# 20-14 QUANTIFYING THE IMPACTS OF SOIL LIQUEFACTION AND LATERAL SPREADING ON PROJECT DELIVERY

## Introduction

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/subsurface material as a result of pore pressure build-up 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 with potentially liquefiable soil require close communication between the bridge designer and the geotechnical engineer.

Potential for soil liquefaction and associated ground displacement such as lateral spreading are typically identified during the project foundation investigation phase and are included with the Foundation Report provided by the geotechnical designer. Identification of liquefaction potential may occur at the planning study phase if adequate geotechnical information is available, or may not occur until the subsurface site investigation is completed.

The cost associated with liquefaction and ground displacement can be difficult to assess before completing a comprehensive analysis. Often project schedules and resource constraints prevent the completion of an adequate analysis at the time project programming or other preliminary costs are needed. In this memo, cost ranges derived from limited historical data have been provided as a tool to develop preliminary cost estimates prior to completing a final design.

The effects of liquefaction and associated ground displacement on structures, and their combination with inertial effects, are a complex issue and the subject of considerable research. The process outlined in this memo provides the designer with guidelines for quantifying the effects of seismically induced liquefaction and lateral spreading on project delivery.

# I – 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 increased pore water pressures. This transformation causes a significant reduction of the soil shear strength and stiffness. The excess pore pressure is normally 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 loose to firm 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. Dissipation of excess pore water pressure after shaking has stopped normally leads to changes in volume and shear strength gain. 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 an evaluation of its effects on bridge foundations. This evaluation is typically performed by the project geotechnical designer and normally 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 large 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 geotechnical designer 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. In general, the severity can be classified as follows:

1. **Negligible** – No saturated liquefiable material 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 or to cause soil liquefaction.

2. **Liquefaction without Lateral Spreading** – When liquefaction is likely to occur at the bridge site, surface and subsurface conditions can exist such that permanent lateral ground displacements are not likely to occur. Excess pore water pressure will reduce 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** – When liquefaction is likely to occur at the bridge site, surface and subsurface conditions can 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.

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

Designers should also note that, in many instances, the generated excess pore water pressure may not be sufficient to trigger liquefaction, but still lead to a substantial reduction in soil shear strength, which may lead to significant ground displacement. This condition can also exert additional lateral forces to bridge substructures.

# II – Impact on Project Scope

It is important that liquefaction potential and its severity be identified as early as possible in the project development process since liquefaction can have a tremendous impact on project cost, schedule, and scope. For large and/or important projects, it would be advantageous to request a subsurface site investigation as early as possible and before the project is funded for construction. If soil liquefaction potential is not identified until the project is in the design phase, a critical assessment based on available data relating its impact on project cost, schedule, and scope must be made, and all liquefaction design issues addressed.

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 (See *Memo to Designers 9-3*). The geotechnical designer should include in the Preliminary Geotechnical Recommendations an estimate of the limits of potential liquefaction so a determination can be made regarding adjoining and adjacent structures not included in the original project scope which are likely vulnerable to liquefaction. Information pertaining to adjacent vulnerable structures should be forwarded to the Office of Earthquake Engineering for evaluation.

### *Performance Criteria*

Mitigation measures for liquefaction/lateral spreading shall ensure that the resulting design be consistent with minimum seismic performance criteria established for the project. These performance criteria are described in *Memo to Designers 20-1 Attachment 1.*

### *Project Risks & Mitigation Strategies*

When liquefaction/lateral spreading is identified for bridges in a project, it presents conditions that may require mitigation. Table 2 identifies potential risks to the project as well as possible mitigation strategies. The appropriate mitigation strategy should be incorporated into the project scope at the planning stage and developed as early as possible. Developing a liquefaction mitigation plan usually requires adequate subsurface investigation at the project site. The planning phase should be targeted for this work.

All mitigation strategies shall be presented at a Type Selection Meeting or Seismic Strategy Meeting for review and approval.

## III – Impact on Project Cost & Schedule

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 competent soil. The cost increase is dependent on factors such as the type and extent of liquefiable material, ground motion parameters, and foundation type. While the impact of soil liquefaction on a project's actual cost estimate may not be fully evaluated until the final foundation recommendations and mitigation measures are developed, it is necessary to estimate the expected cost increase in the APS. Early detection allows for appropriate allocation of budget resources, reduces the possibility of changes in project scope, streamlines the design process, and encourages the project schedules that reflect the appropriate scope.

If liquefaction potential is suspected, the Project Manager should be contacted and given the option for more time to perform exploratory drilling. If additional time is not feasible, and for new ordinary standard bridges, the designer may use Table 3 to estimate the anticipated APS foundation cost increase associated with liquefaction. The data in Table 3 is derived from limited historical data requiring interpretation based on experience and engineering judgment.

It is important to recognize that a significant portion of the cost associated with soil liquefaction is related to countermeasures combating 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 and provided to the Project Manager and Project Development Team. It is necessary to have alternatives evaluated for impacts to traffic, environmental, or other functional areas.

The cost analysis should include comparing nonstructural mitigation measures (i.e. soil densification, stone column, etc…) to structural mitigation measures to determine the most cost effective solution to mitigate the effects of liquefaction, lateral spreading, and embankment instability.

The following items should be considered:

1. The cost increase is relative to a comparable foundation on competent soils.
2. Engineering judgment is required for the selection of an appropriate foundation cost increase.
3. The designer may adjust the APS quantity (i.e. pile/shaft size, type, number, and/or length) to reflect the anticipated foundation cost increase shown in Table 3.
4. Factors associated with higher cost increase include: Presence of lateral spreading forces, presence of stiff crust overlying liquefiable soil, permanent ground displacements expected following a seismic event, thicker layers of a liquefiable soil.
5. Foundations designated in poor soils (see SDC 6.2.2B) typically result in higher foundation costs. If liquefiable materials are subsequently found to be present within these soils then the impact of liquefaction may not add significant cost to the original foundation cost.
6. Foundation cost increase may be the result of non-structural mitigation measures, such as soil densification, stone columns, etc.

| TABLE 1<br>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.<br>• 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.<br>• Permanent horizontal displacements unlikely to develop.<br>• 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.<br>• New piles may need to extend deeper to compensate for reduced axial and lateral load-carrying capacity.<br>• 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.<br>• Surface and subsurface conditions favorable for the development of permanent lateral ground displacement such as:<br>  • Gently sloping ground surface, or level ground adjacent to a free face.<br>  • Sloping base of liquefiable deposit.<br>  • 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.<br>• Permanent horizontal displacements will develop and adversely affect pile foundations, pile caps and abutments. High soil pressure on foundations systems expected if a stiff, non-liquefiable deposit overlies liquefied material.<br>• Post-liquefaction settlements may be significant. Down drag forces will affect axial load carrying capacity of pile foundations under service loading conditions. | • Foundation strengthening required.<br>• Countermeasures against reduced axial capacity, down drag forces and lateral pressure include CISS piles or large diameter CIDH piles.<br>• Ground improvement may be considered in conjunction with foundation strengthening.<br>• Bridge system may need to be modified to allow larger permanent ground displacements without collapse.<br>• Increase ductility of foundation to absorb estimated permanent lateral displacement.<br>• Bridge relocation to an alternate non-liquefiable site should be considered. |

| TABLE 2<br>LIQUEFACTION RISKS & MITIGATION STRATEGIES | | | |
|---|---|---|---|
| **Project Type** | **Project Stage** | **Project Risks** | **Risk Mitigation Strategies** |
| **New or replacement bridges**<br><br>**New portion of bridge widenings** | **WBS 150-160**<br>**Planning**<br>(PSR/PDS or APS) | **With Subsurface Exploration.**<br>• Significantly reduces substantial risk; scope, cost, & schedule must reflect mitigating alternatives | • N/A |
| | | **Without Subsurface Exploration.**<br>• Unknown high-risk scope. (Note: some mitigating alternative may affect the Environmental Document.)<br>• Higher costs<br>• Unknown schedule impacts | • Undertake subsurface exploration & liquefaction assessment to define scope, costs & schedule.<br>• If substructure exploration not feasible, use Table 3 to adjust estimate cost. Assume mitigation alternative are necessary. Risks must be identified and provided to project stakeholders. |
| | **WBS 240**<br>**Type Selection**<br>(GP Development)<br>or<br>**Final Design**<br>(Type Section through PS&E) | **Subsurface Exploration at Planning Stage.**<br>• Minimal unidentified risk expected. | • N/A |
| | | **No Subsurface Exploration at Planning Stage.**<br>• High-risk scope (Note: some mitigation alternative may affect Environmental Document.)<br>• Higher costs<br>• Unknown schedule impacts | • Perform liquefaction assessment and identify mitigating alternative and present at Type Selection Meeting for final determination. |
| **Existing bridges (Widening or Major Modifications)** | **WBS 150-160**<br>**Planning**<br>(PSR/PDS or APS) | **Without Subsurface Exploration**<br>• Unknown high-risk scope (Note: some mitigation alternative may affect Environmental Document.)<br>• Higher costs<br>• Unknown schedule impacts | • Undertake subsurface exploration & liquefaction assessment to define scope, costs & schedule.<br>If substructure exploration not feasible, use Table 3 to adjust cost estimate. Assume mitigation alternatives are necessary. Risks must be identified and provided to project stakeholders. |
| | | **With Subsurface Exploration.**<br>• Significantly reduces substantial risk; scope, cost, & schedule must reflect mitigating alternatives | • N/A |
| | **WBS 240**<br>**Type Selection**<br>(GP Development)<br>or<br>**Final Design**<br>(Type Section through PS&E) | **Subsurface Exploration at Planning Stage.**<br>• Minimal unidentified risk expected. | • N/A |
| | | **No Subsurface Exploration at Planning Stage.**<br>• High-risk scope (Note: some mitigation alternative may affect Environmental Document.)<br>• Higher costs<br>• Unknown schedule impacts | • Perform liquefaction assessment and identify mitigating alternatives and present at Type Selection or Strategy Meeting for concurrence on final determination. |
| **Existing Bridge (Minor Modifications)** | **WBS 150-240**<br>**Planning, Type Selection**<br>**Final Design** | • 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 planned scope of project and should not be included. Projects requiring foundation work should be considered a major modification. | • If potential liquefaction is suspected or found to be moderate or high, provide this information to the Office of Earthquake Engineering for evaluation. |

**TABLE 3**
**LIQUEFACTION SEVERITY VS ESTIMATED COST INCREASE**
**(FOR PLANNING PURPOSES)**

| **Liquefaction Severity** | **Estimated Bridge Foundations Cost Increase at Impacted Locations (%)** |
|---|---|
| Negligible Liquefaction | 0 |
| Liquefaction without Lateral Spreading | 0 to 300 |
| Liquefaction with Lateral Spreading | 200 to 500 |

# References

1. California Department of Transportation, *Bridge Memo to Designers 9-3*
2. California Department of Transportation *Seismic Design Criteria 6.2.2B*
3. California Department of Transportation *Bridge Memo to Designers 20-15*
4. California Department of Transportation *Bridge Memo to Designers 20-1, Attachment 1*

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