20.12 LIQUEFACTION AND LATERAL SPREADING

20.12.1 GENERAL

This BDM provides guidelines for designing against seismically induced liquefaction and lateral spreading. According to the SDC (Caltrans, 2025), soils with a potential for liquefaction and lateral spreading are considered non-competent and are classified as Class S2 soils.

Seismically induced soil liquefaction (liquefaction) may cause excessive ground displacement manifested by settlement and lateral spreading. Lateral spreading can be defined as the horizontal displacement of gently sloping surface or subsurface material resulting from the build-up of excess pore water pressure or liquefaction during an earthquake. This has caused substantial damage to bridges and other structures in past earthquakes. Liquefaction can significantly affect the design of foundations and bridge support elements. The effects may be mitigated through ground improvements or structural design. Due to the complexity of soil-foundation-structure interaction, projects involving potentially liquefiable soil require close communication between the bridge designer and the geotechnical professional.

Potential for soil liquefaction and associated ground displacement, such as lateral spreading, is typically identified by the geoprofessional.

20.12.2 NOTATION

CIDH = Cast-In-Drilled-Hole

CISS = Cast-In-Steel-Shell

20.12.3 CAUSES, EFFECTS, AND CLASSIFICATION

Soil liquefaction is a general term used to characterize a phenomenon during ground shaking by which saturated granular materials undergo a transformation from a solid to a liquid-like state as a result of generated excess pore water pressures. This transformation causes a significant reduction in the soil shear strength and stiffness. The excess pore pressure is usually induced by the tendency of loose granular materials to compact when subjected to cyclic shear deformation under undrained conditions. Soils most susceptible to generating excess pore water pressure are loose to medium-dense granular soils such as sands, silty sands, silty to sandy gravels, and non-plastic or low plasticity silts.

In loose saturated sandy soil, the loss of shear strength induced by excess pore water pressure may lead to large shear deformations. The dissipation of excess pore water pressure after shaking has stopped, typically leads to changes in volume and gain in shear strength. The type of ground failure induced by liquefaction is highly dependent on the initial state of the soil and on the magnitude of static shear stress acting on the ground before the onset of liquefaction.

Designing for soil liquefaction requires evaluating its effects on bridge foundations. This evaluation is typically performed by the project geo-professional and usually involves three steps:

Step 1 An evaluation is performed to identify potentially liquefiable materials and to assess whether these materials are likely to liquefy under the design earthquake motion.

Step 2 If liquefaction potential has been positively identified, an assessment of permanent ground displacements resulting from liquefaction is performed.

This step is of fundamental importance because permanent ground displacements usually generate large demands on bridge foundations, and hence, are responsible for a significant increase in foundation costs.

Step 3 An evaluation of the magnitude of forces acting on the bridge foundation generated by the permanent ground displacement is performed.

This step requires frequent interaction between the geo-professional and the bridge designer since the magnitude of such forces is inherently dependent on the response of the foundation system to ground displacements.

The severity of liquefaction on bridge foundations depends on various factors, including subsurface conditions, design ground motion parameters, and the likelihood of developing severe permanent ground displacements (see Table 20.12.3-1). In general, the severity can be classified as follows:

1. **Negligible** – No saturated liquefiable materials are present at or in the vicinity of the bridge site, or the level of shaking is not sufficient to induce excessive pore water pressure to cause soil liquefaction or reduced soil shear strength.

2. **Liquefaction without Lateral Spreading** – While liquefaction is likely to occur at the bridge site, surface and subsurface conditions exist such that permanent lateral ground displacements are not likely to occur. Excess pore water pressure will reduce the axial and lateral load-carrying capacity of pile foundations. Dissipation of excess pore water will result in post-liquefaction volumetric strains, which will cause surface and subsurface settlements.

3. **Liquefaction with Lateral Spreading** – Liquefaction is likely to occur at the bridge site, and surface/subsurface conditions exist such that permanent lateral ground displacements are likely to occur (i.e., lateral spreading and settlements). Conditions favorable for the development of permanent lateral ground displacement include, but are not limited to, gently sloping ground surfaces, level ground adjacent to a free face of a body of water such as a river, lake, or ocean, and approach embankments or channel side slopes constructed over liquefiable

material. The latter is the most severe case of liquefaction related ground failure, as significant lateral pressures may be exerted on the foundation.

Evaluation of bridges under severe earthquake shaking has indicated that most damage to bridge structures at liquefied sites was related to horizontal ground movements in the presence of competent, non-liquefiable soil (stiff crust) overlying liquefied material.

Table 20.12.3-1 Liquefaction Severity Levels

Liquefaction Severity	Example of Subsurface Conditions	Possible Effects on Bridge Foundation	Mitigating Alternatives
Negligible	• Subsurface materials are not prone to liquefy	• N/A	• N/A
Liquefaction without Lateral Spreading	• Acceleration levels high enough to cause liquefaction. • Surface and subsurface conditions not favorable for the development of permanent lateral ground displacements	• Reduction in shear strength of liquefiable soils affects axial and lateral capacity of bridge foundations; foundation performance may be affected. • Permanent horizontal displacements unlikely to develop. • Post-liquefaction settlements will likely develop. • Depending on the subsurface stratification, down drag forces may develop.	• Strengthening of existing pile foundations likely to be required. • New piles may need to have higher lateral capacity and/or extend deeper to compensate for reduced axial and lateral load-carrying capacity. • Countermeasures against reduced axial and lateral capacity, as well as potential down drag forces, include larger pile size, CISS piles or CIDH piles.

Liquefaction with Lateral Spreading	• Acceleration levels high enough to cause liquefaction.Continuous liquefiable material across site.
	• Surface and subsurface conditions favorable for the development of permanent lateral ground displacement, such as:
	  ◦ Gently sloping ground surface, or level ground adjacent to a free face.
	  ◦ Sloping base of liquefiable deposit.
	  ◦ Approach embankments built over liquefiable material.
		• Reduction in shear strength of liquefiable soils severely affects lateral and axial capacity of bridge foundations; foundation performance is considerably affected.
		• Permanent horizontal displacements will develop and adversely affect pile foundations, pile caps, and abutments. High soil pressure on foundation systems expected if a stiff, non- liquefiable deposit overlies liquefied material.
		• Post-liquefaction settlements may be significant. Down drag forces will affect axial load carrying capacity of pile foundations under permanent loading conditions.
			• Foundation strengthening required. Countermeasures against reduced axial capacity, down drag forces, and lateral pressure include CISS piles or large diameter CIDH piles.
			• Ground improvement may be considered in conjunction with foundation strengthening.
			• Bridge system may need to be modified to allow larger permanent ground displacements without collapse.
			• Increase ductility of foundation to absorb estimated permanent lateral displacement.
			• Bridge relocation to an alternate non-liquefiable site should be considered.
			• Extend pile tip into more competent soil or rock layer

20.12.4 IMPACT ON PROJECT SCOPE, COST, AND SCHEDULE

Liquefaction can have a tremendous impact on project cost, schedule, and scope. It is important to request a subsurface site investigation as early as possible to identify liquefaction potential and its severity in the project development process.

For bridge widening projects, there may be a need to retrofit the existing adjoining structure and design the widening for liquefaction and induced ground movement. In some cases, it may be advantageous to use the widening of the structure as a liquefaction mitigation/retrofit measure for the existing structure.

Project sites with liquefiable materials usually require relatively large and/or ductile foundations to account for the additional demands. Therefore, foundations designed to resist liquefaction will typically result in higher foundation costs relative to those for similar structures in Class S1 (i.e., competent) soil. The cost increase is dependent on factors such as the type and extent of liquefiable material, ground motion parameters, and foundation type.

It is important to recognize that a substantial portion of the cost associated with soil liquefaction is attributed to countermeasures aimed at mitigating permanent ground displacements. Permanent ground displacements such as surface settlement, lateral spreading, and slope failure of approach embankments normally result in higher demands on bridge foundations.

The resulting mitigation alternatives must be described in sufficient detail so that alternatives may be evaluated for impacts on traffic, environmental, or roadway construction sequence, or construction safety practices.

The cost analysis should include comparing non-structural mitigation measures, such as soil densification, stone columns, etc., to structural mitigation measures, to determine the most effective solution to mitigate the effects of liquefaction, lateral spreading, and embankment instability.

20.12.5 PROJECT RISKS AND MITIGATION STRATEGIES

When liquefaction/lateral spreading is identified for bridges in a project, it may require mitigation. Mitigation measures for liquefaction/lateral spreading should ensure that the resulting design is consistent with the seismic performance criteria for the project. Per the Caltrans Seismic Design Criteria (SDC), the design of bridges on a site with liquefaction hazard, but without lateral spreading, is covered by the provisions of the SDC. The design of bridges on sites with liquefaction and lateral spreading hazards, however, requires a project-specific design criteria.

Table 20.12.5-1 identifies potential risks to the project and possible mitigation strategies. Selecting the appropriate mitigation strategy usually requires adequate subsurface investigation at the project site.

Table 20.12.5-1 Liquefaction Risks & Mitigation Strategies

Project Type	Project Risks	Risk Mitigation Strategies
New or replacement bridges & New portion of bridge widenings	**With Subsurface Exploration.** • Significantly reduces substantial risk; scope, cost, and schedule must reflect mitigating alternatives	• N/A
	Without Subsurface Exploration. • Unknown high-risk scope. (Note: some mitigating alternatives may affect the Environmental Document) • Higher costs • Unknown schedule impacts	• Undertake subsurface exploration and liquefaction assessment to define scope, costs, and schedule. • Assume mitigation alternatives are necessary and covered in the Environmental Document. Risks must be identified and provided to project stakeholders.
	Subsurface Exploration at Planning Stage. • Minimal unidentified risk expected	• N/A
	No Subsurface Exploration at Planning Stage. • High-risk scope (Note: some mitigation alternatives may affect the Environmental Document) • Higher costs • Unknown schedule impacts	• Perform liquefaction assessment and identify mitigation alternatives

Table 20.12.5-1 Liquefaction Risks & Mitigation Strategies (Continued)

Project Type	Project Risks	Risk Mitigation Strategies
Existing bridges (Widening or Major Modifications)	**Without Subsurface Exploration** • Unknown high-risk scope (Note: some mitigation alternatives may affect the Environmental Document). • Higher costs • Unknown schedule impacts	• Undertake subsurface exploration and liquefaction assessment to define scope, costs, and schedule. • Assume that mitigation alternatives are necessary and have been included in the Environmental Document. Risks must be identified and provided to project stakeholders.
	With Subsurface Exploration. • Significantly reduces substantial risk; scope, cost, and schedule must reflect mitigating alternatives	• N/A
	Subsurface Exploration at Planning Stage. • Minimal unidentified risk expected	• N/A
	No Subsurface Exploration at Planning Stage. • High-risk scope (Note: some mitigation alternatives may affect the Environmental Document) • Higher costs • Unknown schedule impacts	• Perform liquefaction assessment and identify mitigation alternatives
Existing Bridge (Minor Modifications)	• Identification of liquefaction/lateral spreading could significantly affect project cost, scope, and schedule. As minor modifications are not considered to include foundations, liquefaction mitigation is beyond the planned scope of the project and should not be included. Projects requiring foundation work should be considered a major modification	• If potential liquefaction exists based on geotechnical recommendations, provide this information to the Caltrans Office of Earthquake Engineering, Analysis, and Research for evaluation

20.12.6 REFERENCE

1. Caltrans. (2025). *Seismic Design Criteria*, Version 2.1. California Department of Transportation, Sacramento, CA.