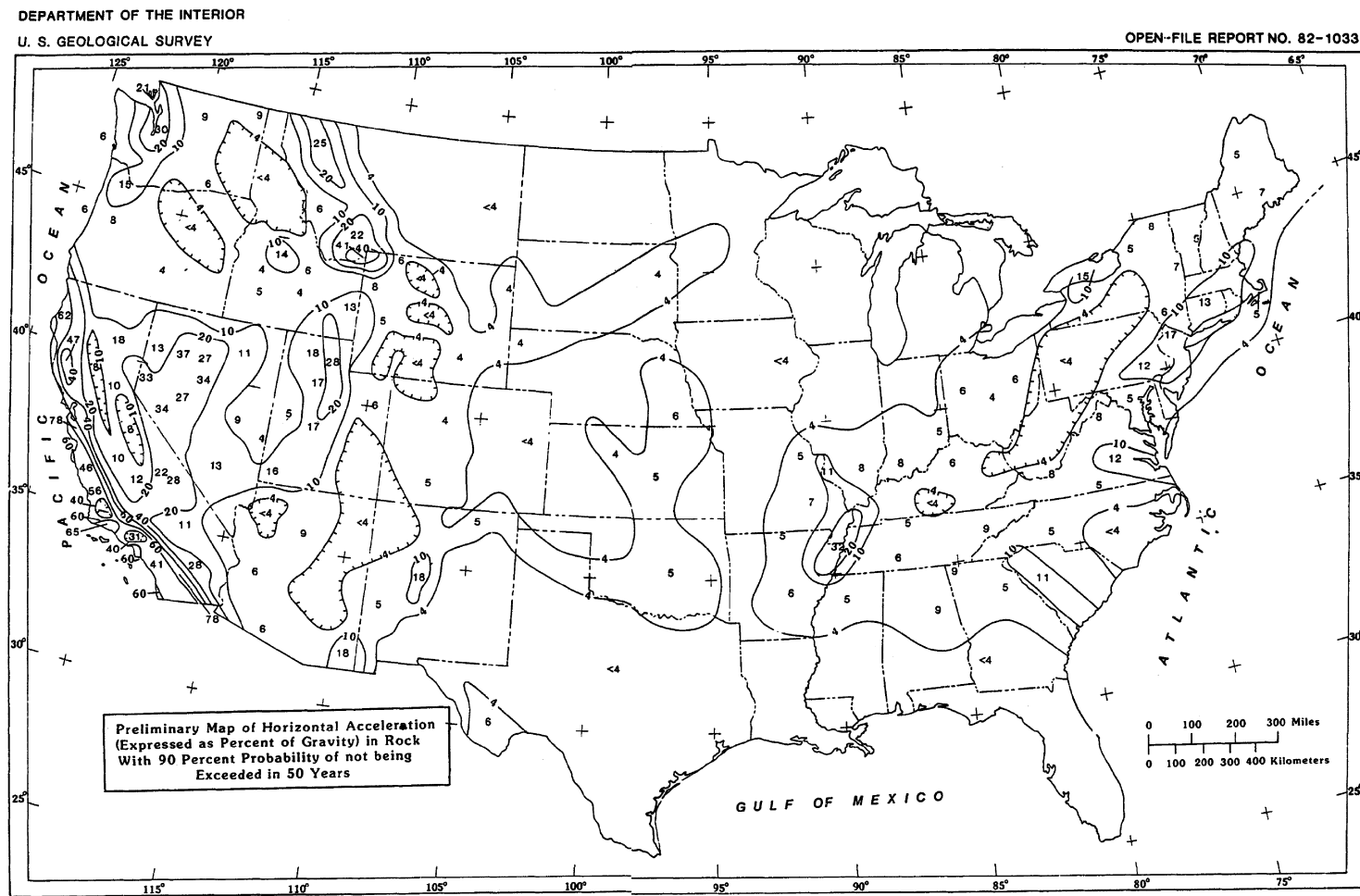


Figure 9-1-2. Plate 2 – 475-year Return Period – United States

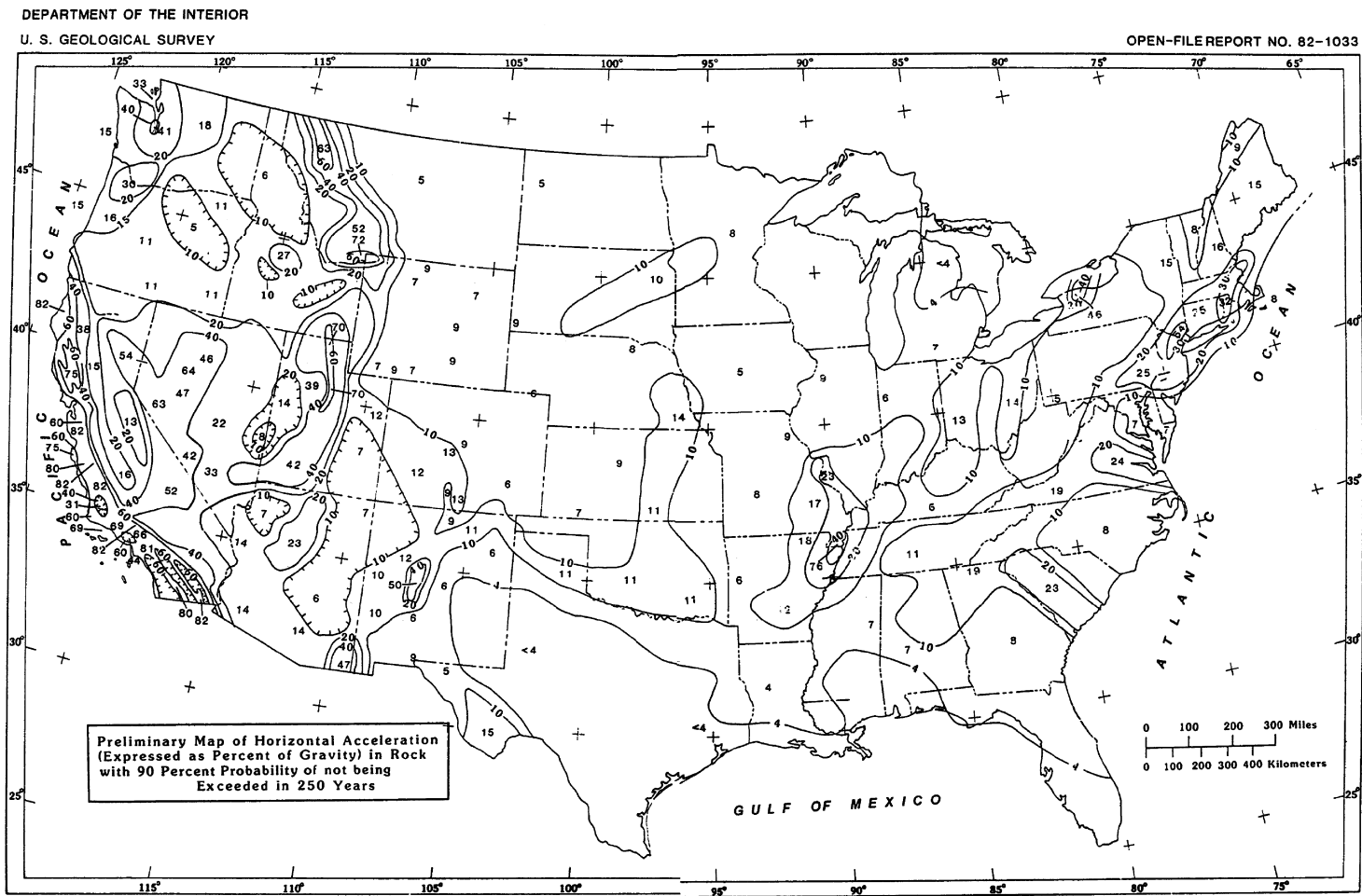


Figure 9-1-3. Plate 3 – 2,400-year Return Period – United States

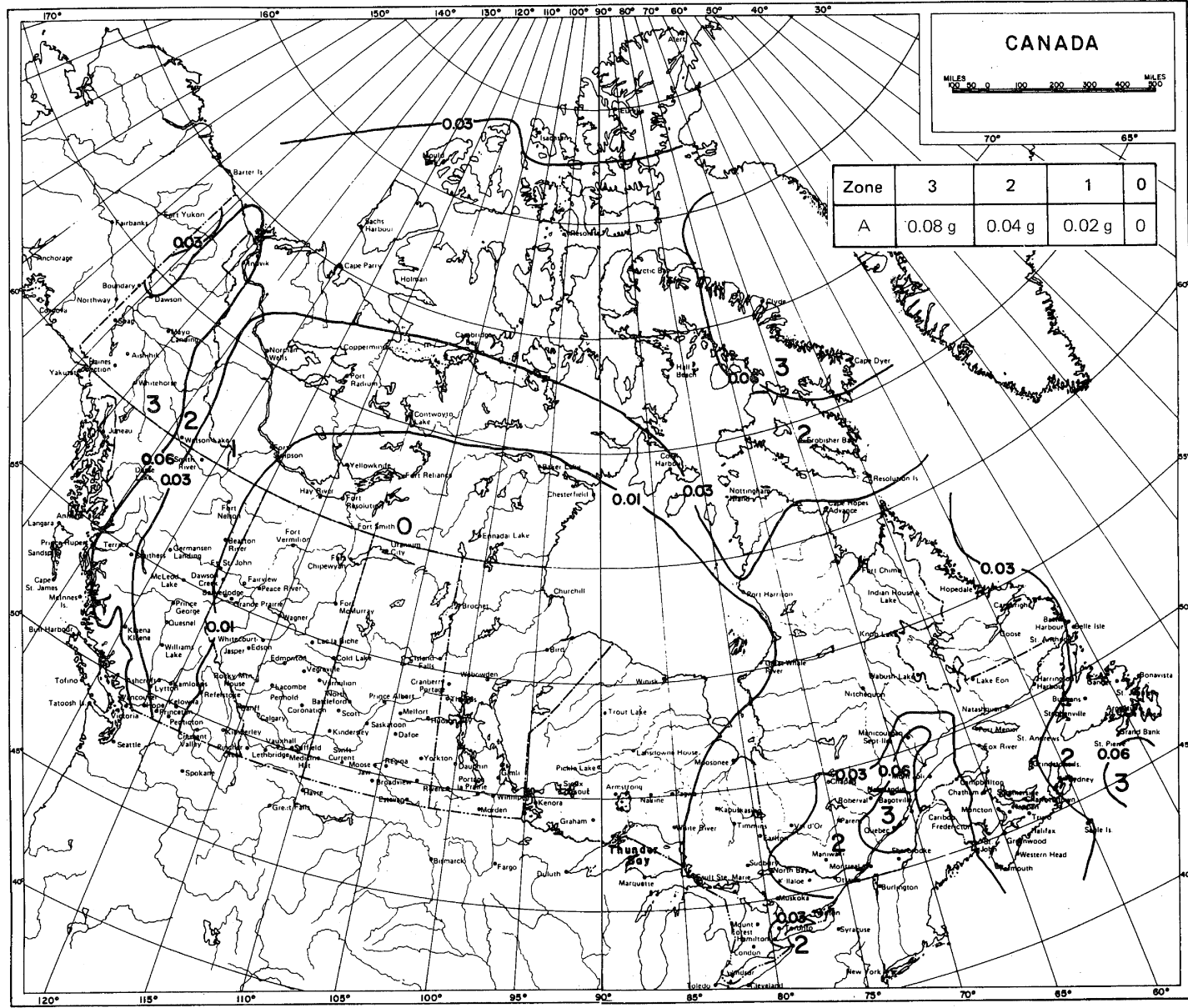


Figure 9-1-4. Plate 4 – 100-year Return Period – Canada

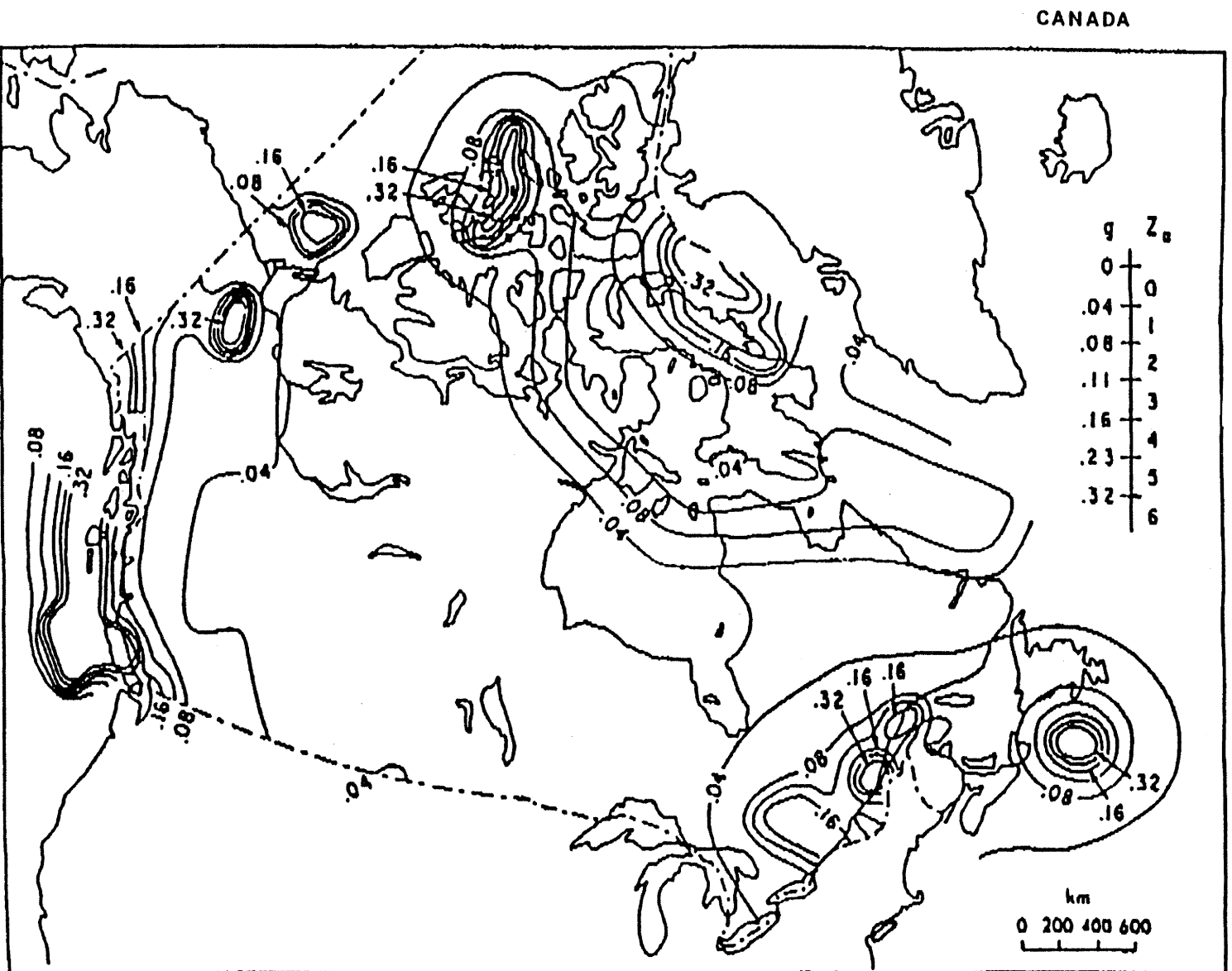


Figure 9-1-5. Plate 5 – 475-year Return Period – Canada

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1.3.3 PERFORMANCE CRITERIA (1998) R(2004)¹

The requirements for each of the following limit states shall be satisfied.

1.3.3.1 Serviceability Limit State²

The serviceability limit state contains restrictions on bridge stresses, deformations, vibrations and track misalignments due to a Level 1 Ground Motion. Critical members shall remain in the elastic range. Only moderate damage that does not affect the safety of trains at restricted speeds is allowed. The structure shall not suffer any permanent deformation due to deformations or liquefaction of the foundation soil.

1.3.3.2 Ultimate Limit State³

The ultimate limit state ensures the overall structural integrity of the bridge during a Level 2 Ground Motion. The strength and stability of critical members shall not be exceeded. The structure may respond beyond the elastic range, but displacement, ductility and detailing requirements shall be satisfied to reduce damage and loss of structure use. The damage should occur as intended in design and be readily detectable and accessible for repair. The structure shall not suffer any damage which threatens the overall integrity of the bridge due to deformations or liquefaction of the foundation soil.

1.3.3.3 Survivability Limit State⁴

The survivability limit state ensures the structural survival of the bridge after a Level 3 Ground Motion. Extensive structural damage, short of bridge collapse, may be allowed. Structural and geometric safety measures that add redundancy and ductility shall be used to reduce the likelihood of bridge collapse. Failures of the foundation soil shall not cause major changes in the geometry of the bridge. Depending on the importance and the replacement value of a bridge, an individual railroad may allow irreparable damage for the survivability limit state, and opt for new construction.

SECTION 1.4 NEW BRIDGES

1.4.1 SCOPE (2004)

This article applies to bridges with spans not exceeding 500 feet in length. Movable bridges, arch type bridges and bridges with spans exceeding 500 feet in length may require additional analysis and design considerations, which are beyond the scope of this article.

1.4.2 DESIGN APPROACH (2001) R(2006)

Bridge design for seismic loads should start with conceptual considerations to select the appropriate bridge type and configuration. The conceptual phase should be followed by analysis for Level 1 Ground Motion to size the various structure members. Finally, appropriate detailing provisions should be incorporated to allow the bridge to respond well during the Level 2 and 3 Ground Motions. Structures located in areas of low ground motion levels need not meet the conceptual design requirements and detailing provisions provided they are capable of withstanding the full Level 3 Ground Motion loadings within the elastic range.

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

² See [Part 2 Commentary to Seismic Design for Railway Structures](#)

³ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

⁴ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

1.4.3 CONCEPTUAL DESIGN (2001) R(2006)¹

Conceptual design provisions contained herein should be followed as much as practical. The design should maintain a balance between functional requirements, cost and seismic resisting features.

1.4.3.1 Configuration²

The preferred configuration should be incorporated as shown below when possible. Special design and detailing considerations may be necessary for other configurations.

PREFERRED CONFIGURATION	SPECIAL CONSIDERATION
Straight bridge alignment	Curved bridge alignment
Normal piers	Skewed piers
Uniform pier stiffness	Varying pier stiffness
Uniform span stiffness	Varying span stiffness
Uniform span mass	Varying span mass

1.4.3.2 Superstructure³

The preferred superstructure characteristics should be incorporated as shown below when possible. Special design and detailing considerations may be necessary for other superstructure characteristics.

PREFERRED SUPERSTRUCTURE	SPECIAL CONSIDERATION
Simple spans	Continuous spans
Short spans	Long spans
Light spans	Heavy spans
No hinges	Intermediate hinges

1.4.3.3 Substructure⁴

The preferred substructure characteristics should be incorporated as shown below when possible. Special design and detailing considerations may be necessary for other substructure characteristics.

PREFERRED SUBSTRUCTURE	SPECIAL CONSIDERATION
Wide seats	Narrow seats
Seat bent caps	Integral bent caps
Multiple column	Single column

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

² See [Part 2 Commentary to Seismic Design for Railway Structures](#)

³ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

⁴ See [Part 2 Commentary to Seismic Design for Railway Structures](#)



1.4.3.4 Ground Conditions¹

Structures should be founded on competent, stable soils or otherwise designed to satisfy the performance requirements during soil instability.

1.4.4 STRUCTURE RESPONSE (2003)

1.4.4.1 Site Coefficient²

The Site Coefficient (S) shall be determined from [Table 9-1-6](#) based on the foundation soil characteristics.

Table 9-1-6. Site Coefficient

Soil Type	Description	Site Coefficient
1	Rock of any characteristic, either shale-like or crystalline in nature, that may be characterized by a shear wave velocity greater than 2,500 feet per second, or stiff soil conditions where the soil depth is less than 200 feet and the soil types overlying the rock are stable deposits of sand, gravel, or stiff clays.	1.0
2	Deep cohesionless or stiff clay conditions where the soil depth exceeds 200 feet and the soil types overlying rock are stable deposits of sands, gravel, or stiff clays.	1.2
3	20 to 40 feet of soft to medium-stiff clays with or without intervening layers of cohesionless soils.	1.5
4	Soil containing more than 40 feet of soft clays or silts, that may be characterized by a shear wave velocity of less than 500 feet per second.	2.0

1.4.4.2 Damping Adjustment Factor³

The Damping Adjustment Factor (D) may be calculated from the following formula. In the absence of more definitive information, a damping adjustment factor of 1.0 shall be used.

$$D = \left(\frac{1.5}{(0.4\xi + 1)} + 0.5 \right)$$

D = Damping Adjustment Factor

ξ = Percent Critical Damping (e.g. 5%)

¹ See [Part 2 Commentary to Seismic Design for Railway Structures](#)

² See [Part 2 Commentary to Seismic Design for Railway Structures](#)

³ See [Part 2 Commentary to Seismic Design for Railway Structures](#)