EVALUATION OF INFLUENCE ON LATERAL SPREADING DISPLACEMENT DEMAND FOR ADJACENT BRIDGES

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Studies recently conducted by the author and others have demonstrated that relatively simple "equivalent-static" analysis procedures can adequately predict the demands caused by lateral spreading for the purpose of designing bridge foundations. However, an important part of the analysis that remains to be sufficiently addressed in the literature is how to account for the restraining force provided by foundations when the laterally-spreading ground does not have a finite, measureable out-of-plane width. In contrast, in the case where deep foundations support a bridge approach embankment, the transverse width of the embankment is considered explicitly in the analysis by scaling the stiffness and strength properties of the foundations by the width of the embankment in order to estimate the "pinning" force. This study addresses this problem in the context of two parallel, adjacent bridges crossing the Colorado River in Mexico that were subjected to a broad field of laterally-spreading ground during the 2010 **M** 7.2 El Mayor-Cucapah earthquake. Two-dimensional finite element analyses were used to quantify the influence that the presence of each bridge had on the lateral spreading demand for the opposite bridge. The results show that the relatively stiff foundations of the first bridge provided a "shielding" effect to the second bridge, significantly reducing the demand compared to the magnitude of the free-field lateral spreading observed at the site.

Introduction

Liquefaction-induced lateral spreading has been a major cause of damage to bridges and waterfront infrastructure in past earthquakes (Idriss and Boulanger 2008). The underlying mechanics of the lateral spreading phenomenon are difficult to fully capture during foundation design, owing to the complexity of the phenomenon itself and the challenges associated with specifying accurate constitutive model parameters and executing dynamic numerical analyses. Rather, foundation designers desire simple yet effective equivalent-static analysis tools for addressing seismic issues such as lateral spreading on routine projects.

A recent set of guidelines published by the Pacific Earthquake Engineering Research (PEER) Center (Ashford et al. 2011) establishes an equivalent-static analysis approach for design of bridge foundations in laterally spreading ground. In this approach, a profile of horizontal ground displacement is imposed on the free ends of *p-y* springs attached to a beam-on-nonlinear-Winkler-foundation (BNWF) model, and the resulting shear, moment, and displacement of the foundation can be used to evaluate performance criteria and inform the structural design. This functionality is already implemented in some commercial software packages that are used for design of deep foundations under lateral loading such as *LPILE* (Reese et al. 2005).

An issue often confronted in cases of designing for lateral spreading is the so-called "pinning" phenomenon, in which the presence of the foundations causes a reduction in the lateral spreading displacement, which in turn causes a reduction in the demand placed on the foundation. An iterative procedure using a combination of the equivalent-static analysis (ESA) method for lateral spreading and dynamic slope stability analyses used to compute slope displacements (*e.g.*, Bray and Travasarou 2007) can be used to find a compatible slope displacement and foundation resistance (Martin et al. 2002).

A typical case in which this form of pinning is applicable is for a bridge approach embankment supported on deep foundations overlying liquefiable soil. For this case, the restraint against slope displacement provided by the foundations is significant in comparison to the driving force of the finite-width embankment in the downslope direction. During the pinning analysis for this case, the structural resistance provided by the foundations is scaled by the out-of-plane width of the embankment to account for the relative resistance provided by the foundations.

In contrast, when the out-of-plane width of the laterally spreading mass is large relative to the width of the foundation or foundation group, the traditional pinning effect no longer applies. In this case, the restraint provided by the foundation(s) is negligible compared to the inertial force of the broad field of laterally spreading ground. The displacement demand imposed on the foundations in this case is equal to the free-field lateral spreading displacement that would occur at the location of the foundations in their absence. Foundation designers often struggle to grasp this concept because case histories of lateral spreading usually show that the ground displacement in the vicinity of foundations is less than observed in the free field (this can be observed on the west bank in Figure 1). The reduced displacement in the vicinity of the foundations is evidence that the foundations have mobilized a resisting force against the moving ground; imposing the reduced displacement would fail to account for the mobilized force and would result in an underestimate of total demand.

When a structure's foundations are capable of mobilizing significant resistance against the free-field lateral spreading demand such that the ground displacement in the vicinity of the structure is reduced, the foundations of nearby secondary structures may experience a "shielding" effect as a result. This can result in a favorable reduction in the displacement demand imposed on the secondary structure's foundations compared to the free-field ground displacement.

While the shielding effect is relatively simple in principle, reliably quantifying the reduction in displacement demand for design purposes is more challenging and is not currently addressed in the literature. The traditional pinning analysis procedure considers a two-dimensional cross section that is representative of the tributary width of a single foundation within the

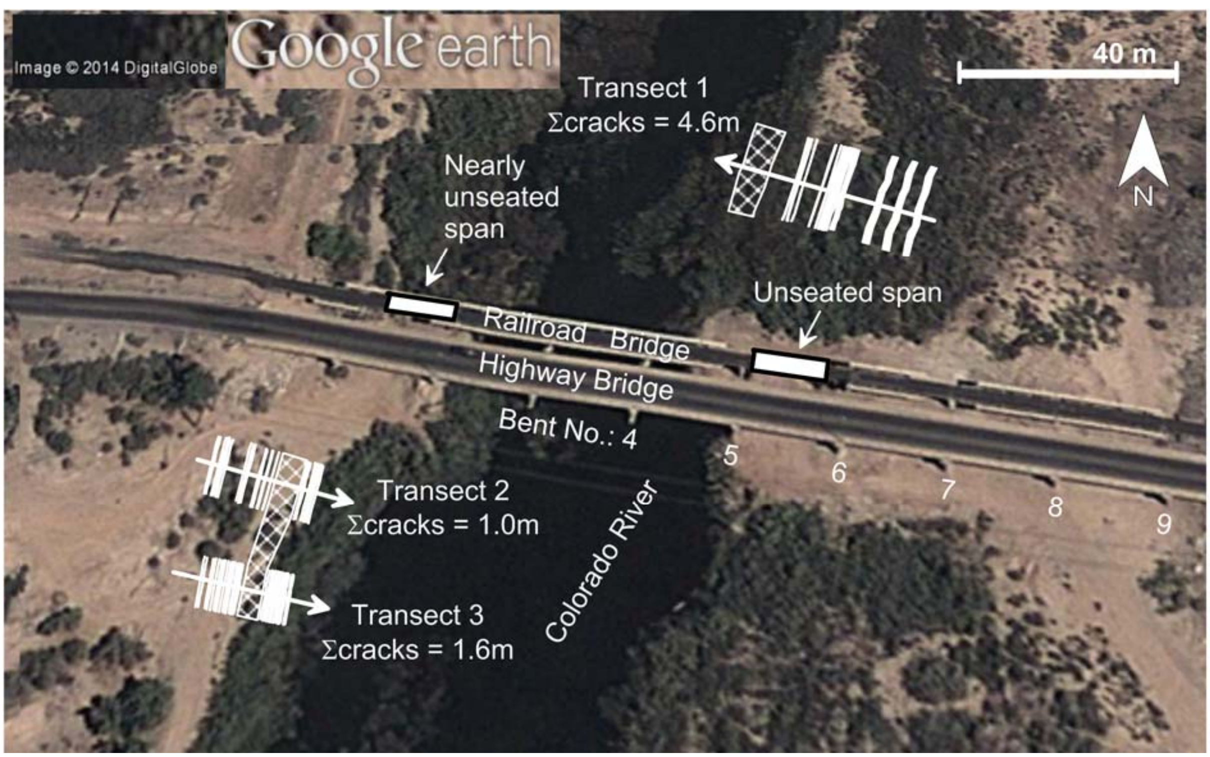

Figure 1: San Felipito Bridges site showing locations of structural damage and mapped ground failures following the 2010 El Mayor-Cucapah earthquake (after GEER, 2010).

embankment. For the case of a very wide lateral spreading feature, the tributary width of each foundation approaches infinity and its relative contribution to resisting the lateral spreading demand approaches zero.

A more appropriate analysis approach would explicitly consider the out-of-plane dimension (*i.e.*, the width) of the lateral spread. An approach utilizing two-dimensional finite element analysis tools in combination with the ESA procedure is described herein to quantify the shielding effect for two adjacent bridges based on observed behavior of the structures following the 2010 **M** 7.2 El Mayor-Cucapah earthquake in northern Baja California, Mexico. A similar approach could be applied to other cases of adjacent bridges, utilities adjacent to bridges, or adjacent waterfront structures in lateral spreading-prone zones.

Case Study Background

The San Felipito Bridges cross the Colorado River about halfway between the USA/Mexico border and the Gulf of California. The crossing consists of a railroad bridge and a parallel highway bridge separated by about seven meters that span the river's roughly 200-m wide flood plain. The river has migrated to the west side of the incised flood plain, leaving a broad, gentle slope of relatively loose, liquefaction-prone deposits on the east bank. A site plan is presented in Figure 1.

Both bridges are simply supported with matching 20-m long precast, prestressed concrete girders supporting their decks. Engineers from the regional transportation authority, *Secretaría de Comunicaciones y Transportes* (SCT) provided the construction plans of the highway bridge, built in 1999. Each bent is supported by four 1.2-m diameter extended-shaft columns that are continuous with drilled shafts of the same diameter to depths of up to 17 m below the ground surface. The longest shafts support the spans over and immediately adjacent to the river crossing. Less is known about the privately owned railroad bridge, which was constructed in 1964 (EERI 2010). Each bent is supported by an oblong-shaped pier wall atop a pile cap, which most likely connects a group of driven timber or steel piles. Construction documents were not available and the actual foundation details are unknown.

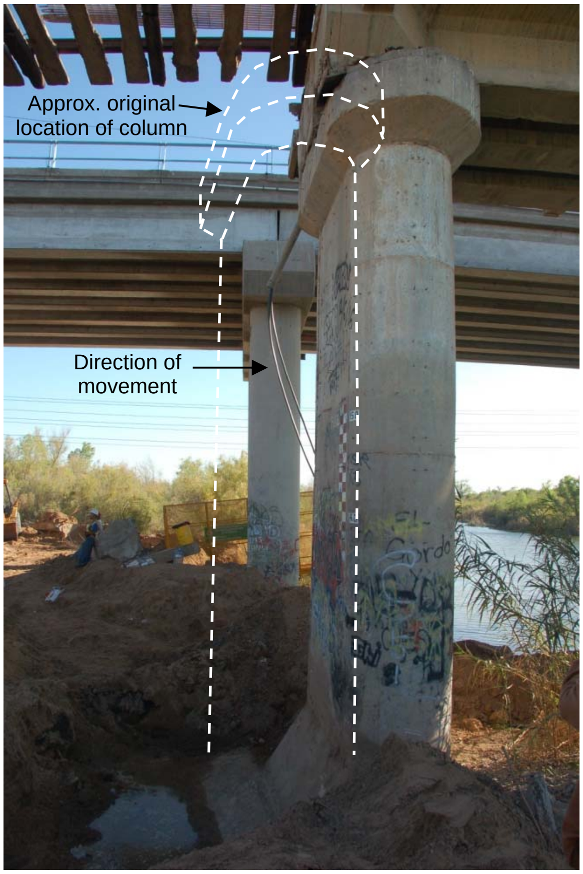

Figure 2: Bent 5 of railroad bridge (foreground) that translated towards river causing unseating collapse, and Bent 5 of highway bridge (background) following 2010 El Mayor-Cucapah earthquake. Photo J. Gingery/GEER (2010).

Teams from the Geotechnical Extreme Events Reconnaissance Association (GEER) and the Earthquake Engineering Research Institute (EERI) documented ground failures and structural damage following the 2010 earthquake (GEER 2010; EERI 2010). A span of the railroad bridge adjacent to the east river bank unseated and collapsed as a result of translation of the Bent 5 pier toward the river during lateral spreading (see Figure 2). The railroad bridge pier adjacent to the west bank also translated toward the river, stopping just short of causing a similar unseating collapse. The highway bridge suffered only moderate damage, including flexural cracking at the base of the Bent 5 columns as a result of the lateral spreading demand. Note in Figure 2 that Bent 5 of the railroad bridge and the highway bridge are directly adjacent to one another and located approximately the same distance from the east river bank.

The author participated in a research study to validate the PEER lateral spreading guidelines (Ashford et al. 2011) against this case study. A team from UCLA performed a series of cone penetration test (CPT) and geophysical tests at the site in October of 2013 to characterize the subsurface. Our investigation was supplemented by portions of boring logs and index tests results performed previously by SCT and Ferromex, the owner of the railroad bridge.

The stratigraphy in the vicinity of Bent 5 of the bridges, which was the focus of the lateral spreading analyses, generally consists of a 1.5-m thick crust of silty sand above the groundwater table underlain by interbedded layers of loose, liquefiable sand and medium dense to very dense sand and silty sand. The fines content generally decreased with increasing depth. Penetration resistance increased with increasing distance from the river, indicating that the deposits nearest the river were likely younger and hence more prone to liquefaction. This pattern likely played a role in defining the margins of the lateral spreading that occurred during the 2010 earthquake.

We used the CPT and previous index test results to develop a profile of idealized stratigraphy and soil properties for the analyses. The estimated soil properties were used to develop *p-y* springs to represent the soil-structure interaction between the foundations and the ground, including the softened load-transfer behavior of the crust due to the underlying liquefied layers as described by Brandenberg et al. (2007). *P-y* springs were based on the API sand formulation (API 1993), and liquefied soil was represented using *p-y* springs reduced by a *p*-multiplier. *T-z* and *q-z* springs were used to represent the axial stiffness of the railroad bridge piles to capture the overturning resistance provided by group-action.

BNWF models of Bent 5 of each bridge were analyzed using the open-source finite element method platform *OpenSees* (McKenna 1997). The ESA procedure was found to capture the observed behavior of both bridges well. The difference in behavior is ultimately attributable to the lateral resistance of the highway bridge foundations being sufficient to resist the fully-mobilized passive pressure of the laterally spreading crust, whereas the lateral resistance of the railroad bridge was not sufficient to resist the crust load without yielding and undergoing large displacement. Complete results of the analyses are presented in Turner et al. (2014).

From the ESA analyses, Bent 5 of the railroad bridge was predicted to undergo sufficient translation to cause an unseating collapse (about 0.85 m of movement was required) for imposed free-field lateral spreading displacements exceeding about 1 m. In the real system, Bent 5 was observed to have translated about 1 m based on measurements taken following the earthquake. However, if the full free-field lateral spreading displacement of approximately 4 m was imposed, Bent 5 was predicted to displace about 3.6 m, which greatly exceeds the observed movement. This result suggested that the presence of the adjacent highway bridge “shielded” the railroad bridge and reduced the lateral spreading demand imposed on the railroad bridge foundations. Had the highway bridge not been present, more spans of the railroad bridge may have collapsed.

This case study provides a unique opportunity to explore methods for quantifying the shielding effect, since the site is well characterized, free field lateral spreading displacements were measured, the performance of the bridges during the earthquake was well documented, and the ESA of the foundations under lateral spreading demand has already been performed.

Approach

The author performed two-dimensional finite element analyses to investigate the shielding effect observed at the San Felipito Bridges. Plain strain analyses of a 1-m thick horizontal slice of the crust (*i.e.,* the domain represents a plan-view of the system) were conducted using the program *Phase2* by Rocscience (2013). The intent was to create a model that only included the highway bridge foundations in order to evaluate the reduction in lateral spreading displacement at the location of Bent 5 of the railroad bridge.

The *Phase2* model includes Bents 5, 6, and 7 of the highway bridge in the center of a 200-m wide by 120-m tall domain. The domain is sufficiently large so that a free-field response occurs outside the zone of influence of the foundations. Bents further to the east (Bents 8, 9 etc.) were not included since they are beyond the zone of observed lateral spreading in the free field, which extended about 40-50 m from the east river bank. Bent 4 is not included in the model because it is located in the middle of the river channel; the lateral spread is assumed to have stopped shortly after entering the river from the east bank and likely did not interact with Bent 4.

Concrete drilled shafts were modeled in *Phase2* with an elastic material having a Young's modulus of 27 GPa and a Poisson's ratio of 0.2. The crust soil was modeled using an elastic perfectly-plastic Mohr Coulomb material with uniform shear strength of 30 kPa, representative of the average passive pressure limit for the upper 1 m of the crust for total stress conditions. From the *OpenSees* analysis, the average stress intensity for the upper 1-m of crust acting against the highway bridge shafts with 4 m of imposed free-field lateral spreading displacement was found to be about 70 kPa with a corresponding foundation displacement of 4.8 cm at the ground surface. The Young's modulus of the soil in the *Phase2* model was adjusted until the stress intensity matched this value at the same foundation displacement (Figure 3); a modulus of about 325 kPa was found to provide a good match. This value is far less than the modulus for comparable soils under typical loading conditions, which is due to the large modulus reduction for such high strain, the softened passive load transfer relationship of the crust underlain by liquefied soil (see Brandenberg et al. 2007), and the imperfect representation of the real boundary conditions (discussed further below). The soil was assigned a Poisson's ratio of 0.25; the results were found to be relatively insensitive to a range of values between 0.2 and 0.35, typical for loose cohesionless soil (Bowles 1996).

The finite element domain was restrained against displacement in the x-direction (*i.e.*, it could not change width) and a displacement was imposed in the y-direction (*i.e.,* towards the river). The real free-field lateral spreading displacement field was maximum nearest the river, where the cumulative displacement was measured as 4.6 m along a transect north of the bridges, and decreased approximately linearly over a distance of about 45 m (Figure 1). Ideally, this gradient of displacement would be applied to the finite element model. However, this could not be accomplished in *Phase2* without creating unrealistic tensile stress throughout the domain. Instead, a uniform displacement of 4 m was imposed over the entire domain. This imposes the appropriate level of demand on the Bent 5 foundations, but is greater than the real displacement imposed on the Bent 6 and Bent 7 foundations. While this does not replicate the observed lateral spreading displacement field, it is still considered reasonable for this exercise for two reasons. First, by imposing a displacement field on the foundations further from the river (Bents 6 and 7) that is greater than the actual displacement field, the displacement at the location of the railroad bridge will be greater than what is really anticipated, and the resulting estimate can be considered an upper bound that is appropriate for design. In other words, the estimated reduction in lateral spreading demand will be a lower-bound value. Second, in practice it is very difficult to determine *a priori* where the margins of a lateral spreading feature will be located. Limit equilibrium slope stability analysis tools are not typically capable of providing accurate estimates of the location of lateral spread headscarps for cases of gentle slopes with low static driving shear stress. The actual locations of the margins of the lateral spreading zone are likely to be dictated by subtle changes in topography or geology that are often difficult to identify with confidence during the subsurface investigation. For a case like the San Felipito Bridges, a reasonable design assumption prior to the 2010 earthquake would have been that the entire flood plain on the east bank would undergo lateral spreading toward the river, and imposing a uniform displacement field to the three bents nearest the east bank of the river would represent a reasonable upper bound for demand.

It should be acknowledged that the two-dimensional, plain strain analysis used here does not capture the three-dimensional boundary conditions of the lateral spreading problem very well. Out-of-plane stress was predicted to be the intermediate principal stress near the foundations, whereas the stress parallel to the face of the foundations would typically be the intermediate principal stress for a passive loading case, and the vertical stress would be the minor principal stress. A plane stress condition likely would give more accurate results, but this option is not part of the *Phase2* software.

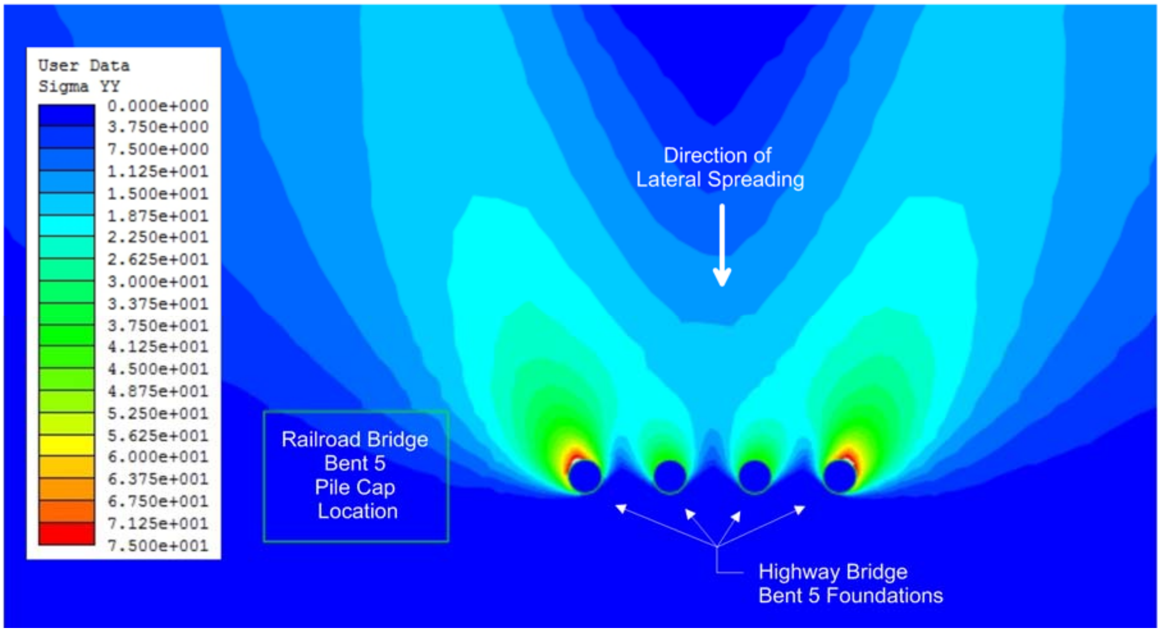

Figure 3: Results of Bent 5 finite element simulations with 4 m of imposed lateral spreading displacement, showing normal stress acting in direction of lateral spreading. Note arching between highway bridge foundations. Stress contours in kPa.

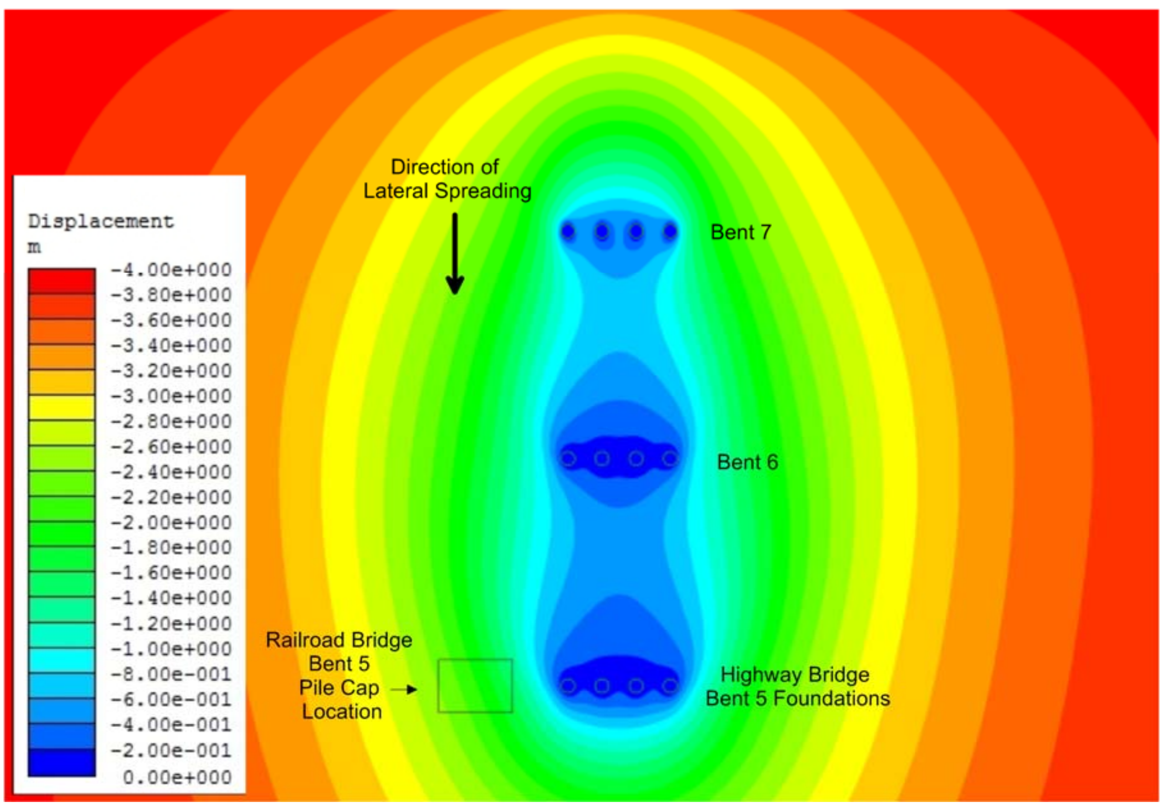

Figure 4: Displacement results (in meters) for finite element model including Bents 5, 6, and 7 of the highway bridge showing approximately 50 percent reduction in displacement at location of railroad bridge Bent 5 compared to free-field lateral spreading displacement of 4 m.

Results

Average displacement towards the river at the location of Bent 5 of the railroad bridge was 2.05 m for an imposed free-field lateral spreading displacement of 4.0 m as shown in Figure 4. This represents a 49-percent reduction from the free field lateral spreading demand. The ESA performed in *OpenSees* still predicted collapse of the railroad bridge for lateral spreading displacements on the order of 2 m, but for many structures a reduction in displacement demand of nearly 50 percent could drastically improve performance and potentially allow for more economical foundations compared with the case in which the full free-field displacement must be resisted.

Further studies were conducted to evaluate the relative contribution of each bent to the overall shielding effect. A model that only included Bent 5 of the highway bridge provided a 30 percent reduction from the free-field displacement at the location of Bent 5 of the railroad bridge. A model that only included Bents 6 and 7 of the highway bridge provided an 18 percent reduction. This demonstrates that the primary structure foundations closest to the secondary location of interest provide the greatest shielding effect, but foundations at relatively large distances can still provide significant additional shielding.

In contrast, a model that only included Bents 5, 6, and 7 of the railroad bridge predicted only a 5 percent reduction in the lateral spreading displacement demand at the location of Bent 5 of the highway bridge. Since the highway bridge foundations have sufficient strength and stiffness to resist the fully-mobilized passive pressure of the laterally spreading crust, the low shielding effect provided by the railroad bridge is of little consequence.

Conclusions

A novel procedure has been presented to quantify the shielding effect that the foundations of a primary structure will have on the foundations of a nearby secondary structure. The approach combines the results of equivalent static analysis (ESA) procedures for estimating foundation demand under lateral spreading loading with two-dimensional finite element analyses of the laterally spreading crust layer. The steps can be summarized as follows:

- Perform ESA for primary structure foundations—determine average stress intensity acting on foundations under estimated free-field lateral spreading displacement and corresponding displacement of the foundation;
- Develop finite element model of the crust layer, including foundations of the primary structure, and adjust soil properties until target stress intensity is matched under imposed free-field lateral spreading displacement and appropriate foundation displacement;
- Determine reduction of free-field lateral spreading displacement at the location of the secondary structure foundations;
- Perform ESA for secondary structure foundations using reduced lateral spreading displacement demand.

This procedure has been applied to a case study of two adjacent bridges that were subjected to lateral spreading during the 2010 El Mayor-Cucapah earthquake. Lateral spreading demand at the location of the railroad bridge foundations that were damaged during the earthquake was predicted to be reduced by about 50 percent compared to the free-field displacement demand. The observed performance indicates that the actual reduction may have been as much as about 75 percent. The underestimate of displacement reduction can be partially explained by the fact that a uniform displacement field was applied to the domain, rather than a gradient of displacement that would decrease with increasing distance from the river. For forward design cases, knowingly underestimating the shielding effect is a reasonable approach given the uncertain nature of the lateral spreading phenomenon.

This procedure could be used to quantify the favorable reduction in free-field lateral spreading demand as a result of the shielding effect for similar cases of adjacent bridges, utilities adjacent to bridges, or adjacent waterfront facilities. However, foundation engineers are cautioned to carefully consider the boundary conditions of each individual project and whether or not two-dimensional analyses can adequately capture the real system behavior. It is important to recognize that the results of the procedure presented here are only approximate and should not be treated as a guaranteed representation of actual system performance. For high-value or critical projects, the results of two-dimensional analyses could be used to justify whether or not more sophisticated three-dimensional analyses are warranted.

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