

PNWS-AWWA
2026 Section Conference
Tacoma, WA
May 6-8, 2026

What to Expect in the upcoming

ASCE Manual on Seismic Design of Buried Water and Wastewater Pipelines

What happens **NEXT** is happening **NOW**.

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Principal Engineer & Discipline Leader for Seismic Analysis and Design
Chair, ASCE Task Committee on Seismic Design of Buried Water/Wastewater Pipelines

May 8, 2026

CDM Smith

NEW

ASCE MOP

ON

SEISMIC DESIGN OF BURIED WATER AND WASTEWATER PIPELINES

Agenda

- Need for Seismic Design Guidelines for Buried Pipelines
- Manual of Practice on Seismic Design of Pipelines
  - Criticality Categories
  - Redundancy
  - Seismic Ground Strain Demand
  - Axial Connection Force Capacity
  - Site-specific Seismic Design Parameters
  - Prescriptive Design Approach (Design Tables)
- Other Concurrent Efforts
  - White Paper on Seismic Performance of Pipe Product Systems
  - Standard(s) Development
- Summary

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Why Seismic Design of Pipelines?

- 1906 San Francisco EQ
  - EQ broke all but one water main
  - Firefighters did not have access to water to fight the fires.
  - Fires burned for three days and three nights
  - Fires as hot as 2,700°F.
- 1994 Northridge EQ (Los Angeles, CA)
  - 450,000 people lost water service
  - At least eight hospitals evacuated
- 1995 Kobe EQ (Japan)
  - More than 1.5 million people lost water service
  - 30+ hours to extinguish the fires due to water unavailability in many hydrants



The fires were more catastrophic than the earthquake itself

Source: National Archives Still Picture Records Section, Special Media Archives

- **Water systems have performed poorly in past EQs**
- **Need several years and significant investment to return to pre-EQ service and reliability levels .**



(Courtesy M. O'Rourke)

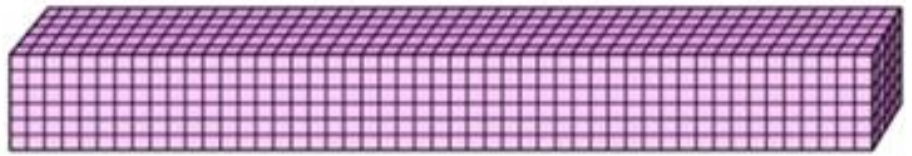
How Earthquakes Damage Pipes

- Transient Ground Deformations (wave propagation)
- Permanent ground deformations
  - Surface Fault rupture
  - Differential settlement
  - Landslides, lateral spreading
  - Cyclic mobility
- Other liquefaction-induced phenomena
  - Buoyancy
  - Lateral pressures

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Wave Propagation

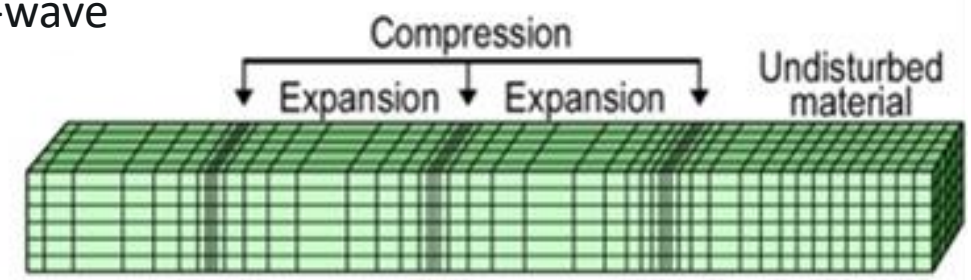
Ground prism



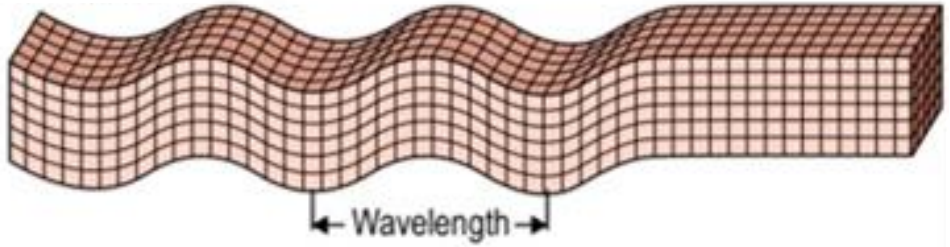
https://ags.aer.ca/activities/all-about-earthquakes

BODY WAVES

P-wave



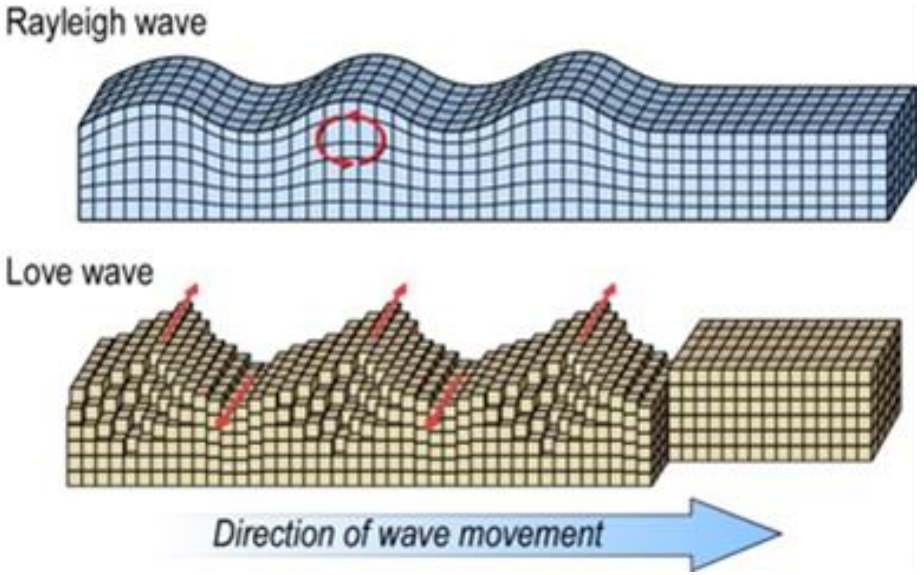
S-wave



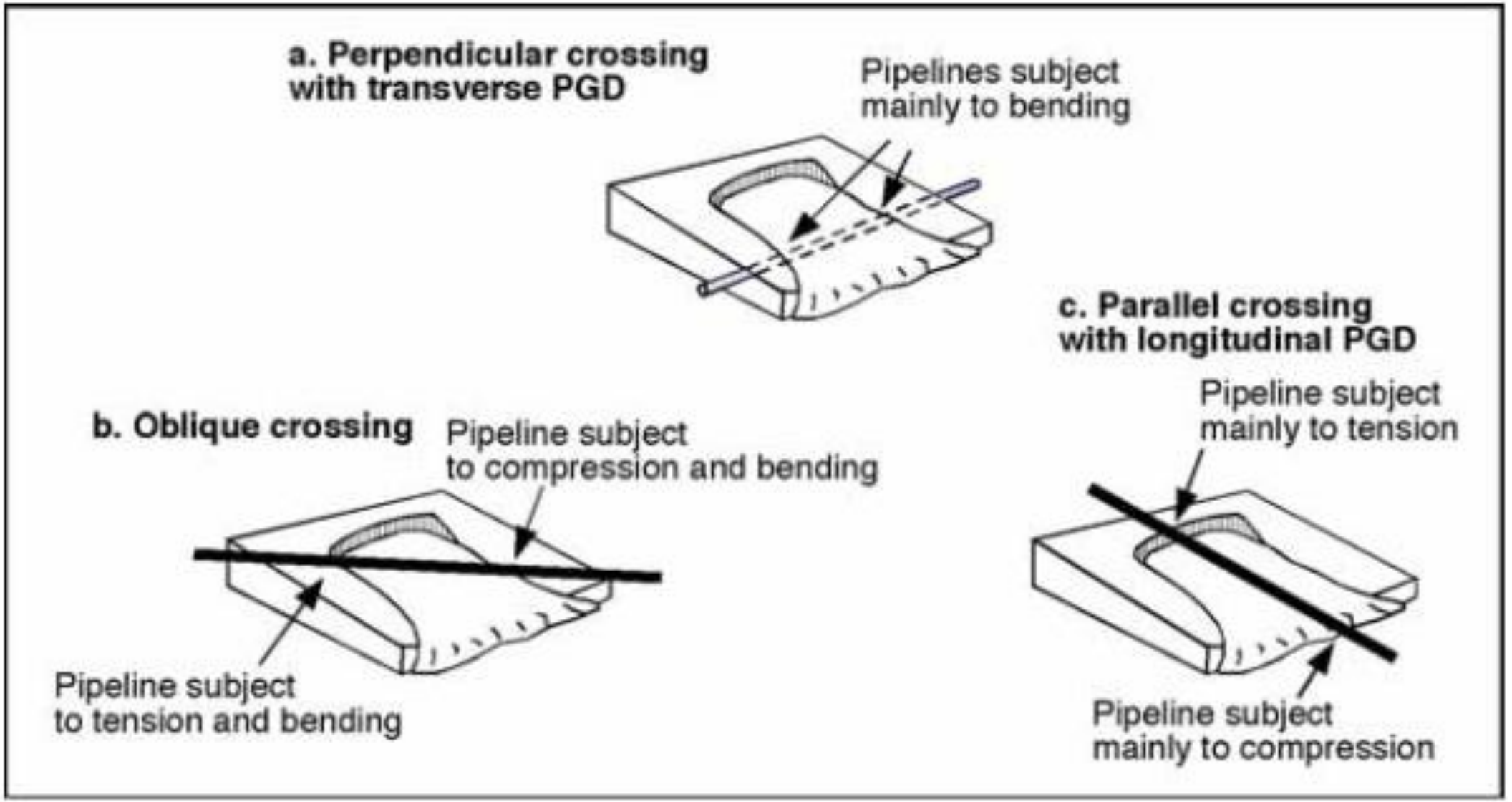
$$\alpha_t = \frac{PGV}{C}$$

$$\kappa_t = \frac{PGA}{C^2}$$

SURFACE WAVES



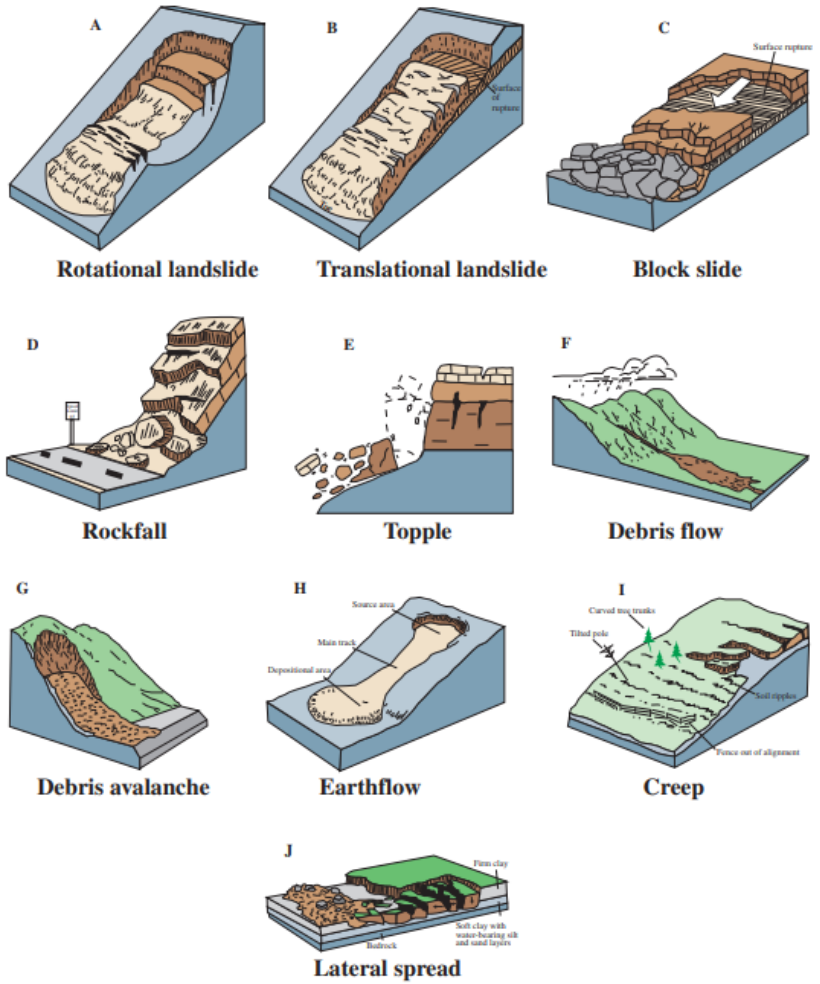
Liquefaction-Induced Lateral Spreading



https://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html

Permanent Ground Deformations from Landslides

- Permanent Ground Deformations occur from Landslides.
- Pipelines passing through sliding mass should either accommodate or resist the PGDs from the landslides.
  - Transverse (Horizontal or Vertical)
  - Axial



Source: https://pubs.usgs.gov/fs/2004/3072/pdf/fs2004-3072.pdf

Objectives for Seismic Design of Pipelines



- Minimize:
  - Loss of lives
  - Damage due to fires – cascading events
  - Service interruptions to critical customers or fire hydrants

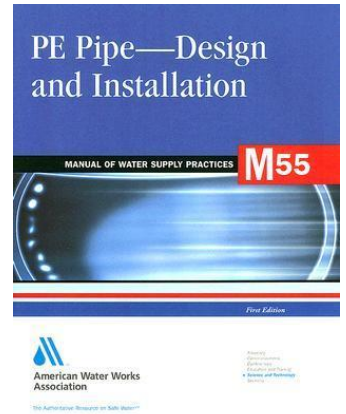
- Life Safety
- Post Disaster Recovery
- Pipeline Asset Management
- Economic

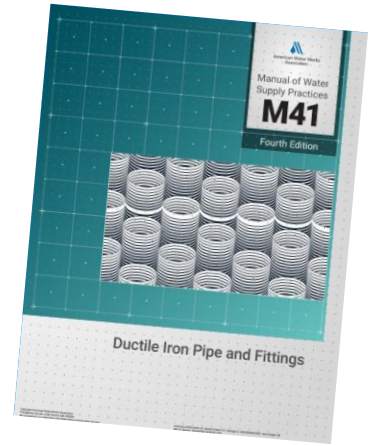
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Current Water/Wastewater Pipeline Design Practices

- Pipeline Design Practice based on:
  - AWWA Design Manuals
  - Trade Organization Design Guidelines

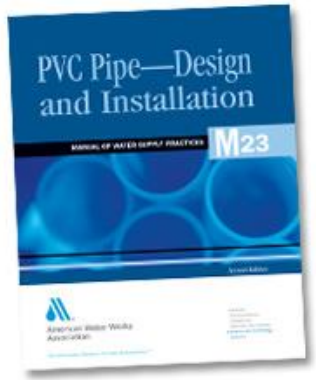


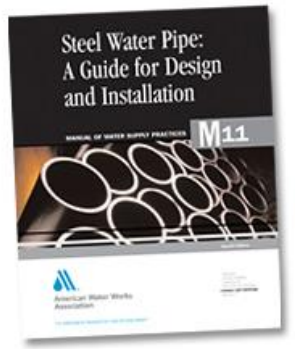


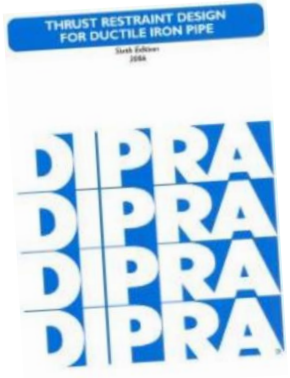


THESE MANUALS/GUIDELINES DO NOT ADDRESS SEISMIC DESIGN EXPLICITLY, EXCEPT

- **Recently published AWWA Manual M41 includes a chapter on seismic design guidelines**
- **Upcoming revision to AWWA M9 will also include a chapter on seismic design**







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Existing Seismic Design Practice/Guidelines

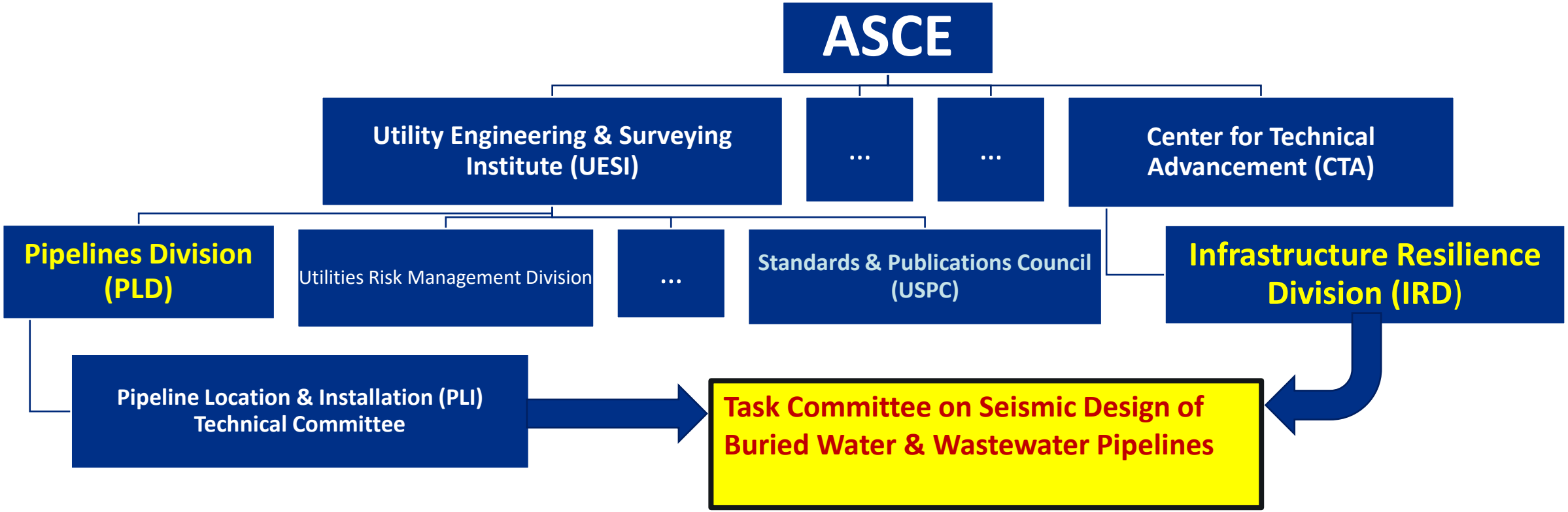
- American Lifelines Alliance (ALA) Guideline
  - "Seismic Guidelines for Water Pipelines", 2005
- ISO Standard(s)
  - ISO 16134 Earthquake & Subsidence Resistant Ductile-Iron Pipelines
- MCEER Monograph #4
  - "Seismic Design of Buried and Offshore Pipelines", 2012
- US standards/codes for gas pipeline industry
- Pipeline Research Council International (PRCI) guidelines
- Guidelines by Major Utilities
  - SFPUC, Metro Vancouver, WSSP , City of Seattle, etc.
- various research reports



Need for a Nationwide Seismic Design Guideline for Water/Wastewater Pipelines is Long Overdue!!

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ASCE is Currently Developing Seismic Design Guidelines …



- Manual of Practice on Seismic Design of Water/Wastewater Pipelines
- White Paper on Seismic Performance of Pipe Product Systems

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Manual of Practice - Goals



http://www.startwiththehouse.com/2013/01/goal-setting/

- Provide seismic design criteria for new buried pipe
- Offer easy to use design instructions
- Help water/wastewater utilities to design resilient systems meeting seismic criteria
- Plan proactively for the next seismic event
- Encourage manufacturers to develop new products (Innovation)

MOP Presents a **Seismic Design Framework** for New Buried Pipelines

- **Prescriptive Design Approach** (~80% of the pipelines)
- Site-Specific Design Approach (~20% of the pipelines)

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MOP Will Contain …

- **Prescriptive Design Approach (Design Tables)**
  - Axial Strain Performance for TGD
    - Criticality Categories I, II, III, & IV
  - Radius of Curvature Performance for TGD
    - Criticality Categories I, II, III, & IV
  - Axial Strain Performance for
    - Lateral Spread (Free Face) PGD
    - Landslide PGD
  - Radius of Curvature Performance for
    - Lateral Spread (Free Face) PGD
    - Landslide PGD
  - Axial Connection Force Capacity (CFC) *(In development)*
- ***Guidance for Site-specific Seismic Design***

- Based on
  - Location Specific Seismic Hazard
  - Subsurface Conditions (Site Class)
  - Pipeline Criticality Category
- Targeted Design Levels and Uncertainties

Criticality Category	Hazard Return Period (years)	Uncertainty
I	50	Mean - 1σ
II	475	Mean
III	975	Mean + 0.5σ
IV	2,475	Mean + 1σ

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Criticality Categories

Criticality Category	Importance Level	Description of Pipeline Category
I	Low	Pipelines whose failure would present a very low hazard to human life. These pipelines are not needed for post-earthquake system performance, response, or recovery. They primarily serve non-essential customers for agricultural or irrigation usage, certain temporary facilities, isolated services, or minor storage facilities, which do not have a significant role in local or regional economy, or any level of fire suppression or wastewater collection following a significant earthquake.
II	Moderate	Pipelines that include the typical conduits within a distribution or collection system that are not used for storage, pumping, treatment, or disinfection. This includes material storage buildings and office buildings not needed for essential emergency response or initial recovery. These pipelines serve typical residential, commercial, and industrial customers within the system and include all components not identified in Criticality Categories I, III, and IV.
III	High	Pipelines whose failure would represent a substantial hazard or mass disruption to human life. Failure may also result in significant social or economic impacts. These components are needed to provide service to **Critical B Customers**. Additionally, this category includes pipelines that, if damaged, may cause secondary disasters not directly impacting life safety or public health. • ***Critical B Customers*** are those needed in support of community resilience and function.
IV	Essential	Pipelines needed to provide service to essential facilities for post-earthquake response, public health, and safety. This includes pipelines needed for primary post-earthquake firefighting. These components are intended to remain functional during and following an earthquake. They include buildings and yard facilities intended for emergency response and recovery. These also include all pipelines in the supply and collection chains to **Critical A Customers**. All storage facilities (tanks and reservoirs), pump stations, regulating stations, treatment and disinfection facilities, including its associated mechanical and electrical equipment, are included in this category. Additionally, this category includes components that, if damaged, may: • Result in emergencies with secondary effects that potentially impacting life safety or public health, • Impede emergency response and operations, and evacuation routes, or • Disrupt other lifeline infrastructure systems. • ***Critical A Customers*** are those directly involved with activities related to life safety and public health

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Criticality Category Reclassification for Redundant Pipelines

- Redundancy is a very important resilience property
  - When implemented with the highest reliability
- How design efficiencies can be attained without sacrificing the reliability to meet the performance objectives
  - Designate a Primary Pipeline (Highest required criticality category)
  - Reduce seismic design criteria for redundant pipelines

Pipeline Criticality Category	L_R= 0 [P]	L_R = 1 [P, S]	L_R = 2 [P, S, A]
I	I	I, I	I, I, I
II	II	II, II	II, II, II
III	III	III, II	III, II, II
IV	IV	IV, III	IV, III, II

NOTES

- A redundancy of L_R = 0 has no redundancy, L_R = 1 has one redundant pipeline, and L_R = 2 has two or more redundant pipelines.
- [P], [S], and [A] are the primary, secondary, and additional pipelines within a system, respectively.

This redundancy reclassification shall not be applied to pipelines which:

1. Otherwise are **required to have a higher Pipeline Criticality Category based on public health, life safety, or other factors**
2. Are **exposed to common cause failures**, such as:
   a) A **leak or break in one pipeline may lead to damage on other redundant pipeline**,
   b) Pipelines are exposed to the same earthquake hazards (e.g., pipelines cross same fault, landslides, and liquefaction zones).
3. There are **foreseeable plans to remove the designated primary or redundant pipeline from operation**.

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Proposed Seismic Ground Strain Capacity Classifications

- Considers
  - Transient Ground Displacement (TGD)
  - Permanent Ground Displacement (PGD)

Parameter (+ and -)	Class	Seismic Strain Capacity	
		Continuous pipelines	Segmental pipelines
Axial Strain (ε_a) or Joint Movement (u)	α_A	$\varepsilon_a < 0.1\%$	$u/L < 0.1\%$
	α_B	$0.1\% \le \varepsilon_a < 0.5\%$	$0.1\% \le u/L < 0.5\%$
	α_C	$0.5\% \le \varepsilon_a < 1\%$	$0.5\% \le u/L < 1\%$
	α_D	$\varepsilon_a \ge 1\%$	$u/L \ge 1\%$
Radius of Curvature (R) or Deflection Angle (ϕ)	ρ_A	$R > 500D$	$\phi D/L < 0.115$ deg
	ρ_B	$100D < R \le 500D$	$0.115 \text{ deg} \le \phi D/L < 0.573$ deg
	ρ_C	$50D < R \le 100D$	$0.573 \text{ deg} \le \phi D/L < 1.15$ deg
	ρ_D	$R \le 50D$	$\phi D/L \ge 1.15$ deg

NOTE:

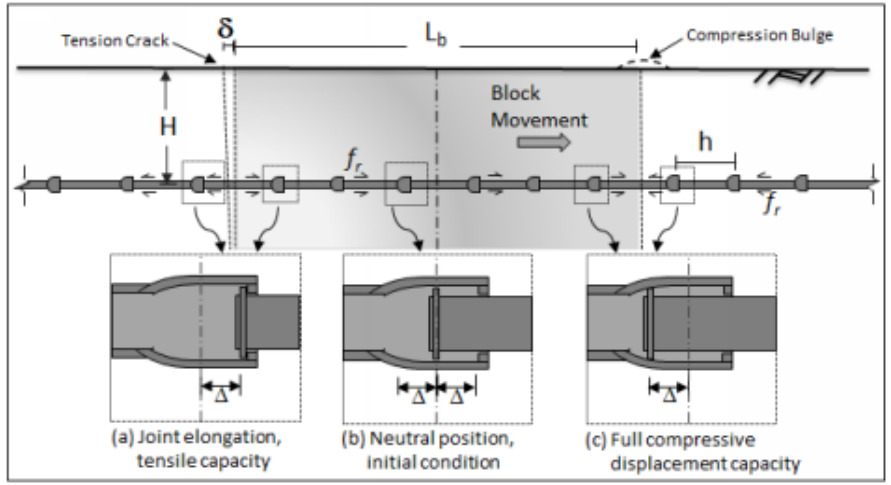
- D – Diameter of pipe
- u/L - ratio of elongation/contraction of the pipe joint (u) over the pipe segment length (L)

Reference:

Current draft of MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines"
Davis, C. A., Rajah, S., Wham, B. P., and Heubach, W. F. "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movement", For the Proceedings of the 2019 ASCE Pipeline Division Specialty Conference "Pipeline Engineering — Concepts in Harmony", ASCE, Nashville, Tennessee, July 2019.

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Proposed Axial Connection Force Capacity (CFC) Classifications



- Several Material and Configuration Options
  - Continuous Pipelines (Pressure/Non-Pressure)
    - HDPE, PVC, Steel
  - Segmented Pipelines (Pressure/Non-Pressure)
    - Concrete, Ductile Iron, Fiberglass, PVC, Steel
  - Segmented Pipelines (Non-Pressure)
    - Clay, HDPE (Corrugated)

PERFORMANCE CLASS	CONNECTION FORCE CAPACITY (lbs/in)	
	Lower limit	Upper Limit
Φ_A	0	4282.7
Φ_B	4282.7	8565.3
Φ_C	8565.3	17130.5
Φ_D	17130.5	∞

Notes:
1. This table is applicable for both continuous and segmented pipelines.
2. This table is applicable for all common water & wastewater pipeline materials.

Reference:

Current draft of MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines"
Wham, B. P., Davis, C. A., and Rajah, S., "Axial Connection Force Capacity Required for Buried Pipelines Subjected to Seismic Permanent Ground Displacement", For the Proceedings of the 2019 ASCE Pipeline Division Specialty Conference "Pipeline Engineering — Concepts in Harmony", ASCE, Nashville, Tennessee, July 2019.

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Comparison with ISO 16134:2020(E) Classifications

Proposed

Parameter (+ and -)	Class	Seismic Strain Capacity	
		Continuous pipelines	Segmental pipelines
Axial Strain (ε_a) or Joint Movement (u)	α_A	$\varepsilon_a < 0.1\%$	$u/L < 0.1\%$
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	α_C	$0.5\% \le \varepsilon_a < 1\%$	$0.5\% \le u/L < 1\%$
	α_D	$\varepsilon_a \ge 1\%$	$u/L \ge 1\%$
Radius of Curvature (R) or Deflection Angle (ϕ)	ρ_A	$R > 500D$	$\phi D/L < 0.115$ deg
	ρ_B	$100D < R \le 500D$	$0.115 \text{ deg} \le \phi D/L < 0.573$ deg
	ρ_C	$50D < R \le 100D$	$0.573 \text{ deg} \le \phi D/L < 1.15$ deg
	ρ_D	$R \le 50D$	$\phi D/L \ge 1.15$ deg

NOTE:

- D – Diameter of pipe
- u/L - ratio of elongation/contraction of the pipe joint (u) over the pipe segment length (L)

Proposed Classification is applicable for all pipe materials; continuous and segmented pipelines; and gravity/pressure pipelines.

ISO 16134:2020(E)

Parameter	Class	Component performance
Expansion/contraction performance	S-1	±1 % of L or more
	S-2	±0,5 % to less than ±1 % of L
	S-3	Less than ±0,5 % of L

Key

L the component length, in millimetres (mm)

d the nominal diameter of pipe, in millimetres (mm)

θ_a the joint deflection angle as shown in Table 4, in degrees (°)

Joint deflection angle	M-1	θ_a or more
	M-2	$\theta_a/2$ to less than θ_a
	M-3	Less than $\theta_a/2$

Key

L the component length, in millimetres (mm)

d the nominal diameter of pipe, in millimetres (mm)

θ_a the joint deflection angle as shown in Table 4, in degrees (°)

Table 4 — Joint deflection angle

Nominal diameter d	80 to 400	450 to 1 000	1 100 to 1 500	1 600 to 2 200	2 400 to 2 600
Joint deflection angle θ_a	8°	7°	5°30′	4°	3°30′
(Ref) Pipe length[a]	6 m	6 m	6 m	5 m	4 m

[a] Ductile iron pipe is available in shorter lengths and, where needed, can be cut during installation to achieve greater pipeline deflection over shorter pipeline lengths.

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Comparison with ISO 16134:2020(E) Classifications

Proposed

PERFORMANCE CLASS	CONNECTION FORCE CAPACITY (lbs/in)	
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Φ_A	0	4282.7
Φ_B	4282.7	8565.3
Φ_C	8565.3	17130.5
Φ_D	17130.5	∞

Notes:
1. This table is applicable for both continuous and segmented pipelines.
2. This table is applicable for all common water & wastewater pipeline materials.

Proposed Classification is applicable for all pipe materials; continuous and segmented pipelines; and gravity/pressure pipelines.

ISO 16134:2020(E)

SLIP-OUT RESISTANCE CLASS	COMPONENT PERFORMANCE	
	(mm, kN units)	(in, kips units)
A	3d kN or more	17.13d kips or more
B	1.5d kN to less than 3d kN	8.57d kips to less than 17.13d kips
C	0.75d kN to less than 1.5d kN	4.28d kips to less than 8.57d kips
D	Less than 0.75d kN	Less than 4.28d kips

NOTE: 1. d is the nominal diameter of the pipe in mm [in]

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Pipe Systems Need to be Assigned Performance Categories …

- Need to assign appropriate performance classes with respect to
  - Axial Strain
  - Radius of Curvature
  - Axial Connection Force Capacity
- Some Pipe Systems Have Seismic Test Results
  - Not Comprehensive to Cover all pipe sizes, joint types, and materials
- Difficult to Provide Comprehensive Guidance
- Additional Tests on Seismic Pipe Systems Need to be Performed

- Therefore, it is necessary to:
  - Document historical performance of different piping systems, and currently available seismic test results. (White Paper)
    - It is meant to be a live document (Initial draft is 90% complete)
  - Standardize Performing Seismic Tests on Piping Systems (Currently in development)
    - ASCE/UESI 91-YY Standard: Structural Testing and Evaluation of Pipeline Systems (STEPS): Assessment for Earthquakes and Other Geohazards
      - Draft has undergone public comment
      - Expected to be published in late 2026

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Site-specific Seismic Design Parameters from ASCE 7-22 and USGS Seismic Hazard Tools

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ASCE 7-22 has 9 different Site Classes

Table 20.2-1. Site Classification.

Site Class	$\bar{v}_s$ Calculated Using Measured or Estimated Shear Wave Velocity Profile (ft/s)
A. Hard rock	>5,000
B. Medium hard rock	>3,000 to 5,000
BC. Soft rock	>2,100 to 3,000
C. Very dense sand or hard clay	>1,450 to 2,100
CD. Dense sand or very stiff clay	>1,000 to 1,450
D. Medium dense sand or stiff clay	>700 to 1,000
DE. Loose sand or medium stiff clay	>500 to 700
E. Very loose sand or soft clay	≥500
F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.2.1

Note: For SI: 1 ft = 0.3048 m; 1 ft/s = 0.3048 m/s.

11.4.2.1 Default Site Conditions Where the soil properties are not known in sufficient detail to determine the site class, risk-targeted maximum considered earthquake (MCE_R) spectral response accelerations shall be based on the most critical spectral response acceleration at each period of Site Class C, Site Class CD, and Site Class D, unless the Authority Having Jurisdiction determines, based on geotechnical data, that Site Class DE, E, or F soils are present at the site.

- Default Site Conditions:
  - Most critical conditions given by Site Class C, CD, and D.
  - Unless AHJ determines Site Class DE, E, or F soils are present.
- ASCE 7 Publishes Hazards Maps only for "Default" Site Class

USGS Seismic Design Geodatabase is available through Various Hazard Tools:

- ASCE Hazard Tool: https://asce7hazardtool.online/
- NSHM Hazard Tool: https://earthquake.usgs.gov/hazards/interactive/
- ???

Site Classes

- Based on the known site subsurface conditions, each site is classified into one of the nine Site Classes (see Table 20.2.1, ASCE 7-22)

Site Class	Average Shear Wave Velocity $\bar{v}_s$ (ft/s) [3]
A. Hard rock	>5,000
B. Medium hard rock	> 3,000 – 5,000
BC. Soft Rock	> 2,100 – 3,000
C. Very dense sand or hard clay	> 1,450 – 2,100
CD. Dense sand or stiff clay	> 1,000 – 1,450
D. Medium dense sand or stiff clay	> 700 – 1,000
DE. Loose sand or medium stiff clay	> 500 – 700
E. Very loose sand or soft clay	≥ 500
F. Soils requiring site response analysis[1]	See Note 2

NOTES:

1. Site response analysis in accordance with Section 21.1 of ASCE 7-22
2. Per Section 20.2.1 of ASCE 7-22
3. Calculated Using Measured or Estimated Shear Wave Velocity Profile

"default site conditions": Most critical spectral acceleration at each period of Site Class C, Site Class CD, and Site Class D.

PGV Data for the 2018 National Seismic Hazard Model (NSHM)

for the Conterminous United States (https://doi.org/10.5066/P9XQ2NGB)

- PGV is appropriate parameter to estimate axial ground strain for TGD
- USGS has recently released PGV Hazard Map data
  - https://www.sciencebase.gov/catalog/item/60ee1234d34edebc7bca359e
- Probabilistic Seismic Hazard Curves
  - Peak Ground Velocity (PGV)
  - Ground Motion Values
  - Hazard Levels
    - 2% probability of exceedance in 50 years (2475 Years)
    - 5% probability of exceedance in 50 years (975 Years)
    - 10% probability of exceedance in 50 years (475 Years)
  - 0.05° x 0.05° grid
    - 24.4° to 50° N latitude
    - -125 ° to -65 ° E longitude
- PGV data includes
  - Basin amplification in the Western U.S. deep sedimentary basins
- For Eight National Earthquake Hazards Reduction Program (NEHRP) 2020 Site Classes
  - Site Class A/B ($V_{s,30}$ = 1,500 m/s)
  - Site Class B ($V_{s,30}$ = 1,080 m/s)
  - Site Class B/C ($V_{s,30}$ = 760 m/s)
  - Site Class C ($V_{s,30}$ = 530 m/s)
  - Site Class C/D ($V_{s,30}$ = 365 m/s)
  - Site Class D ($V_{s,30}$ = 260 m/s)
  - Site Class D/E ($V_{s,30}$ = 185 m/s)
  - Site Class E ($V_{s,30}$ = 150 m/s)

PGV Data for Site Class D (example)

Long, Lat

Annual Frequency of Exceedance

PGV

	A	B	C	D	E	F
1	name	lon	lat	4.04E-04	1.03E-03	2.10E-03
2	NSHMP Conterminous US	-82	24.4	2.70E+00	1.24E+00	5.75E-01
3	NSHMP Conterminous US	-81.95	24.4	2.71E+00	1.25E+00	5.79E-01
4	NSHMP Conterminous US	-81.9	24.4	2.73E+00	1.26E+00	5.85E-01
5	NSHMP Conterminous US	-81.85	24.4	2.74E+00	1.26E+00	5.88E-01
6	NSHMP Conterminous US	-81.8	24.4	2.76E+00	1.28E+00	5.94E-01
7	NSHMP Conterminous US	-81.75	24.4	2.77E+00		5.98E-01
8	NSHMP Conterminous US	-81.7	24.4	2.78E+00		6.00E-01
9	NSHMP Conterminous US	-81.65	24.4	2.79E+00	1.29E+00	6.03E-01
10	NSHMP Conterminous US	-81.6	24.4	2.80E+00	1.30E+00	6.05E-01
11	NSHMP Conterminous US	-81.55	24.4	2.81E+00	1.30E+00	6.08E-01
12	NSHMP Conterminous US	-81.5	24.4	2.81E+00	1.31E+00	6.10E-01
13	NSHMP Conterminous US	-81.45	24.4	2.82E+00	1.31E+00	6.13E-01
14	NSHMP Conterminous US	-81.4	24.4	2.83E+00	1.32E+00	6.14E-01

Contents of map.csv file

Long, Lat

20 Intensity Measure Levels (cm/s)

Annual Frequency of Exceedance

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	name	lon	lat	0.237	0.355	0.532	0.798	1.19	1.8	2.69	4.04	6.06	9.09	13.6	20.5	30.7	46	69	103	155	233	349	525
2	NSHMP Conterminous US	-82	24.4																				
3	NSHMP Conterminous US	-81.95	24.4	4.15E-03	3.10E-03	2.26E-03	1.59E-03	1.08E-03	6.86E-04	4.08E-04	2.20E-04	1.07E-04	4.60E-05	1.74E-05	5.60E-06	1.61E-06	4.25E-07	1.08E-07	2.87E-08	6.52E-09	1.25E-09	1.98E-10	2.33E-11
4	NSHMP Conterminous US	-81.9	24.4	4.17E-03	3.12E-03	2.28E-03	1.61E-03	1.10E-03	6.94E-04	4.13E-04	2.23E-04	1.08E-04	4.66E-05	1.76E-05	5.67E-06	1.64E-06	4.32E-07	1.10E-07	2.93E-08	6.67E-09	1.28E-09	2.03E-10	2.39E-11
5	NSHMP Conterminous US	-81.85	24.4	4.18E-03	3.13E-03	2.29E-03	1.62E-03	1.10E-03	6.97E-04	4.15E-04	2.24E-04	1.09E-04	4.69E-05	1.78E-05	5.74E-06	1.66E-06	4.41E-07	1.13E-07	3.01E-08	6.86E-09	1.32E-09	2.10E-10	2.46E-11
6	NSHMP Conterminous US	-81.8	24.4	4.20E-03	3.15E-03	2.31E-03	1.63E-03	1.11E-03	7.05E-04	4.20E-04	2.27E-04	1.10E-04	4.75E-05	1.80E-05	5.83E-06	1.69E-06	4.49E-07	1.15E-07	3.08E-08	7.04E-09	1.36E-09	2.16E-10	2.54E-11
7	NSHMP Conterminous US	-81.75	24.4	4.22E-03	3.17E-03	2.32E-03	1.64E-03	1.12E-03	7.09E-04	4.23E-04	2.28E-04	1.11E-04	4.79E-05	1.82E-05	5.90E-06	1.71E-06	4.58E-07	1.18E-07	3.17E-08	7.26E-09	1.41E-09	2.24E-10	2.63E-11
8	NSHMP Conterminous US	-81.7	24.4	4.22E-03	3.17E-03	2.33E-03	1.65E-03	1.12E-03	7.12E-04	4.24E-04	2.29E-04	1.12E-04	4.82E-05	1.83E-05	5.96E-06	1.74E-06	4.66E-07	1.21E-07	3.25E-08	7.49E-09	1.45E-09	2.32E-10	2.72E-11
9	NSHMP Conterminous US	-81.65	24.4	4.23E-03	3.19E-03	2.34E-03	1.66E-03	1.13E-03	7.16E-04	4.27E-04	2.31E-04	1.12E-04									1.51E-09	2.41E-10	2.84E-11
10	NSHMP Conterminous US	-81.6	24.4	4.24E-03	3.19E-03	2.34E-03	1.66E-03	1.13E-03	7.18E-04	4.28E-04	2.32E-04	1.13E-04	4.89E-05								1.56E-09	2.51E-10	2.95E-11
11	NSHMP Conterminous US	-81.55	24.4	4.25E-03	3.20E-03	2.35E-03	1.67E-03	1.14E-03	7.22E-04	4.31E-04	2.33E-04	1.14E-04	4.93E-05	1.88E-05	6.16E-06	1.82E-06	4.95E-07	1.31E-07	3.55E-08	8.27E-09	1.62E-09	2.61E-10	3.08E-11
12	NSHMP Conterminous US	-81.5	24.4	4.25E-03	3.21E-03	2.36E-03	1.67E-03	1.14E-03	7.24E-04	4.32E-04	2.34E-04	1.14E-04	4.96E-05	1.90E-05	6.22E-06	1.84E-06	5.05E-07	1.34E-07	3.66E-08	8.56E-09	1.69E-09	2.72E-10	3.22E-11
13	NSHMP Conterminous US	-81.45	24.4	4.26E-03	3.22E-03	2.37E-03	1.68E-03	1.15E-03	7.28E-04	4.34E-04	2.35E-04	1.15E-04	4.99E-05	1.91E-05	6.30E-06	1.87E-06	5.15E-07	1.37E-07	3.77E-08	8.86E-09	1.75E-09	2.84E-10	3.37E-11
14	NSHMP Conterminous US	-81.4	24.4	4.26E-03	3.22E-03	2.37E-03	1.68E-03	1.15E-03	7.30E-04	4.36E-04	2.36E-04	1.16E-04	5.02E-05	1.93E-05	6.36E-06	1.90E-06	5.25E-07	1.41E-07	3.89E-08	9.17E-09	1.82E-09	2.96E-10	3.52E-11
15	NSHMP Conterminous US	-81.35	24.4	4.28E-03	3.24E-03	2.39E-03	1.70E-03	1.16E-03	7.38E-04	4.41E-04	2.39E-04	1.17E-04	5.09E-05	1.95E-05	6.45E-06	1.93E-06	5.36E-07	1.45E-07	4.00E-08	9.48E-09	1.89E-09	3.09E-10	3.68E-11
16	NSHMP Conterminous US	-81.3	24.4	4.28E-03	3.25E-03	2.39E-03	1.70E-03	1.17E-03	7.40E-04	4.42E-04	2.40E-04	1.18E-04	5.11E-05	1.97E-05	6.52E-06	1.96E-06	5.46E-07	1.48E-07	4.12E-08	9.80E-09	1.96E-09	3.21E-10	3.84E-11
17	NSHMP Conterminous US	-81.25	24.4	4.30E-03	3.27E-03	2.41E-03	1.72E-03	1.18E-03	7.48E-04	4.47E-04	2.43E-04	1.19E-04	5.17E-05	1.99E-05	6.61E-06	1.99E-06	5.57E-07	1.52E-07	4.23E-08	1.01E-08	2.03E-09	3.34E-10	4.00E-11
18	NSHMP Conterminous US	-82	24.45	4.21E-03	3.14E-03	2.29E-03	1.62E-03	1.10E-03	7.00E-04	4.17E-04	2.25E-04	1.09E-04	4.69E-05	1.77E-05	5.67E-06	1.62E-06	4.20E-07	1.05E-07	2.76E-08	6.22E-09	1.18E-09	1.87E-10	2.20E-11
19	NSHMP Conterminous US	-81.95	24.45	4.22E-03	3.15E-03	2.30E-03	1.63E-03	1.11E-03	7.03E-04	4.19E-04	2.26E-04	1.10E-04	4.72E-05	1.78E-05	5.72E-06	1.64E-06	4.26E-07	1.07E-07	2.81E-08	6.33E-09	1.21E-09	1.90E-10	2.23E-11
20	NSHMP Conterminous US	-81.9	24.45	4.23E-03	3.16E-03	2.31E-03	1.63E-03	1.11E-03	7.06E-04	4.21E-04	2.27E-04	1.11E-04	4.76E-05	1.80E-05	5.78E-06	1.66E-06	4.33E-07	1.09E-07	2.87E-08	6.48E-09	1.24E-09	1.95E-10	2.28E-11
21	NSHMP Conterminous US	-81.85	24.45	4.24E-03	3.17E-03	2.32E-03	1.64E-03	1.12E-03	7.09E-04	4.23E-04	2.28E-04	1.11E-04	4.79E-05	1.81E-05	5.84E-06	1.68E-06	4.39E-07	1.11E-07	2.92E-08	6.62E-09	1.26E-09	1.99E-10	2.33E-11
22	NSHMP Conterminous US	-81.8	24.45	4.25E-03	3.18E-03	2.33E-03	1.65E-03	1.12E-03	7.12E-04	4.25E-04	2.30E-04	1.12E-04	4.82E-05	1.83E-05	5.90E-06	1.70E-06	4.47E-07	1.13E-07	3.00E-08	6.80E-09	1.30E-09	2.05E-10	2.40E-11

Contents of curves.csv file

- 2018_nshm_D_vs30_260_0p05_degree_maps
  - Maps
    - Gridded PGV ground motions
    - file header: name longitude, latitude, 2% probability of exceedance in 50 years, 5% probability of exceedance in 50 years, and 10% probability of exceedance in 50 years
  - Curves
    - Gridded PGV hazard curves
    - file header: name, longitude, latitude, intensity measure levels (20 columns) in centimeters per second
    - data: annual frequency of exceedance values are given for each intensity measure level at each grid point (name, lon, lat)

Spectral Response Acceleration

MCE_R Spectral Response Acceleration (S_{aM})

$$S_{aM} = min\left[S_{a,RT}, max\left(S_{a,84th}, S_{a,DLL}\right)\right]$$

Where,

- $S_{a,RT}$ is the risk-targeted spectral acceleration
- $S_{a,84th}$ is the 84th percentile spectral acceleration
- $S_{a,DLL}$ is the deterministic lower limit spectral acceleration given in Table 21.2-1 of ASCE 7-22 (ASCE 2022a).

Spectral Acceleration S_a

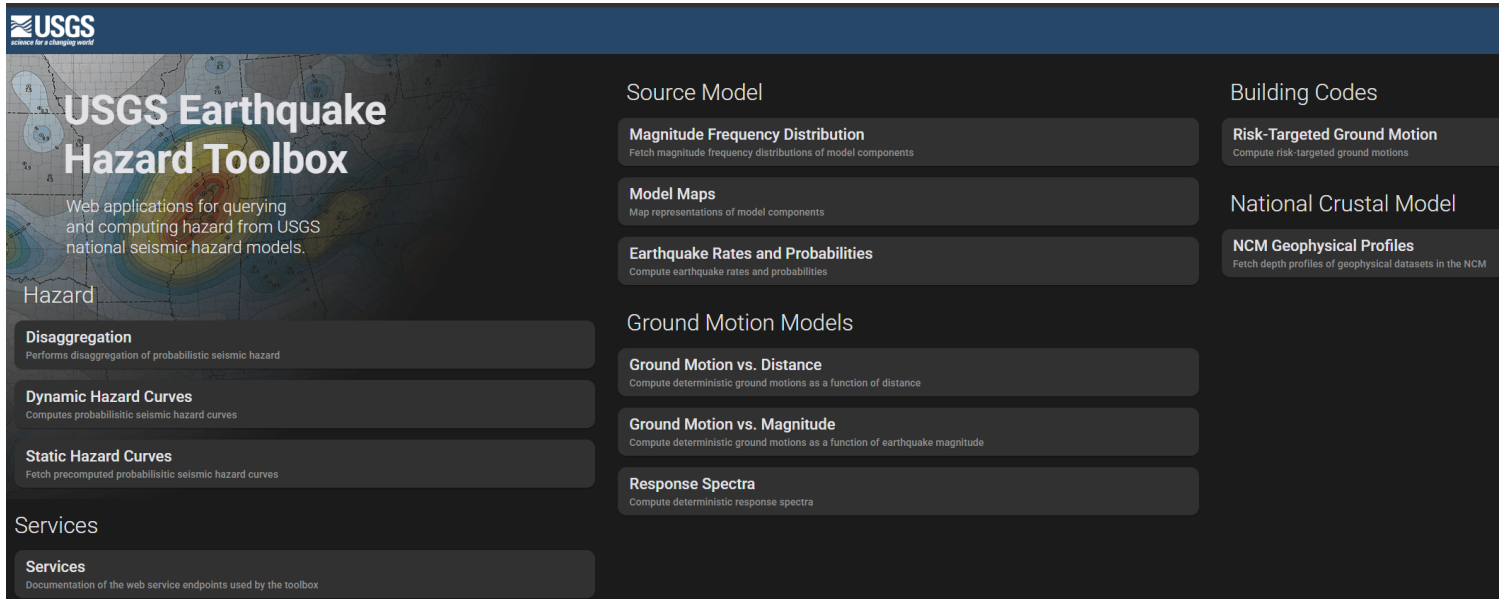
[corresponding to spectral period and site class]

$$S_a = max\left(S_{a,84th}, S_{a,DLL}\right)$$

- Online Hazard Tools
  - USGS Seismic Design Geodatabase for ASCE 7-22 (USGS Web Service)" [http://doi.org/10.5066/F7NK3C76]
  - ASCE 7 Hazard Tool [https://asce7hazardtool.online/]
  - Whole Building Design Guide: BSSC Tool For 2020 NEHRP Provisions Seismic Design Map Values [https://www.wbdg.org/additional-resources/tools/bssc-2020-nehrp]
- Online hazard tools include the site-specific meta data components utilized in the calculation of S_{aM}.
- Therefore, the spectral acceleration S_a corresponding to the spectral period and site class can be readily obtained.

USGS Earthquake Hazard Toolbox

- Seismic parameters can be obtained using publicly available tools in the USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/)



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Design Tables for Axial Strain Capacity to Resist Transient Ground Deformation

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Estimation of Ground Strain

- Body Waves (S-Wave)

$$\varepsilon_g = \frac{V_{max}}{2C_S} \qquad (3.7)$$

where C_S is theoretically the apparent propagation velocity of the S-wave with respect to the ground surface given in Equation 3.1 and Table 3.2.

C_s = 1000 m/s for Category IV

C_s = 1500 m/s for Category III

C_s = 2000 m/s for Category II

- Surface Waves (R-Wave)

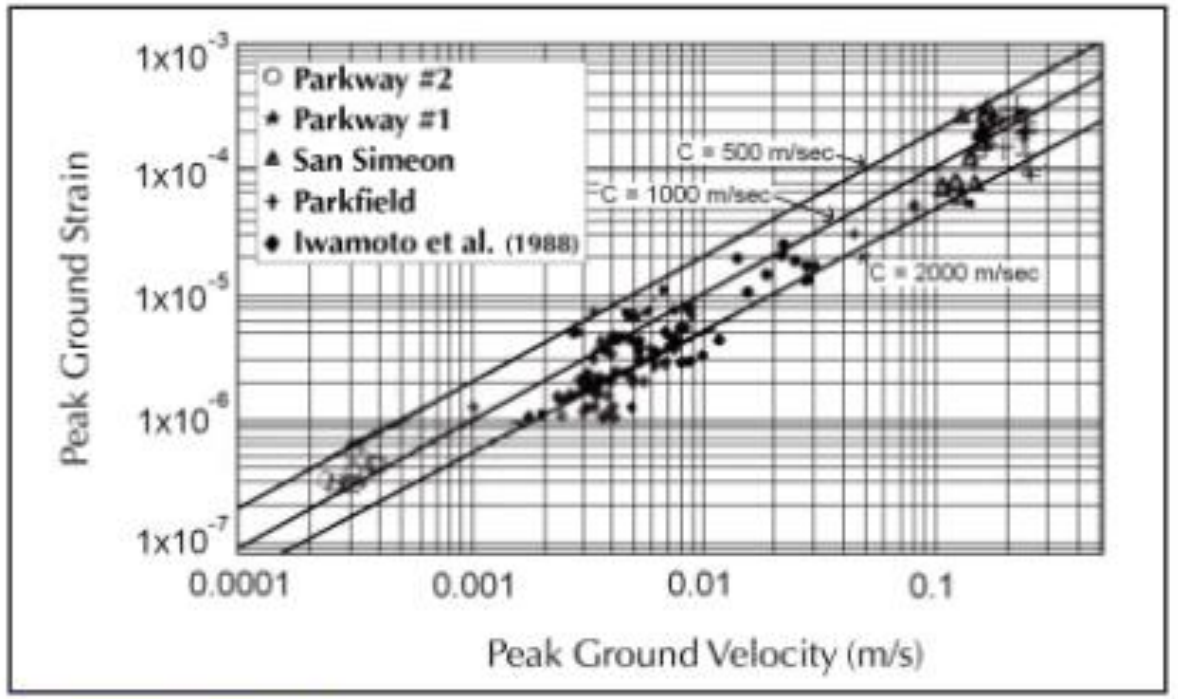
$$\varepsilon_g = \frac{V_{max}}{C_R} \qquad (3.5)$$

where V_{max} is the maximum horizontal ground velocity in the direction of wave propagation and C_R is the propagation velocity of the R-wave.

C_R = Min (2Vs,250) m/s for Category IV

C_R = Min (2Vs, 500) m/s for Category III

C_R = Min (2Vs, 1000) m/s for Category II



After Paolucci and Smerzini, 2008

Figure 3.9 Peak Ground Strain as function of Peak Ground Velocity

Reference: O'Rourke, M.J., & Liu, J.X. (2012). "Seismic Design of Buried and Offshore Pipelines," MCEER Monograph No. MCEER-12-MN04, MCEER, Buffalo, New York, November 28.

Design Table: Axial Strain Performance Capacity for TGD - Criticality Category IV

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

PGV is more appropriate parameter to estimate ground strain for TGD, which can be obtained from USGS Earthquake Hazard Toolbox .

Parameter (+ and -)	Class	Seismic Strain Demand
Axial Strain (α)	α_A	0.01% up to 0.1%
	α_B	0.1% up to 0.5%
	α_C	0.5% up to 1%
	α_D	1% or greater*

Reference:

Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines

Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Axial Strain Performance from Transient Ground Deformation
Criticality Category IV

Peak Ground Velocity, PGV (cm/sec)[1]	Axial Strain Performance Classes α_A, α_B, α_C, α_D[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
PGV ≤ 25	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	Site Specific[5]
25 < PGV ≤ 50	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
50 < PGV ≤ 75	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
75 < PGV ≤ 100	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
100 < PGV ≤ 125	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_C	
125 < PGV ≤ 150	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_C	
150 < PGV ≤ 175	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_C	
175 < PGV ≤ 200	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_C	
200 < PGV ≤ 225	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_C	
225 < PGV ≤ 250	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
250 < PGV ≤ 275	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
275 < PGV ≤ 300	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
300 < PGV ≤ 325	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
325 < PGV ≤ 350	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
350 < PGV ≤ 375	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
375 < PGV ≤ 400	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
400 < PGV ≤ 425	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
425 < PGV ≤ 450	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
450 < PGV ≤ 475	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
475 < PGV ≤ 500	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	
500 < PGV ≤ 525	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	
525 < PGV	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	Detailed.	

NOTE(S):

1. PGV Values are obtained from PGV Data for the 2018 National Seismic Hazard Model (NSHM), published by USGS (https://doi.org/10.5066/P9XQ2NGB) corresponding to Longitude, Latitude, and Site Class. For Category I/II pipelines obtain PGV corresponding to 475-year retuen period; For Category III pipelines obtain PGV corresponding to 975-year return period; For Category IV pipelines obtain PGV corresponding to 2475-year retuen period.
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Axial Strain Performance Categories α_A, α_B,α_C,α_D are as defined in the ground strain table by Davis et al. (2019).
4. Detailed design required.
5. Site specific seismic evaluation and detailed design required.

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Design Table: Axial Strain Performance Capacity for TGD - Criticality Category III

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

PGV is more appropriate parameter to estimate ground strain for TGD, which can be obtained from USGS Earthquake Hazard Toolbox .

Parameter (+ and -)	Class	Seismic Strain Demand
Axial Strain (α)	α_A	0.01% up to 0.1%
	α_B	0.1% up to 0.5%
	α_C	0.5% up to 1%
	α_D	1% or greater*

Reference:

Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines

Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Axial Strain Performance from Transient Ground Deformation
Criticality Category III

Peak Ground Velocity, PGV (cm/sec)[1]	Axial Strain Performance Classes α_A, α_B, α_C, α_D[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
PGV ≤ 25	α_A	α_A	α_A	α_A	α_A	α_A	α_A	α_A	Site Specific[5]
25 < PGV ≤ 50	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
50 < PGV ≤ 75	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
75 < PGV ≤ 100	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
100 < PGV ≤ 125	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
125 < PGV ≤ 150	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_C	
150 < PGV ≤ 175	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_C	
175 < PGV ≤ 200	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
200 < PGV ≤ 225	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
225 < PGV ≤ 250	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_C	
250 < PGV ≤ 275	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_C	
275 < PGV ≤ 300	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_D	
300 < PGV ≤ 325	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_D	
325 < PGV ≤ 350	α_C	α_C	α_C	α_C	α_C	α_C	α_C	α_D	
350 < PGV ≤ 375	α_C	α_C	α_C	α_C	α_C	α_C	α_D	α_D	
375 < PGV ≤ 400	α_C	α_C	α_C	α_C	α_C	α_C	α_D	α_D	
400 < PGV ≤ 425	α_C	α_C	α_C	α_C	α_C	α_C	α_D	α_D	
425 < PGV ≤ 450	α_C	α_C	α_C	α_C	α_C	α_C	α_D	α_D	
450 < PGV ≤ 475	α_C	α_C	α_C	α_C	α_C	α_C	α_D	α_D	
475 < PGV ≤ 500	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
500 < PGV ≤ 525	α_D	α_D	α_D	α_D	α_D	α_D	α_D	α_D	
525 < PGV	α_D	α_D	α_D	α_D	α_D	α_D	α_D	Detailed.	

NOTE(S):

1. PGV Values are obtained from PGV Data for the 2018 National Seismic Hazard Model (NSHM), published by USGS (https://doi.org/10.5066/P9XQ2NGB) corresponding to Longitude, Latitude, and Site Class. For Category I/II pipelines obtain PGV corresponding to 475-year retuen period; For Category III pipelines obtain PGV corresponding to 975-year retuen period; For Category IV pipelines obtain PGV corresponding to 2475-year retuen period.
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Axial Strain Performance Categories α_A, α_B,α_C,α_D are as defined in the ground strain table by Davis et al. (2019).
4. Detailed design required.
5. Site specific seismic evaluation and detailed design required.

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Design Table: Axial Strain Performance Capacity for TGD - Criticality Category II

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

PGV is more appropriate parameter to estimate ground strain for TGD, which can be obtained from USGS Earthquake Hazard Toolbox .

Parameter (+ and -)	Class	Seismic Strain Demand
Axial Strain (α)	α_A	0.01% up to 0.1%
	α_B	0.1% up to 0.5%
	α_C	0.5% up to 1%
	α_D	1% or greater*

Reference:

Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines

Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Axial Strain Performance from Transient Ground Deformation
Criticality Category II

Peak Ground Velocity, PGV (cm/sec)[1]	Axial Strain Performance Classes α_A, α_B, α_C, α_D[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
PGV ≤ 25	α_A	α_A	α_A	α_A	α_A	α_A	α_A	α_A	Site Specific[5]
25 < PGV ≤ 50	α_A	α_A	α_A	α_A	α_A	α_A	α_B	α_B	
50 < PGV ≤ 75	α_A	α_A	α_A	α_A	α_B	α_B	α_B	α_B	
75 < PGV ≤ 100	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
100 < PGV ≤ 125	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_B	
125 < PGV ≤ 150	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_C	
150 < PGV ≤ 175	α_B	α_B	α_B	α_B	α_B	α_B	α_B	α_C	
175 < PGV ≤ 200	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
200 < PGV ≤ 225	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
225 < PGV ≤ 250	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
250 < PGV ≤ 275	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_C	
275 < PGV ≤ 300	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_D	
300 < PGV ≤ 325	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_D	
325 < PGV ≤ 350	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_D	
350 < PGV ≤ 375	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
375 < PGV ≤ 400	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
400 < PGV ≤ 425	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
425 < PGV ≤ 450	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
450 < PGV ≤ 475	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
475 < PGV ≤ 500	α_C	α_C	α_C	α_C	α_C	α_C	α_D	α_D	
500 < PGV ≤ 525	α_C	α_C	α_C	α_C	α_C	α_D	α_D	α_D	
525 < PGV	α_C	α_C	α_C	α_C	α_C	α_D	α_D	Detailed.	

NOTE(S):

1. PGV Values are obtained from PGV Data for the 2018 National Seismic Hazard Model (NSHM), published by USGS (https://doi.org/10.5066/P9XQ2NGB) corresponding to Longitude, Latitude, and Site Class. For Category I/II pipelines obtain PGV corresponding to 475-year retuen period; For Category III pipelines obtain PGV corresponding to 975-year retuen period; For Category IV pipelines obtain PGV corresponding to 2475-year retuen period.
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Axial Strain Performance Categories α_A, α_B,α_C,α_D are as defined in the ground strain table by Davis et al. (2019).
4. Detailed design required.
5. Site specific seismic evaluation and detailed design required.

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Design Table: Axial Strain Performance Capacity for TGD - Criticality Category I

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

PGV is more appropriate parameter to estimate ground strain for TGD, which can be obtained from USGS Earthquake Hazard Toolbox.

Suitable for small diameter pipes up to 8-inches; for larger diameter pipes, Criticality type II design tables shall be used.

Parameter (+ and -)	Class	Seismic Strain Demand
Axial Strain (α)	α_A	0.01% up to 0.1%
	α_B	0.1% up to 0.5%
	α_C	0.5% up to 1%
	α_D	1% or greater*

Reference:
Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Axial Strain Performance from Transient Ground Deformation
Criticality Category I

Peak Ground Velocity, PGV (cm/sec)[1]	Axial Strain Performance Classes α_A, α_B, α_C, α_D[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
PGV ≤ 25	α_A	α_A	α_A	α_A	α_A	α_A	α_A	α_A	Site Specific[5]
25 < PGV ≤ 50	α_A	α_A	α_A	α_A	α_A	α_A	α_B	α_B	
50 < PGV ≤ 75	α_A	α_A	α_A	α_A	α_B	α_B	α_B	α_B	
75 < PGV ≤ 100	α_A	α_A	α_A	α_A	α_B	α_B	α_B	α_B	
100 < PGV ≤ 125	α_A	α_A	α_A	α_B	α_B	α_B	α_B	α_B	
125 < PGV ≤ 150	α_A	α_A	α_A	α_B	α_B	α_B	α_B	α_C	
150 < PGV ≤ 175	α_A	α_A	α_B	α_B	α_B	α_B	α_B	α_C	
175 < PGV ≤ 200	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
200 < PGV ≤ 225	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
225 < PGV ≤ 250	α_B	α_B	α_B	α_B	α_B	α_B	α_C	α_C	
250 < PGV ≤ 275	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_C	
275 < PGV ≤ 300	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_D	
300 < PGV ≤ 325	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_D	
325 < PGV ≤ 350	α_B	α_B	α_B	α_B	α_B	α_C	α_C	α_D	
350 < PGV ≤ 375	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
375 < PGV ≤ 400	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
400 < PGV ≤ 425	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
425 < PGV ≤ 450	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
450 < PGV ≤ 475	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
475 < PGV ≤ 500	α_B	α_B	α_B	α_B	α_C	α_C	α_D	α_D	
500 < PGV ≤ 525	α_B	α_B	α_B	α_B	α_C	α_D	α_D	α_D	
525 < PGV	α_B	α_B	α_B	α_C	α_C	α_D	α_D	Detailed.	

NOTE(S):

1. PGV Values are obtained from PGV Data for the 2018 National Seismic Hazard Model (NSHM), published by USGS (https://doi.org/10.5066/P9XQ2NGB) corresponding to Longitude, Latitude, and Site Class. For Category I/II pipelines obtain PGV corresponding to 475-year retuen period; For Category III pipelines obtain PGV corresponding to 975-year retuen period; For Category IV pipelines obtain PGV corresponding to 2475-year retuen period.
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Axial Strain Performance Categories α_A, α_B,α_C,α_D are as defined in the ground strain table by Davis et al. (2019).
4. Detailed design required.
5. Site specific seismic evaluation and detailed design required.

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Design Tables for Axial Strain Capacity to Resist Transient Ground Deformation

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Estimation of Curvature

TRANSIENT GROUND STRAIN AND CURVATURE

Using the function $y(x) = PGA * \sin(\pi fx / C)$, the transient axial ground strain α_t and curvature κ_t are (Newmark, 1967):

$$\alpha_t = \frac{PGV}{C} \tag{4}$$

$$\kappa_t = \frac{PGA}{C^2} \tag{5}$$

Where PGV and PGA are the peak ground particle velocity and peak ground acceleration, respectively, f is the wave frequency, and C is the apparent wave propagation velocity. For S-waves C ranges from about 2 km/s to 5 km/s (O'Rourke and Liu, 2012). For R-waves C is the phase velocity corresponding to a wavelength equal to four times the separation distance, which in turn is approximately $0.9V_s$ (O'Rourke and Liu, 2012), where V_s is the shear wave velocity of the near surface soil and can range from 100 m/s for relatively loose soft soils to over 1,000 m/s for firm hard ground. PGV can range from below 10 cm/s in the far field to over 200 cm/s in the near field. PGA can range from below 0.01g in the far field to over 1g in the near field.

Reference:

- Davis, C. A., Rajah, S., Wham, B. P., and Heubach, W. F. (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.
- O'Rourke, M.J., & Liu, J.X. (2012). "Seismic Design of Buried and Offshore Pipelines," MCEER Monograph No. MCEER-12-MN04, MCEER, Buffalo, New York, November 28.

Design Table: Radius of Curvature Performance Capacity for TGD - Criticality Category VI

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

Spectral Acceleration is more appropriate parameter to estimate radius of curvature for TGD, which can be obtained from USGS Earthquake Hazard Toolbox.

Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	$R_A > 344$m (1130 ft)	$\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) $< R_B \leq 344$m (1130 ft)	$0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) $< R_C \leq 115$ m (376 ft)	$0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft)
	ρ_D	$R_D \leq 46$ m (150 ft)	$\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft)

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Radius of Curvature Performance from Transient Ground Deformation - Criticality Category IV

Spectral Acceleration at 1s , $S_{M1}(g)$[1]	Radius of Curvature Performance Classes $\rho_A, \rho_B, \rho_C, \rho_D$[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
$S_{M1} \leq 0.2$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	Design for PGD
0.2 g < $S_{M1} \leq 0.4$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.4 g < $S_{M1} \leq 0.6$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.6 g < $S_{M1} \leq 0.8$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
0.8 g < $S_{M1} \leq 1.0$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.0 g < $S_{M1} \leq 1.2$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.2 g < $S_{M1} \leq 1.4$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.4 g < $S_{M1} \leq 1.6$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.6 g ≤ S_{M1}	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	

NOTE(S):

1. The MCE_R, 5% damped, spectral response acceleration parameter at a period of 1s adjusted for site class effects as defined in Section 11.4.4 of ASCE 7-16
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Radius of Curvature Performance Categories $\rho_A, \rho_B, \rho_C, \rho_D$ are as defined in the ground strain table by Davis et al. (2019).

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Design Table: Radius of Curvature Performance Capacity for TGD - Criticality Category III

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

Spectral Acceleration is more appropriate parameter to estimate radius of curvature for TGD, which can be obtained from USGS Earthquake Hazard Toolbox.

Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	$R_A > 344$m (1130 ft)	$\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) $< R_B \leq 344$m (1130 ft)	$0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) $< R_C \leq 115$ m (376 ft)	$0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft)
	ρ_D	$R_D \leq 46$ m (150 ft)	$\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft)

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Radius of Curvature Performance from Transient Ground Deformation - Criticality Category III

Spectral Acceleration at 1s , $S_{M1}(g)$[1]	Radius of Curvature Performance Classes $\rho_A, \rho_B, \rho_C, \rho_D$[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
$S_{M1} \leq 0.2$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	Design for PGD
0.2 g < $S_{M1} \leq 0.4$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.4 g < $S_{M1} \leq 0.6$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.6 g < $S_{M1} \leq 0.8$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.8 g < $S_{M1} \leq 1.0$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.0 g < $S_{M1} \leq 1.2$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.2 g < $S_{M1} \leq 1.4$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.4 g < $S_{M1} \leq 1.6$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.6 g ≤ S_{M1}	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	

NOTE(S):

1. The MCE_R, 5% damped, spectral response acceleration parameter at a period of 1s adjusted for site class effects as defined in Section 11.4.4 of ASCE 7-16
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Radius of Curvature Performance Categories $\rho_A, \rho_B, \rho_C, \rho_D$ are as defined in the ground strain table by Davis et al. (2019).

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Design Table: Radius of Curvature Performance Capacity for TGD - Criticality Category II

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

Spectral Acceleration is more appropriate parameter to estimate radius of curvature for TGD, which can be obtained from USGS Earthquake Hazard Toolbox.

Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	$R_A > 344$m (1130 ft)	$\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) $< R_B \leq 344$m (1130 ft)	$0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) $< R_C \leq 115$ m (376 ft)	$0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft)
	ρ_D	$R_D \leq 46$ m (150 ft)	$\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft)

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Radius of Curvature Performance from Transient Ground Deformation - Criticality Category II

Spectral Acceleration at 1s , $S_{M1}(g)$[1]	Radius of Curvature Performance Classes $\rho_A, \rho_B, \rho_C, \rho_D$[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
$S_{M1} \leq 0.2$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	Design for PGD
0.2 g < $S_{M1} \leq 0.4$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.4 g < $S_{M1} \leq 0.6$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.6 g < $S_{M1} \leq 0.8$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
0.8 g < $S_{M1} \leq 1.0$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	
1.0 g < $S_{M1} \leq 1.2$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.2 g < $S_{M1} \leq 1.4$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.4 g < $S_{M1} \leq 1.6$ g	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	
1.6 g ≤ S_{M1}	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C	

NOTE(S):

1. The MCE_R, 5% damped, spectral response acceleration parameter at a period of 1s adjusted for site class effects as defined in Section 11.4.4 of ASCE 7-16
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Radius of Curvature Performance Categories $\rho_A, \rho_B, \rho_C, \rho_D$ are as defined in the ground strain table by Davis et al. (2019).

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Design Table: Radius of Curvature Performance Capacity for TGD - Criticality Category I

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7-22 & USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/) .

Spectral Acceleration is more appropriate parameter to estimate radius of curvature for TGD, which can be obtained from USGS Earthquake Hazard Toolbox.

Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	$R_A > 344$m (1130 ft)	$\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) $< R_B \leq 344$m (1130 ft)	$0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) $< R_C \leq 115$ m (376 ft)	$0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft)
	ρ_D	$R_D \leq 46$ m (150 ft)	$\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft)

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Design Table for Radius of Curvature Performance from Transient Ground Deformation - Criticality Category I

Spectral Acceleration at 1s , $S_{M1}(g)$[1]	Radius of Curvature Performance Classes $\rho_A, \rho_B, \rho_C, \rho_D$[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
$S_{M1} \leq 0.2$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	Design for PGD
0.2 g < $S_{M1} \leq 0.4$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	
0.4 g < $S_{M1} \leq 0.6$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	
0.6 g < $S_{M1} \leq 0.8$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	
0.8 g < $S_{M1} \leq 1.0$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	
1.0 g < $S_{M1} \leq 1.2$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	
1.2 g < $S_{M1} \leq 1.4$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	
1.4 g < $S_{M1} \leq 1.6$ g	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	
1.6 g ≤ S_{M1}	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	ρ_A	

NOTE(S):

1. The MCE_R, 5% damped, spectral response acceleration parameter at a period of 1s adjusted for site class effects as defined in Section 11.4.4 of ASCE 7-16
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3. Radius of Curvature Performance Categories $\rho_A, \rho_B, \rho_C, \rho_D$ are as defined in the ground strain table by Davis et al. (2019).
4. This table is suitable for small diameter pipes up to 8-inches; for larger diameter pipes, Criticality type II design table should be used.

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Design Tables for Connection Force Capacity to Resist Transient Ground Deformation

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Pipe Strain in Relation to Ground Strain
- w/ and w/o Slippage at the Soil-Pipe Interface

- Pipe strain is assumed conservatively as equal to ground strain (No Slippage)

$$F = EA\varepsilon_{cr}$$

  - Where,
    F- Max axial force
    E – Young's modulus of the material
    A – Cross-sectional area of the pipe
    ε_{cr} - Pipe strain
    ε_g - Ground strain

- With this assumption, the maximum axial force generated in the pipe, is dependent on the pipe material properties.
- In reality,
  - Pipe strain is equal to Ground strain, when there is no slippage
  - Pipe strain is less than Ground strain, when there is slippage

Reference: Shinozuka, M. and Koike, T. (1979). "Estimation of Structural Strains in Underground Lifeline Pipes," Technical Report No. NSF-PFR-78-15049-CU-4, Department of Civil Engineering and Engineering Mechanics, Columbia University in the New York, March.

- Shinozuka et al. (2013) derived the following:
  - $F \approx \pi D \frac{\lambda}{4} \tau_{cr}$ (full slippage)
  - $F \approx qD \frac{\lambda}{2} \tau_{cr}$ (Partial slippage) $1 \leq q \leq \pi/2$
  - Where,
    D – diameter of the pipe
    λ – wavelength
    τ_{cr} - shear stress at which slippage initiates
- CFC force can now be estimated without the pipe material properties (except the critical shear stress at the interface)
  - For small strains – assume onset of slippage
  - For large ground strains – assume full slippage

Design Table: Connection Force Capacity for TGD - Criticality Category IV

CLASS	CONNECTION FORCE CAPACITY (lbs/in)	
	Lower limit	Upper Limit
Φ_A	0	4282.7
Φ_B	4282.7	8565.3
Φ_C	8565.3	17130.5
Φ_D	17130.5	∞

Notes:
1. This table is applicable for both continuous and segmented pipelines.
2. This table is applicable for all common water & wastewater pipeline materials.

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- Shinozuka, M. and Koike, T. (1979). "Estimation of Structural Strains in Underground Lifeline Pipes," Technical Report No. NSF-PFR-78-15049-CU-4, Department of Civil Engineering and Engineering Mechanics, Columbia University in the New York, March.
- Rajah, S. (2026) "Prescriptive Approach to Design Buried Pipelines for Connection Force Demand due to Transient and Permanent Ground Deformations", Pipelines 2026, ASCE.

Design Table for Connection Force Capacity Demands from Transient Ground Deformation
Criticality Category IV

Peak Ground Velocity, PGV (cm/sec)[1]	Connection Force Capacity Performance Classes Φ_A, Φ_B, Φ_C, Φ_D[3]								
	Site Class A[2]	Site Class B[2]	Site Class BC[2]	Site Class C[2]	Site Class CD[2]	Site Class D[2]	Site Class DE[2]	Site Class E[2]	Site Class F[2]
PGV ≤ 25	Φ_A	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Site Specific[5]
25 < PGV ≤ 50	Φ_A	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	
50 < PGV ≤ 75	Φ_A	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	
75 < PGV ≤ 100	Φ_A	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	
100 < PGV ≤ 125	Φ_A	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	Φ_B	
125 < PGV ≤ 150	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
150 < PGV ≤ 175	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
175 < PGV ≤ 200	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
200 < PGV ≤ 225	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
225 < PGV ≤ 250	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
250 < PGV ≤ 275	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
275 < PGV ≤ 300	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
300 < PGV ≤ 325	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
325 < PGV ≤ 350	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
350 < PGV ≤ 375	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
375 < PGV ≤ 400	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
400 < PGV ≤ 425	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
425 < PGV ≤ 450	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
450 < PGV ≤ 475	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
475 < PGV ≤ 500	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
500 < PGV ≤ 525	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	
525 < PGV	Φ_B	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	Φ_C	

NOTE(S):
1. PGV Values are obtained from PGV Data for the 2018 National Seismic Hazard Model (NSHM), published by USGS (https://doi.org/10.5066/P9XQ2NGB) corresponding to Longitude, Latitude, and Site Class. For Category I/II pipelines obtain PGV corresponding to 475-year return period; For Category III pipelines obtain PGV corresponding to 975-year return period; For Category IV pipelines obtain PGV corresponding to 2475-year return period.
2. Site Class classifications per Section 11.4.2 and Chapter 20 of ASCE 7-22. If site class is not known, or assumed to be default, the most stringent design of the Site Classes C, CD and D should be used.
3.Connection Force Capacity Performance Categories ΦA, ΦB,ΦC,ΦD are as defined in the Connection Force Capacity Classification Table.
4. Detailed design required.
5. Site specific seismic evaluation and detailed design required.

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Design Tables for Permanent Ground Deformation from Lateral Spread Hazards

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Estimating Lateral Spread Displacement - Gillins & Bartlett (2014) Modifications to Youd et al. (2012)

- For Free-face Conditions:

$$\log(D_H) = -8.552 + 1.318M - 1.073\log(R^*) - 0.016R + 0.445log(W) + 0.592\,log(T_{15}) - 0.683x_1 - 1.200x_2 + 0.252x_3 - 0.040x_4 - 0.535x_5$$

- For gently sloping Conditions:

$$\log(D_H) = -8.208 + 1.318M - 1.073\log(R^*) - 0.016R + 0.337\,log(S) + 0.592\,log(T_{15}) - 0.683x_1 - 1.200x_2 + 0.252x_3 - 0.040x_4 - 0.535x_5$$

Where, D_H= the estimated lateral ground displacement, in meters; M = the moment magnitude of the earthquake; R = the nearest horizontal or map distance from the site to the seismic energy source, in kilometers; R^*= modified source distance value given by eq. (2); W = the free-face ratio defined as the height H of the free face divided by the distance L from the base of the free face to the point in question, in percent.; T_{15} = the cumulative thickness of saturated granular layers with corrected blow counts, $(N_1)_{60}$, less than 15, in meters; F_{15} = the average fines content (fraction of sediment sample passing a No. 200 sieve) for granular materials included within T_{15}, in percent; and $D50_{15}$ = the average mean grain size for granular materials within T_{15} , in millimeters.

$$R^* = R + R_o \quad (2)$$

Where, R_o = a distance factor that is a function of earthquake magnitude, M, defined by eq. (3), as:

$$R_o = 10^{(0.89M - 5.64)} \quad (3)$$

Valid Ranges of Input Parameters

Youd et al. (2002) identified valid ranges of statistically significant input parameters for the application of their MLR model, as follows:

- Moment magnitudes of the earthquakes: $6 \leq M \leq 8$
- Free face ratio ($H = 100H/L$ %): $1 < W(\%) < 20$
- Ground slope (S%): $0.1 < S(\%) < 6$
- Cumulative thickness of saturated granular layers, with $(N_1)_{60} \leq 15$: $1 < T_{15}(m) < 15$
- Fines content for materials within T_{15}: F_{15}, within the bounds shown in Youd et al. (2002).
- Mean grain size for materials within T_{15}: $D50_{15}$, within the bounds shown in Youd et al. (2002).

Youd et al. (2002) also identified valid ranges for the depth to the top layer of the liquefiable layers, Z_T, in meters, as $1 < Z_T(m) < 10$. This range limitation has been included to envelope the ranges of liquefiable depths included in the dataset, but the parameter itself has been determined to be non-significant to the MLR model.

Reference:

- **Gillins, D. T., and Bartlett, S. F. (2014). "Multilinear regression equations for predicting lateral spread displacement soil type and CPT data." J. Geotech. Geoenviron. Eng..**
- Rajah, S. (2023) "Prescriptive Approach to Design Buried Pipelines for Permanent Ground Deformations from Liquefaction-Induced Lateral Spread Hazards ", Pipelines 2023, ASCE.

Design Table: Axial Strain & Radius of Curvature Performance Demand from - Lateral Spread (Free Face) PGD

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7.

Parameter·(+·and·-)¤	Class¤	Seismic·Strain·Capacity¤	
		Continuous·pipelines¤	Segmental·pipelines¤
Axial·Strain·(ε_a)·or·Joint·Movement·(u)¤	α_A¤	ε_a·<·0.1%¤	u/L·<·0.1%¤
	α_B¤	0.1%·≤·ε_a·<·0.5%·¤	0.1%·≤·u/L·<·0.5%·¤
	α_C¤	0.5%·≤·ε_a·<·1%¤	0.5%·≤·u/L·<·1%¤
	α_D¤	ε_a·≥·1%¤	u/L·≥·1%¤
Radius· of· Curvature· (R)·or·Deflection·Angle·(ϕ)¶ ¤	ρ_A¤	R·>·500D¤	ϕD/L·<·0.115·deg¤
	ρ_B¤	100D·<·R·≤·500D¤	0.115·deg·≤·ϕD/L·<·0.573·deg¤
	ρ_C¤	50D·<·R·≤·100D¤	0.573·deg·≤·ϕD/L·<·1.15·deg¤
	ρ_D¤	R·≤·50D·¤	ϕD/L·≥·1.15·deg¤

NOTE:¶
- → D=Diameter·of·pipe¶
- → u/L=ratio·of·elongation/contraction·of·the·pipe·joint·(u)·over·the·pipe·segment·length·(L)¤

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- **Gillins, D. T., and Bartlett, S. F. (2014). "Multilinear regression equations for predicting lateral spread displacement soil type and CPT data." J. Geotech. Geoenviron. Eng.,**
- Rajah, S. (2023) "Prescriptive Approach to Design Buried Pipelines for Permanent Ground Deformations from Liquefaction-Induced Lateral Spread Hazards ", Pipelines 2023, ASCE.
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Free-face ratio, W (%)	Axial Strain Performance Categories $\alpha_A, \alpha_B, \alpha_C, \alpha_D$[1]				Radius of Curvature Performance Categories $\rho_A, \rho_B, \rho_C, \rho_D$[2]			
	Criticality Category				Criticality Category			
	I	II	III	IV	I	II	III	IV
1.0	α_A	α_C	α_D	α_D	ρ_A	ρ_B	ρ_B	ρ_B
2.0	α_A	α_D	α_D	α_D	ρ_A	ρ_B	ρ_B	ρ_C
3.0	α_A	α_D	α_D	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
4.0	α_A	α_D	α_D	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
6.0	α_A	α_D	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
8.0	α_A	α_D	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
10.0	α_A	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
12.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
14.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
16.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
18.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
20.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C

NOTE(S):

1. Axial Strain Performance Categories $\boldsymbol{\alpha_A}$, $\boldsymbol{\alpha_B}$, $\boldsymbol{\alpha_C}$ & $\boldsymbol{\alpha_D}$ are as defined in the ground strain table in Davis et al. (2019).
2. Radius of Curvature Performance Categories $\boldsymbol{\rho_A}$, $\boldsymbol{\rho_B}$, $\boldsymbol{\rho_C}$ & $\boldsymbol{\rho_D}$ are as defined in the ground strain table in Davis et al. (2019)
3. Design table approach cannot be used; detailed design required.

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Design Table: Axial Strain & Radius of Curvature Performance Demand from - Lateral Spread (Gently Sloping) PGD

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7.

Parameter·(+·and·-)¤	Class¤	Seismic·Strain·Capacity¤	
		Continuous·pipelines¤	Segmental·pipelines¤
Axial·Strain·(ε_a)·or·Joint¤ Movement·(u)¤	α_A¤	ε_a·<·0.1%¤	u/L·<·0.1%¤
	α_B¤	0.1%·≤·ε_a·<·0.5%·¤	0.1%·≤·u/L·<·0.5%·¤
	α_C¤	0.5%·≤·ε_a·<·1%¤	0.5%·≤·u/L·<·1%¤
	α_D¤	ε_a·≥·1%¤	u/L·≥·1%¤
Radius· of· Curvature· (R)· or·Deflection·Angle·(ϕ)¶ ¤	ρ_A¤	R·>·500D¤	ϕD/L·<·0.115·deg¤
	ρ_B¤	100D·<·R·≤·500D¤	0.115·deg·≤·ϕD/L·<·0.573·deg¤
	ρ_C¤	50D·<·R·≤·100D¤	0.573·deg·≤·ϕD/L·<·1.15·deg¤
	ρ_D¤	R·≤·50D·¤	ϕD/L·≥·1.15·deg¤

NOTE:¶
- → D—Diameter·of·pipe¶
- → u/L—ratio·of·elongation/contraction·of·the·pipe·joint·(u)·over·the·pipe·segment·length·(L)¤

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- **Gillins, D. T., and Bartlett, S. F. (2014). "Multilinear regression equations for predicting lateral spread displacement soil type and CPT data." J. Geotech. Geoenviron. Eng..**
- Rajah, S. (2023) "Prescriptive Approach to Design Buried Pipelines for Permanent Ground Deformations from Liquefaction-Induced Lateral Spread Hazards ", Pipelines 2023, ASCE.
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

Free-face ratio, W (%)	Axial Strain Performance Categories $\alpha_A, \alpha_B, \alpha_C, \alpha_D$[1]				Radius of Curvature Performance Categories $\rho_A, \rho_B, \rho_C, \rho_D$[2]			
	Criticality Category				Criticality Category			
	I	II	III	IV	I	II	III	IV
0.1	α_A	α_C	α_D	α_D	ρ_A	ρ_B	ρ_B	ρ_B
0.5	α_A	α_D	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
1.5	α_A	α_D	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
2.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
2.5	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
3.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
3.5	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
4.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
4.5	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_C
5.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_D
.5.5	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_D
6.0	α_B	See Note 3	See Note 3	See Note 3	ρ_A	ρ_B	ρ_B	ρ_D

NOTE(S):

1. Axial Strain Performance Categories α_A, α_B, α_C & α_D are as defined in the ground strain table in Davis et al. (2019).
2. Radius of Curvature Performance Categories ρ_A, ρ_B, ρ_C & ρ_D are as defined in the ground strain table in Davis et al. (2019)
3. Design table approach cannot be used; detailed design required.

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Design Table: Connection Force Capacity Performance Demand from - Lateral Spread (Free Face) PGD

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7.

Parameter·(+·and·-)¤	Class¤	Seismic·Strain·Capacity¤	
		Continuous·pipelines¤	Segmental·pipelines¤
Axial·Strain·(ε_a)·or·Joint Movement·(u)¤	α_A¤	ε_a·<·0.1%¤	u/L·<·0.1%¤
	α_B¤	0.1%·≤·ε_a·<·0.5%·¤	0.1%·≤·u/L·<·0.5%·¤
	α_C¤	0.5%·≤·ε_a·<·1%¤	0.5%·≤·u/L·<·1%¤
	α_D¤	ε_a·≥·1%¤	u/L·≥·1%¤
Radius· of· Curvature· (R)· or·Deflection·Angle·(ϕ)¶ ¤	ρ_A¤	R·>·500D¤	ϕD/L·<·0.115·deg¤
	ρ_B¤	100D·<·R·≤·500D¤	0.115·deg·≤·ϕD/L·<·0.573·deg¤
	ρ_C¤	50D·<·R·≤·100D¤	0.573·deg·≤·ϕD/L·<·1.15·deg¤
	ρ_D¤	R·≤·50D·¤	ϕD/L·≥·1.15·deg¤

NOTE:¶
- → D·—Diameter·of·pipe¶
- → u/L·--ratio·of·elongation/contraction·of·the·pipe·joint·(u)·over·the·pipe·segment·length·(L)¤

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- **Gillins, D. T., and Bartlett, S. F. (2014). "Multilinear regression equations for predicting lateral spread displacement soil type and CPT data." J. Geotech. Geoenviron. Eng.,**
- Rajah, S. (2023) "Prescriptive Approach to Design Buried Pipelines for Permanent Ground Deformations from Liquefaction-Induced Lateral Spread Hazards ", Pipelines 2023, ASCE.
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

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Design Table: Connection Force Capacity Performance Demand from - Lateral Spread (Gently Sloping) PGD

Prescriptive Design Table based on Seismic Parameters Readily available from ASCE 7.

Parameter·(+·and·-)¤	Class¤	Seismic·Strain·Capacity¤	
		Continuous·pipelines¤	Segmental·pipelines¤
Axial·Strain·(ε_a)·or·Joint·Movement·(u)¤	α_A¤	ε_a <·0.1%¤	u/L <·0.1%¤
	α_B¤	0.1%·≤·ε_a <·0.5%·¤	0.1%·≤·u/L <·0.5%·¤
	α_C¤	0.5%·≤·ε_a <·1%¤	0.5%·≤·u/L <·1%¤
	α_D¤	ε_a·≥·1%¤	u/L·≥·1%¤
Radius· of· Curvature· (R)·or·Deflection·Angle·(ϕ)¶¤	ρ_A¤	R·>·500D¤	ϕD/L <·0.115·deg¤
	ρ_B¤	100D·<·R·≤·500D¤	0.115·deg·≤·ϕD/L·<·0.573·deg¤
	ρ_C¤	50D·<·R·≤·100D¤	0.573·deg·≤·ϕD/L·<·1.15·deg¤
	ρ_D¤	R·≤·50D·¤	ϕD/L·≥·1.15·deg¤

NOTE:¶
- → D—Diameter·of·pipe¶
- → u/L·-·ratio·of·elongation/contraction·of·the·pipe·joint·(u)·over·the·pipe·segment·length·(L)¤

Reference:

- Working draft of the ASCE MOP (2026) "Seismic Design of Buried Water/Wastewater Pipelines
- **Gillins, D. T., and Bartlett, S. F. (2014). "Multilinear regression equations for predicting lateral spread displacement soil type and CPT data." J. Geotech. Geoenviron. Eng..**
- Rajah, S. (2023) "Prescriptive Approach to Design Buried Pipelines for Permanent Ground Deformations from Liquefaction-Induced Lateral Spread Hazards ", Pipelines 2023, ASCE.
- Davis, C. A., S. Rajah, B. P. Wham, and W. F. Heubach (2019). "Strain Demands on Buried Pipelines from Earthquake-Induced Ground Movements," Proceedings: Pipelines 2019 (pp. 357–367). Reston, VA: American Society of Civil Engineers.

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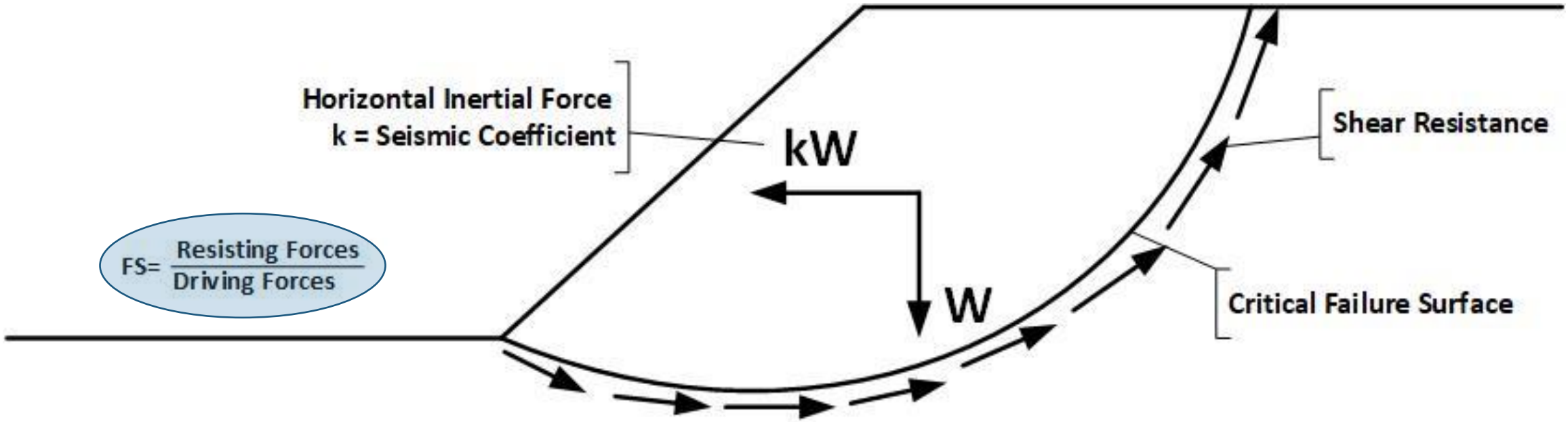
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Design Tables for Permanent Ground Deformation from Landslide Hazards

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Pseudostatic Slope Stability



"... the effect of the ***seismic loading*** is approximated by a destabilizing horizontal inertial force, expressed as a ***product of*** a ***seismic coefficient (k)*** approximating the effects of the seismic loading and the ***weight of the sliding mass (W)*** …"

Seismic Coefficient

Bray and Macedo (2019)

$$k = exp\left[\frac{-a + \sqrt{b}}{0.49}\right]$$

$$a = 2.491 - 0.344 \ln\left(S_a(1.3T_s)\right)$$

- **Improved equations (compared to Bray and Travasarou (2009)) based on larger data set**
- Site Dependent
- Allowable displacement dependent

$$b = a^2 - 0.98\left\{\ln(D_a) + 5.894 - 2.703 \ln\left(S_a(1.3T_s)\right) + 0.089\left[\ln\left(S_a(1.3T_s)\right)\right]^2 - 3.152T_s + 0.910(T_s)^2 - 0.6070M - \varepsilon\right\}$$

when $T_s \geq 0.10\ sec.$

$$b = a^2 - 0.98\left\{\ln(D_a) + 4.551 - 2.703 \ln\left(S_a(1.3T_s)\right) + 0.089\left[\ln\left(S_a(1.3T_s)\right)\right]^2 + 9.688T_s - 0.6070M - \varepsilon\right\}$$

when $T_s < 0.10\ sec.$

- D_a is the allowable seismic displacement in centimeters
- T_s is the fundamental period of sliding mass in seconds
- ***S_a (1.3T_s) is the 5% damped spectral acceleration at a period of 1.3T_s in units of g for site conditions corresponding to outcropping ground below potential sliding mass***
- M is moment magnitude of the earthquake
- ε is the percent exceedance of this displacement threshold
  - $\varepsilon = 0$ for median displacement estimate
  - *σ is the standard deviation*
  - **$\varepsilon = 1x\sigma = 0.74$ for 16% exceedance displacement estimate).**

Allowable Seismic Displacement Threshold Values

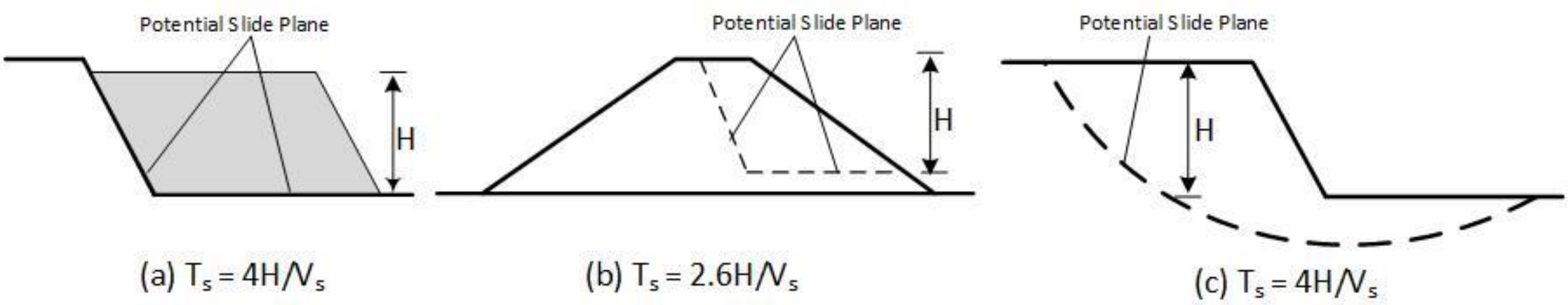
Blake et al. (2002)

- Two different threshold values to establish a screening criterion
  - Majority opinion: 5 cm
  - Minority opinion: 15 cm
- Allowable displacement level for selection of seismic coefficient
  - Criticality of the structure on or within the slope
  - Engineering judgment.

An allowable seismic displacement threshold of 5 cm was used to establish the seismic coefficients to develop the design tables.

Initial & Degraded Fundamental Period of the Sliding Mass

Bray (2007)



Where,

- H is the average height of the potential sliding mass
- V_s is the average shear wave velocity of the sliding mass.

For the purposes of the use of the design tables, the estimate of initial fundamental period using the equation $T_s = 4H/V_s$ should yield reasonable outcome.

ESTIMATING SEISMIC SLOPE DISPLACEMENTS
Bray and Macedo (2019)

- Non-zero seismic slope displacement (D) in centimeters

$$\ln(D) = a_1 - 2.482\ln(k_y) - 0.244(\ln(k_y))^2 + 0.344\ln(k_y)\ln(S_a(1.3T_s)) + 2.649\ln(S_a(1.3T_s)) - 0.090(\ln(S_a(1.3T_s)))^2 + a_2T_s + a_3(T_s)^2 + 0.603M_w \pm \epsilon_1$$

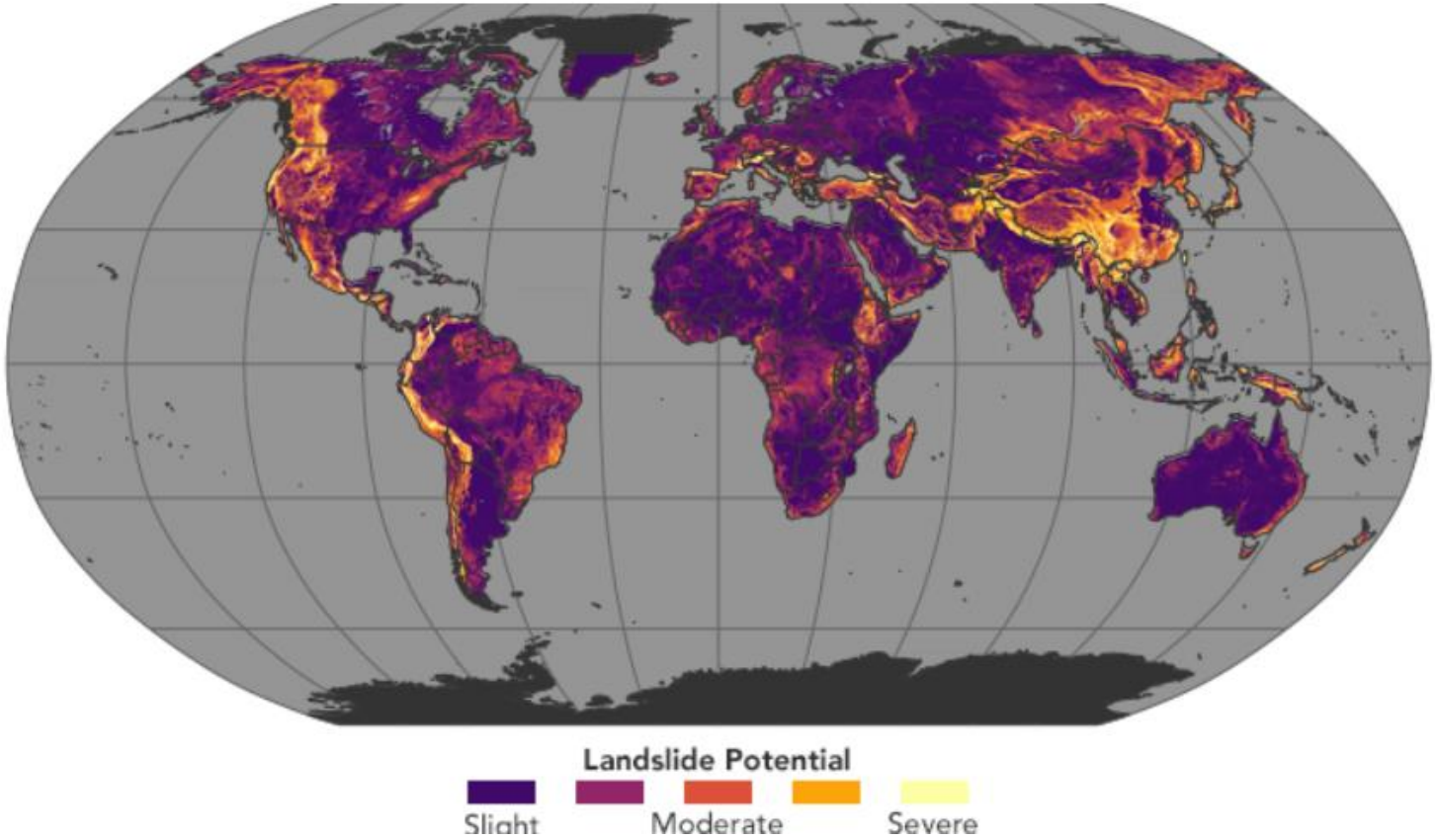
Where,

- k_y= yield coefficient
- T_s = fundamental period of sliding mass in seconds
- $S_a(1.3T_s)$ = 5% damped spectral acceleration at a period of $1.3T_s$ in units of g for site conditions corresponding to outcropping ground below potential sliding mass
- M_w= moment magnitude
- ϵ_1 = normally distributed random variable with zero mean and standard deviation (σ) of 0.72
- a_1=-5.981; a_2=3.223; and a_3=-0.945, for systems with $T_s \geq 0.10$ sec
- a_1=-4.684; a_2=9.471; and a_3=0.0, for systems with $T_s < 0.10$ sec

- Assumption is that yield coefficient (k_y) to remain constant during seismic shaking.
- Materials within the slope do not experience severe strength loss during the earthquake shaking.

LANDSLIDE SUSCEPTIBILITY MAPS

- NASA (Stanley and Kirschbaum 2017) landslide susceptibility map
  - uses five levels of susceptibility to landsliding
    - Very low (VL)
    - Low (L)
    - Moderate (M)
    - High (H)
    - Very high (VH)



Estimated Yield Acceleration for Landslide Susceptibility Categories

Slide Category	Amplification Factor [1]	Degraded Fundamental Period ($1.3T_s$), sec [2]	NASA Landslide Susceptibility Categories [3]				
			Very Low (VL)	Low (L)	Moderate (M)	High (H)	Very High (VH)
Shallow Slide	1.00	0.2	0.3	0.25	0.2	0.15	0.1
Gentle (< 15º grade) slopes;	1.00	0.5	0.80	0.60	0.40	0.2	0.05
Slightly Steep (15º to 30º grade) slopes	1.25	0.5	0.70	0.40	0.20	0.1	0.05
Moderately Steep (30º to 45º grade) slopes	1.25	0.5	0.20	0.15	0.10	0.04	NS[4]
Steep (45º to 60º grade) slopes	1.25	0.5	0.1	0.05	0.03	NS[4]	NS[4]
Very Steep (>60º grade) slopes	1.50	0.5	NS[4]	NS[4]	NS[4]	NS[4]	NS[4]

NOTES:

(1) Topographic amplification factor for shallow slides in moderately steep slopes is 1.25 as recommended by Rathje and Bray (2001); and 1.5 for steep slopes (>60 degrees) per Ashford and Sitar (2002).

(2) Spectral acceleration at degraded period is 1.3 times the initial fundamental period of the slope is the most efficient ground motion parameter for all slopes, per Bray and Macedo (2019).

(3) Per Kirschbaum and Stanley 2018.

(4) NS – Not suitable for prescribed design tables; site-specific evaluations required.

- Six Slide Categories Considered:
  - Shallow Slide
  - Gentle (< 15º grade) slopes
  - Slightly Steep (15º to 30º grade) slopes
  - Moderately Steep (30º to 45º grade) slopes
  - Steep (45º to 60º grade) slopes
  - Very Steep (>60º grade) slopes
- Five Landslide Susceptibility Categories
  - Very Low
  - Low
  - Moderate
  - High
  - Very High

Summary – Prescriptive Design Tables for PGD from Landslides

- The prescriptive design recommendations are presented in the form of design tables tabulated against
  - Pipeline criticality categories
  - Site-specific landslide susceptibility
  - Site-specific spectral acceleration
- Simplifying assumptions were made regarding the fundamental period of the sliding mass.
- Key approaches utilized and key assumptions made in the development of the prescriptive design tables for pipeline design to accommodate PGDs from landslide hazards have been documented.
- Prescriptive design tables for pipeline design to accommodate PGDs from landslide hazards have been developed.
  - Four Criticality Categories
    - I, II, III, and IV
  - Six Slide Categories Considered:
    - Shallow Slide
    - Gentle (< 15º grade) slopes
    - Slightly Steep (15º to 30º grade) slopes
    - Moderately Steep (30º to 45º grade) slopes
    - Steep (45º to 60º grade) slopes
    - Very Steep (>60º grade) slopes
  - Five Landslide Susceptibility Categories
    - Very low (VL)
    - Low (L)
    - Moderate (M)
    - High (H)
    - Very high (VH)

Design Tables

Criticality Category IV Pipelines in Moderately Steep (30º to 45º) Slope Landslides

- Four Criticality Categories
  - I, II, III, and IV
- Six Slide Categories Considered:
  - Shallow Slide
  - Gentle (< 15º grade) slopes
  - Slightly Steep (15º to 30º grade) slopes
  - Moderately Steep (30º to 45º grade) slopes
  - Steep (45º to 60º grade) slopes
  - Very Steep (>60º grade) slopes
- Five Landslide Susceptibility Categories

CONNCTION FORCE CAPACITY TABLES ARE BEING DEVELOPED

Site Specific Spectral Acceleration at Fundamental Period of the Sliding Mass, S_{aM}(g) [1]	Criticality Category IV – Moderately Steep (30° to 45°) Slope Landslides									
	Axial Strain Performance Categories $\alpha_A, \alpha_B, \alpha_C, \alpha_D$ [3]					Radius of Curvature Performance Categories $\rho_A, \rho_B, \rho_C, \rho_D$ [4]				
	NASA Landslide Susceptibility Classification [2]					NASA Landslide Susceptibility Classification [2]				
	Very Low (VL) [2]	Low (L) [2]	Moderate (M) [2]	High (H) [2]	Very High (VH) [2]	Very Low (VL) [2]	Low (L) [2]	Moderate (M) [2]	High (H) [2]	Very High (VH) [2]
$S_{aM} \leq 0.2$ g	α_A	α_A	α_A	α_A	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B
0.2 g < $S_{aM} \leq$ 0.4 g	α_A	α_A	α_A	α_B	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B
0.4 g < $S_{aM} \leq$ 0.6 g	α_A	α_A	α_B	α_B	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B
0.6 g < $S_{aM} \leq$ 0.8 g	α_A	α_B	α_B	α_C	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B
0.8 g < $S_{aM} \leq$ 1.0 g	α_B	α_B	α_B	α_C	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_B
1.0 g < $S_{aM} \leq$ 1.2 g	α_B	α_B	α_B	α_D	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C
1.2 g < $S_{aM} \leq$ 1.4 g	α_B	α_B	α_C	α_D	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C
1.4 g < $S_{aM} \leq$ 1.6 g	α_B	α_B	α_C	α_D	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_B	ρ_C
1.6 g < $S_{aM} \leq$ 1.8 g	α_B	α_C	α_C	α_D	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_C	ρ_C
1.8 g < $S_{aM} \leq$ 2.0 g	α_B	α_C	α_D	Detailed [5]	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_C	ρ_C
2.0 g < $S_{aM} \leq$ 2.2 g	α_C	α_C	α_D	Detailed [5]	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_C	ρ_C
2.2 g < $S_{aM} \leq$ 2.4 g	α_C	α_C	α_D	Detailed [5]	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_C	ρ_C
2.4 g < $S_{aM} \leq$ 2.6 g	α_C	α_D	α_D	Detailed [5]	Detailed [5]	ρ_B	ρ_B	ρ_B	ρ_C	ρ_C
2.6 g < $S_{aM} \leq$ 2.8 g	α_C	α_D	α_D	Detailed [5]	Detailed [5]	ρ_B	ρ_B	ρ_C	ρ_C	ρ_C
2.8 g < $S_{aM} \leq$ 3.0 g	α_C	α_D	Detailed [5]	Detailed [5]	Detailed [5]	ρ_B	ρ_B	ρ_C	ρ_C	ρ_C
3.0 g ≤ S_{aM}	α_D	α_D	Detailed [5]	Detailed [5]	Detailed [5]	ρ_B	ρ_C	ρ_C	ρ_C	ρ_D

NOTE(S):

1. Site specific spectral response acceleration at degraded fundamental period of the sliding mass
2. NASA Landslide Susceptibility Classification (Kirschbaum and Stanley 2018)
3. Axial Strain Performance Categories α_A, α_B, α_C & α_D are as defined in the ground strain table in Davis et al. (2019).
4. Radius of Curvature Performance Categories ρ_A, ρ_B, ρ_C & ρ_D are as defined in the ground strain table in Davis et al. (2019)
5. Detailed design required.

Concurrent and Future Guidelines/Standards

Concurrent Efforts

- A White Paper is being concurrently developed (Initial Draft is almost ready)
- ASCE/UESI 91-YY Standard: Structural Testing and Evaluation of Pipeline Systems (STEPS): Assessment for Earthquakes and Other Geohazards
  - Draft has undergone public comment
  - Expected to be published in late 2026

Future Standards

- After publication of MOP
  - Standard for Seismic Design of Buried Water/Wastewater Pipelines

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Summary

- ASCE is currently developing
  - A Manual of Practice (MOP) on Seismic Design of Buried Water/Wastewater Pipelines
  - A White Paper on Seismic Performance of Pipe Product Systems
  - A Standard “Structural Testing and Evaluation of Pipeline Systems (STEPS)” to provide laboratory testing guidance
- The proposed MOP provides Prescriptive and Site-Specific Design Approaches for the Design of Buried Water/Wastewater Pipelines
  - Prescriptive Design Tables Based on
    - Location Specific Seismic Hazards
    - Subsurface Conditions (Site Class)
    - Pipeline Criticality Category
  - Site Specific Design Approach

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Questions?

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