INNOVATIVE FOUNDATION ALTERNATIVE FOR HIGH SPEED RAIL APPLICATION

Quarterly Progress Report
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Seung Jae Lee, Ph.D. and Atorod Azizinamini, Ph.D., P.E.
Graduate Student – Roberto Rodriguez
Affiliation: Department of Civil and Environmental Engineering
Florida International University
Miami, FL

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

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1 Background and Introduction

Bridges are key components of the high speed rail (HSR) infrastructure, while whole new construction of HSR bridges along a HSR line will take some tremendous cost and time. Utilizing the existing structure and foundation for HSR applications provides a good alternative to the challenge, but the methods for upgrading the existing substandard bridges to meet the HSR standards remain largely undeveloped in the engineering community. Focus also needs to be given to the seismic retrofit, considering California started the first HSR line construction to connect the bay area and southern California.

This project proposes an innovative micropile-based foundation system as ABC solution to tackle the challenges. The concept was inspired by the micropile foundations for transmission towers using prefabricated caps, which are similarly leveraged to ‘rapidly’ construct micropile foundation islands. These islands are then connected to the existing foundation using dampers to control the unwanted motions. The developed foundation system may also provide a potential solution to new construction of HSR bridges, where traditional deep foundations may not work.

The team will validate the design concept through detailed finite element soil-foundation-structure interaction analysis by modeling the full bridge systems that incorporate the foundation systems. Extensive nonlinear time history analysis will be conducted to study the seismic response of HSR bridges with the innovative foundations. Upon successful completion of tasks, the feasibility of the proposed approach will be demonstrated with the optimal design sought between the overall performance of the new foundation system and construction cost. This project will deliver the ABC guideline to apply the innovative foundation systems for HSR.

2 Problem Statement

One of the transportation solutions that have been always considered in the past few decades is the high speed rail (HSR) where plans for the HSR date back to the High Speed Ground Transportation Act of 1965 (Public Law 89-220, 79 Stat. 893). However, full implementation of an inter-state HSR has never been accomplished. Only recently and after several delays, California is on track for a HSR line that connects the bay area to southern California and construction for the HSR infrastructure started as of 2017. Bridges are key components of the HSR infrastructure and the state plan is to consider new construction as well as utilizing existing structure and foundation if appropriate. The inherent characteristics of HSR raise new problems beyond those found in typical highway construction, so comprehensive approach on the bridge structure and foundation system needs to be made to systematically tackle the challenges. Upgrading of existing bridges is of particular concern, e.g., (a) HSR bridge superstructures require high stiffness and are likely to be heavy, so upgrading of the existing structure for HSR will apply significant surcharge on the bridge foundation, for which a retrofit solution also needs to be developed; (b) The stiff, heavy components will induce seismic forces that are much higher than in highway bridges, so the ABC solutions developed for highway bridges will have to be reworked to satisfy the more stringent requirements in seismic areas; (c) Construction issues also have to be optimized regarding how this upgrade can be best accommodated in a short period time without causing high costs and traffic disruptions.

The overall goal of this project is to develop an innovative foundation system that can be ‘rapidly’ installed for HSR bridges and perform feasibility study. To this end, micropiles are leveraged as the ABC solution to retrofit the existing conventional bridge foundation systems or a potential solution to new construction, where traditional deep foundations may not work. Micropiles have been broadly adopted as foundation supporting elements to existing structures in the geotechnical engineering practice [1], and there are many good reasons to employ the micropiles for this project to develop innovative foundation alternative for high speed rail application: (a) Axial and lateral resistance of the foundation can be effectively increased to resist the HSR load. Network of micropiles can be also leveraged to reinforce the soil mass [2]; (b) Battered (inclined) micropiles presents high seismic resistance, which is suitable for seismic retrofitting in California; (c) Installation of micropiles is inherently an ABC solution, as it can be rapidly completed in a short time window with minimal interference to traffic. Construction noise and vibration level is low compared to other types of foundation; (d) Micropiles can be installed for virtually any soil and even for some difficult geologic profiles, so the technique can be universally applied to a wide range of subsurface conditions; (e) The equipment used for installing micropiles is relatively small, thus useful for retrofitting or construction in locations hard to access.

The research will focus on both component and full bridge systems modeling and detailed seismic analysis will be conducted to investigate the seismic performance of the full bridge with the innovative foundation system.

3 Research Approach and Methods

Our approach for this proposed study is an analytical and computational approach where detailed finite element modeling and analyses will be considered. OpenSees, an opens source framework developed by the Pacific Earthquake Engineering Center, will be adopted for the finite element computation [3]. Component and system modeling and analysis will be conducted in a collaborative effort between FIU and UNR. The two teams will work together closely throughout the project. However, the PI from FIU will be mostly in charge of the component modeling which involves design of the innovative foundation system and the soil-foundation interaction. On the other hand, the PI from UNR will be mostly in charge of incorporating foundation and soil models into a full bridge system to conduct seismic analysis for different bridge systems with both conventional and the innovative foundation system. The specific research objectives include: (1) synergizing available national and international data on HSR bridge configurations and foundation systems; (2) develop innovative foundation systems and validate the design concept through soil-foundation interaction analysis; (3) develop detailed finite element models for full bridge systems that incorporate the foundation systems and integrate soil-foundation-structure interaction; (4) conduct extensive nonlinear time history analysis to investigate the seismic response of HSR bridges with innovative foundations.

4 Description of Research Project Tasks

A comprehensive analytical and computational approach will be used and several research activities will be executed to accomplish the objectives of this study. A summary of the proposed research tasks is as follows:

Task 1 – Literature search on HSR bridges and components

Task 2 – Conceptual development of Innovative foundation system

Task 3 – Component modeling of foundation system and soil-foundation interaction

Task 4 – Develop HSR computational models for different configurations

Task 5 – Conduct analytical studies of the bridge model

Task 6 – Summarize the results in a final report

Task 1 – Update literature search on HSR bridge configurations and different components types and modeling

This task will perform extensive literature review to collect data on the different components and configurations of HSR using national and international studies and available design guidelines. Another major focus of this literature review is to compile the case histories of micropile projects that offered cost-effective and efficient means for underpinning the existing foundation and seismic retrofitting. The literature review efforts will particularly focus on finding information related to the micropile foundation design against dynamic loads to better proceed with the conceptual development of innovative foundation system for HSR application. The literature review is currently in progress at two fronts. The retrofit and micropiles design and applications is one. The other front focuses on collecting information on HSR infrastructure around the world especially HSR bridge archetypes. Table 1 summarizes the HSR in operation and under construction along with other statistics from around the world. At least 19 countries around the world are building or planning new high-speed rail lines. Few examples include:

- China invested in building the world’s most extensive HSR system.
- Saudi Arabia began construction on 276-mile HSR line connecting holy cities of Medina and Mecca via Jeddah.
- Within the European Union, Spain is constructing about 1,500 miles of HSR lines.
- France is planning more than 2,500 miles of new HSR lines.
- England proposed second phase of its national high-speed rail network.

Table 1 - HSR in Operation and Under Construction Worldwide

	In Operation				Under Construction			Total		
Country	First year of operation	Miles	Percent of Total	Top Speed (mph)	Miles	Percent of Total	Top Speed (mph)	Miles	Percent of Total	Annual Ridership
China	2003	3,914	37.2	220	2,696	55.9	220	6,610	43.1	290,540,000
Japan	1964	1,655	15.7	190	235	4.9	230	1,890	12.3	288,836,000
Spain	1992	1,278	12.2	190	1,098	22.7	190	2,376	15.5	28,751,000
France	1981	1,178	11.2	200	130	2.7	200	1,309	8.5	114,395,000
Germany	1991	798	7.6	190	235	4.9	190	1,033	6.7	73,709,000
Italy	1981	574	5.5	190	—		—	574	3.7	33,377,000
South Korea	2004	256	2.4	190	116	2.4	190	372	2.4	37,477,000
USA	2000	362	2.1	150	—		—	362	1.5	3,200,000
Taiwan	2007	214	2.0	190	—		—	214	1.4	32,349,000
Turkey	2009	146	1.4	160	317	6.6	160	463	3.0	942,000
Belgium	1997	130	1.2	190	—		—	130	0.8	9,561,000
The Netherlands	2009	75	0.7	190	—		—	75	0.5	6,005,000
United Kingdom	2003	70	0.7	190	—		—	70	0.5	9,220,000
World Total	—	10,513	100.0	—	4,827	100.0	—	15,340	100.0	928,362,000

Notes: Data is sorted by miles in operation. China's annual ridership is an estimate based on various news reports. USA's annual ridership reflects FY 2010 ridership on Amtrak's Acela Express service on the Northeast Corridor.

Source: UIC (2011; 2009).

Recently, a study in CA [7] investigated the probabilistic seismic response of HSR bridges. Other studies were reviewed to develop typical HSR bridge configuration to be sued for this study. A summary of the conducted effort to date is presented below.

Configurations and modeling of HSR Prototype Bridge (adopted from Li & Conte [4])

Increasing urbanization has imposed significant transportation needs to provide commuter services, thus prompting the worldwide development of high-speed rail systems, including the newly launched California high-speed train project. To accommodate the changing terrains along the railway alignments, high-speed rail bridge structures play an indispensable role in supporting railway systems. The construction of high-speed rail bridges in highly seismic active areas (e.g., San Francisco and Los Angeles areas) calls for carrying out a detailed and comprehensive seismic analysis for these bridge types. Figure 1 shows an isotropic view of a California High-Speed Rail (CHSR) prototype bridge, which was designed in collaboration with Parsons Brinckerhoff, Inc, an engineering firm assisting the CHSR Authority in developing the design criteria and technical standards. This prototype bridge is hypothetically located in downtown San Jose, California, for the study of the feasibility and optimality of seismic isolation in a CHSR prototype bridge.

It is a straight 9-span bridge, consisting of three 110.5-m-long and 14.6-m-tall frames with 3 spans of 33.5 m each and with 2 interior expansion joints between the central and 2 end frames, as well as 2 abutment expansion joints at the bridge ends and on top of the bridge deck is a typical ballast-less track system. A comprehensive three-dimensional nonlinear finite element (FE) model of the CHSR prototype bridge was developed using the nonlinear FE analysis software framework OpenSees.

The track-structure interaction was accounted for by explicit modeling of the rails (on both the bridge and the left and right extensions) using linear elastic beam-column elements with material and section properties specified in the AREMA manual for rail type 141RE. The connection between the rail and structure or subgrade was represented by a series of elastic-perfectly-plastic springs in the longitudinal direction and elastic springs in the transverse and vertical directions, respectively. The bridge deck, a posttensioned single-cell box girder (12.8 m wide at the top), was modeled using elastic beam-column elements, considering the fact that the bridge deck was designed to remain elastic as a capacity protected component. The bridge pier columns of circular cross-section with a diameter 2.44 m were modeled using displacement- based beam-column elements with nonlinear fiber sections. Realistic uniaxial nonlinear constitutive material models were assigned to the concrete (cover and core) and steel fibers. The connection between adjacent bridge decks, i.e., slotted hinge joint devices, was modeled using zero-length elements, each comprising a gap hook and a bilinear hysteretic spring in series in the longitudinal direction and bilinear hysteretic springs in the transverse and vertical directions, respectively. The abutment shear keys were modeled using a shear key model developed and calibrated based on experimental results. The connections between the bridge deck and pier columns, i.e., the seismic isolators, were modeled using zero-length elements with 2 uncoupled bilinear inelastic materials for the horizontal shear behavior.

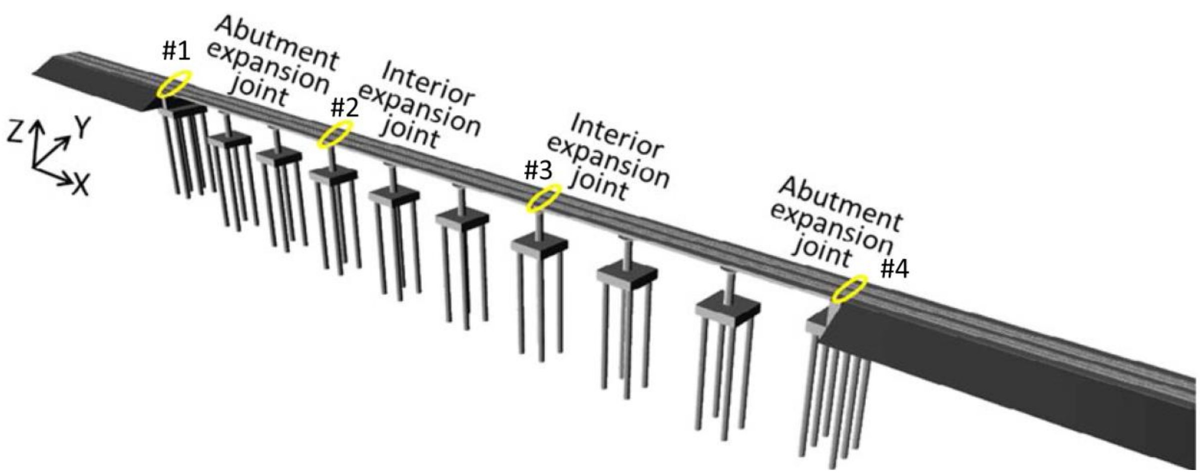

Figure 1. Isotropic view of a high-speed rail prototype bridge

Typical foundation seismic retrofits rely upon three principles: mitigation of potential liquefaction of soils, reinforce the structure to prevent collapse, and increase the lateral capacity of the existing foundation. This literature review focuses on the latter two. Several sources in literature are found to describe the use of deep foundation systems in addition to forms of ground improvement method if required. Due to strong soil nonlinear behavior caused by earthquake-induced inertial loading, a fully coupled nonlinear solution using finite elements is ideal, however it should be noted that in practice Winkler on Beam solutions have been used to simulate the soil-pile interaction [5].

Geotechnical engineers begin the design of the foundation system by performing a seismic hazard analysis at the site of question to determine the anticipated level of shaking and select a comprehensive foundation solution determined by the project constraints. An analysis on soil-foundation-structure interaction is performed to determine the foundation stiffness versus deflection to properly design the members against axial, lateral, and uplift capacity. An important note regarding a piled raft foundation system is that most of the foundation stiffness is governed by the pile cap stiffness.

Micropile has been used for foundation retrofit. A literature shows on a micropile-based foundation seismic retrofit of the Boeing field control tower in Seattle, Washington [6]. The original construction built in the 1960s was founded on timber piles of unknown length and soil borings performed indicated liquefiable soils in the depths of approximately 35 feet. The foundation retrofit included the use of drilled shafts adjacent to the tower, which was tied to new structural steel bracing which was added to increase the tower to overturning during design earthquake loading. The drilled shafts were placed outside the existing pile cap and consisted of dimensions 4 in diameter and 45 ft in depth. The pile configuration involved placing groups of four drilled shafts on the east and west side of the foundation.

Another case study demonstrated the use of micropile-based foundation groups in San Francisco bay area [7]. The foundation retrofit consisted of the use Type "D" micropile groups through an existing foundation pile cap at 5 existing bents. The micropiles were one foot in diameter and consisted of high yield 2.25" treated steel rod extending over the entire length of the pile and a 9 5/8" diameter high yield N80 steel casing extending down to approximately the top of the bonded length of the pile. The micropiles were then subsequently load tested to confirm design assumptions. The piles performed well and reached close to the design limit of 0.5 inch in compression. Load testing also confirmed that under cyclic loading, the displacement shall not exceed the tension dead load, or the risk of pile failure is imminent.

Task 2 – Conceptual development of innovative foundation system

There are two different design mechanisms contributed by micropiles when used as foundation supporting elements, which are (a) Direct structural support (Case 1 micropiles) and (b) Soil reinforcement (Case 2 micropiles). Case 1 micropiles are commonly referred to the case where vertically installed micropiles are directly supporting the foundation load. On the other hand, Case 2 micropiles are typically a network of reticulated elements working as a composite pile-soil foundation by encompassing and reinforcing the internal soil [8]. This project is particularly interested in developing (c) a third type of mechanism (hereafter, referred as Case 3) to 'significantly' enhance overall seismic performance of bridge in high seismic areas: The mechanism is realized by utilizing the dampers installed between the existing foundation and neighboring 'micropile islands'. This design was inspired by the micropile foundations with prefabricated caps used for transmission towers against high winds [9]. As the prefabricated cap is used along with the rapid micropile installation, the construction is fast. Furthermore, the seismic retrofit can be easier for the bridge foundations in locations with limited access. Case 3 mechanism may be combined with the other types of design mechanism (i.e., Case 1 or 2) to increase the resistance against the increased load due to HSR.

The team leverages OpenSees 2-D finite element modeling to simulate the response of micropile in foundation retrofitting scenarios. A result of the numerical study is shown in Figure 2, where the soil and foundation system were modeled using surface elements. A 10 kN load was applied in the positive horizontal direction on the pile cap element. A series of parametric studies is currently performed to demonstrate the early stage of the concept by changing a set of parameters related material, geometric and the connection between the bridge pier and micro piles.

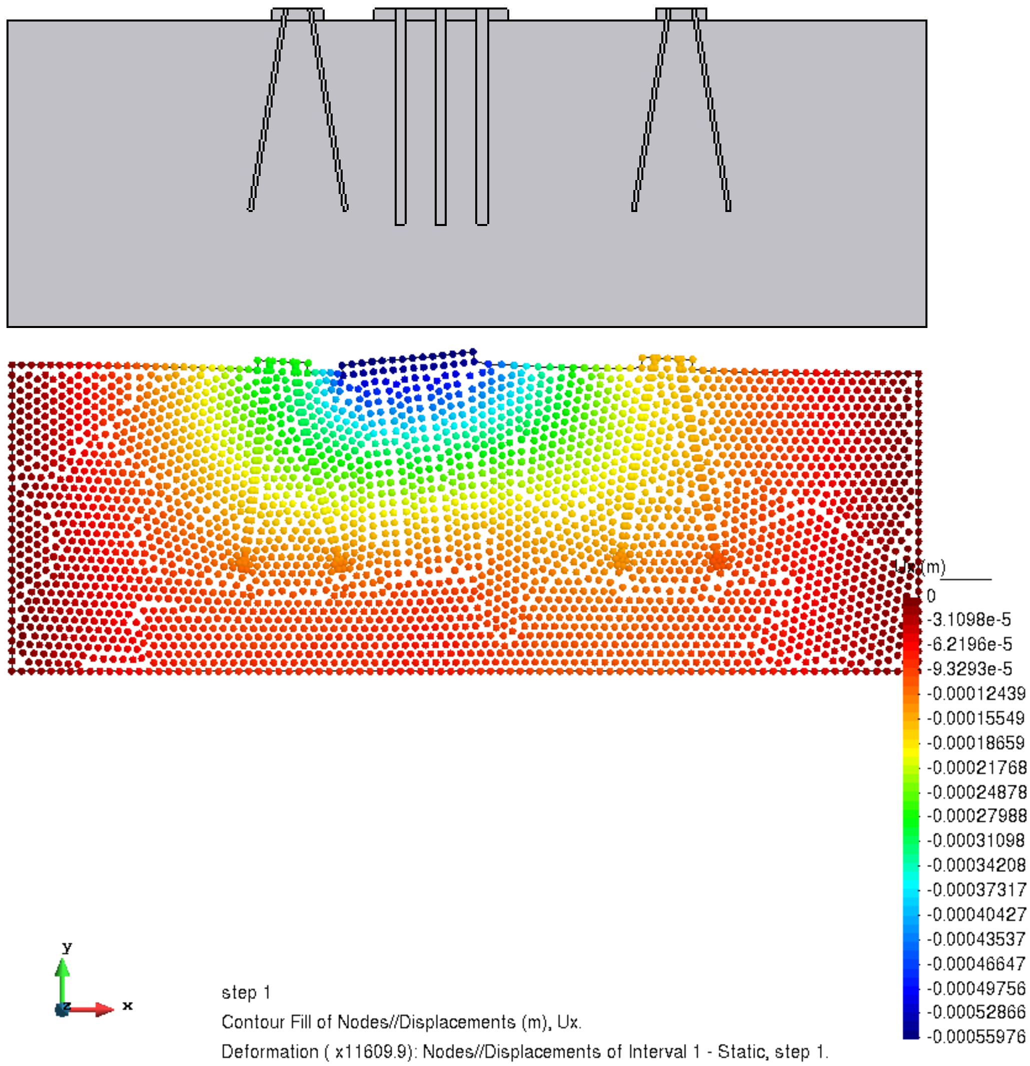

Figure 2: Geometry of finite element model and simulated displacement

Task 3 - Component modeling of Innovative foundation system and soil-foundation interaction

There are some number of design factors to consider in designing the micropile-based foundation system. Given the target design mechanism, i.e., combination of Case 3 with Case 1 or 2, these factors can be considered at three different levels: (1) Individual micropile island: the factors do not only require to determine the geometry and material properties of individual micropiles, e.g., angle of batter, size of casing and embedment length, but also configuration of the micropiles in the island such as the number of micropiles and spacing. The group effect caused by the configuration of micropiles will be carefully examined, which may negatively impact the total capacity of the group if micropiles are too closely spaced, because the overlapped influence zones of the closely spaced individual micropiles will reduce the nominal capacity. On the other hand, if the spacing of micropiles is large, the cost to prefabricate the micropile cap will increase; (2) Layout of micropile islands: the influence of the overall layout of islands will be examined, including the number of islands and spatial arrangement of them. For example, if the islands are too close to the existing foundation, the soil between the island and the existing foundation may be more susceptible to their relative motions. On the other hand, if the islands are placed too far, the construction cost will increase; (3) Connection between the micropile islands and the existing foundation: viscoelastic dampers will be considered as the energy dissipating system to suppress the motion of existing foundation. The parametric studies on these factors will be systematically performed through finite element soil-foundation interaction analysis. The feasibility of the proposed approach will be demonstrated and the optimal design will be also sought between the overall performance of the new foundation system and construction cost. OpenSees will be adopted for this task. 2D foundation system will be considered first for proof concept, and then the concept will be expanded to 3D. To expedite the parametric studies, the structure above the foundation will be modeled as a single degree of freedom. Dynamic amplification, resultant forces and bending moments at various locations of the micropiles and the existing structure will be analyzed. The viscoelastic dampers will be modeled using the standard linear solid model. No further development has been done on this task to date.

Task 4 - Develop detailed analytical models for representative HSR bridge configurations with regular or irregular geometry

As discussed above, one of the objectives of Task 1 is to collect sufficient information on HSR infrastructure, with focus on bridges, from published studies, report, or design codes and guidelines. The objective of Task 4, which will be executed at UNR in parallel with Task 2 at FIU, is to develop representative bridge models for HSR. The California high speed train project technical memorandum for design [10] will be considered to identify the main components of bridge configurations under consideration by the CA HSR Authority and the associated design loads. Moreover, the research team will identify existing bridges or infrastructure that could be potentially used for future HSR with further retrofitting using the innovative foundations proposed in this study. Another option to consider for developing bridge configurations is considering design examples from other countries that have excelled in HSR infrastructure engineering. Several bridge configurations with regular and irregular geometries could be considered (e.g. curved bridges or bridges with unequal pier heights). All bridge models will be developed in OpenSees and will consider the different components for soil, foundation, and structure for full interaction. As part of this task, ground motions that represent the seismic hazard in CA and at specific sites where the HSR is expected to be extended will be selected. Suites of ground motions will be assembled to represent different scenarios, e.g. near fault rupture, and to be used in the analysis in Task 5.

The team leverages OpenSees for study of various seismic performance enhancement techniques. These have included a numerical parametric study on the effects of steel jackets and isolation bearings. The prototype is a box girder bridge consisted of three spans of equal 100 feet. The cross-section properties are selected based upon a simple two track train configuration. Columns were modeled as elastic beam column elements with nonlinear fiber sections capturing the confinements effects of reinforced concrete. Steel jackets are put on or off. Foundations are modeled as soil springs with p-z, t-z, and q-z springs. Isolation bearings are modeled as a bilinear zero length elements with the properties summarized in Table 2. Nonlinear time history analysis is performed using motions from the Northridge SCS station depicted in Figure 3.

Table 2: Isolation bearing material properties

Material Properties	Value
Yield Strength	100 kip
Initial Elastic Strength	100 kip/in
Post-yield Elastic Stiffness Ratio	0.2

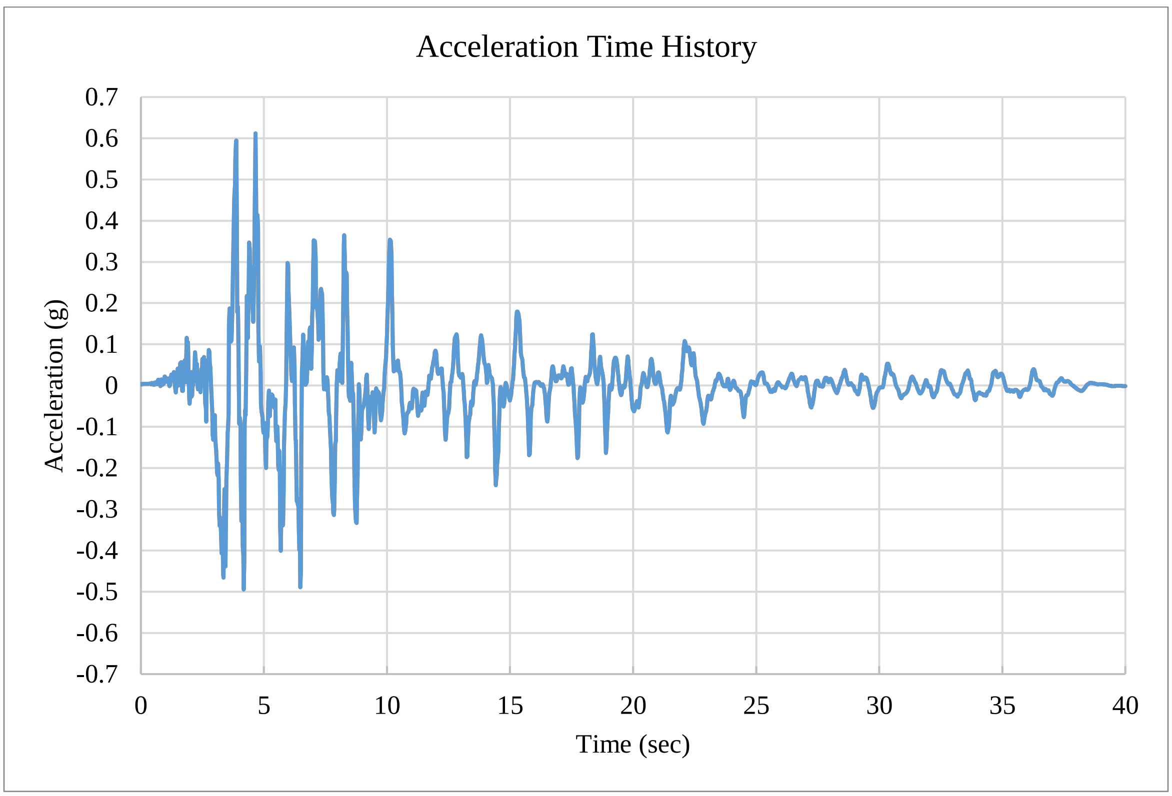

Figure 3: Northridge Sylmar Converter Station (SCS) horizontal time history

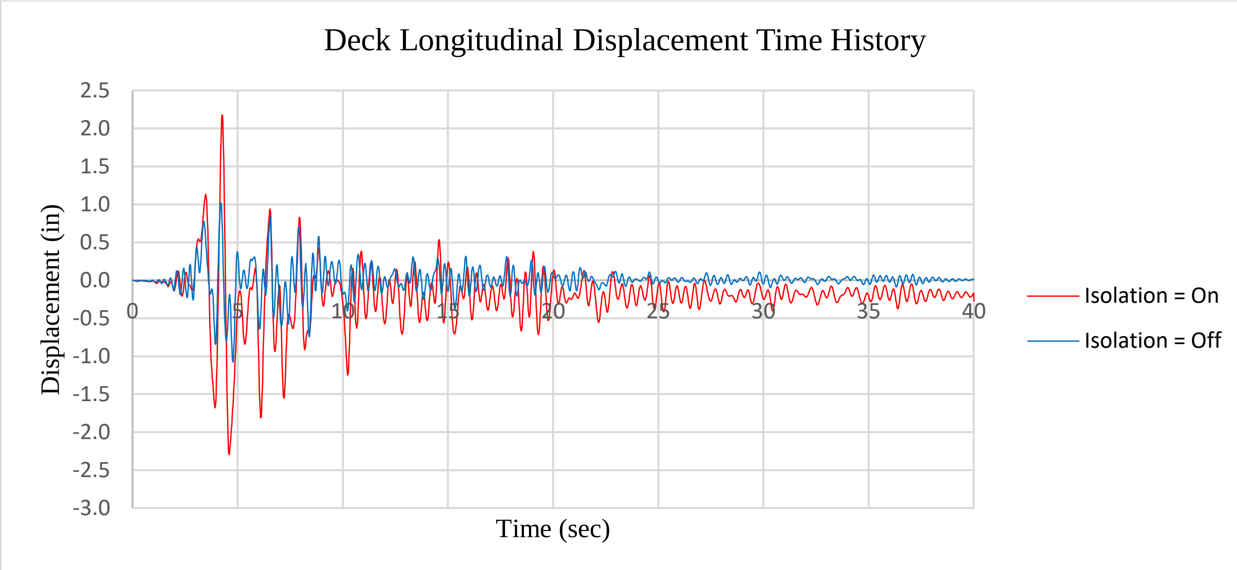

Figure 4: Deck Longitudinal Displacement Time History

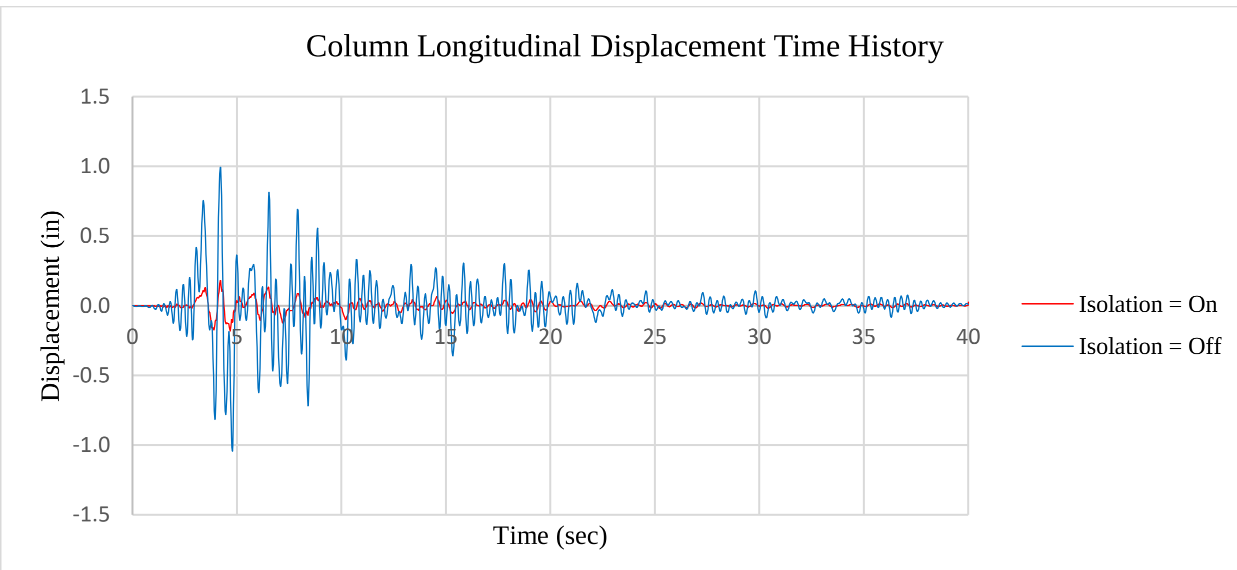

Figure 5: Column Longitudinal Displacement Time History

The preliminary results demonstrated an increase in the natural period of the structure, an increase in deck displacement, and decrease in column seismic forces. These results were in well agreement with those found in literature [11].

The configuration of the prototype bridge will be modified to include more realistic parameters. Acceleration response spectrum has been developed using the Caltrans Acceleration Response Spectra (ARS) website and ground motions spectrally matched to perform a non-linear time history analysis. Figure 6 shows the results of the preliminary ground motion study. Furthermore, properties of the isolation bearings will be designed for the displacement demand of the structure. Upon completion of these tasks, further refinements to deck geometry and bridge configurations.

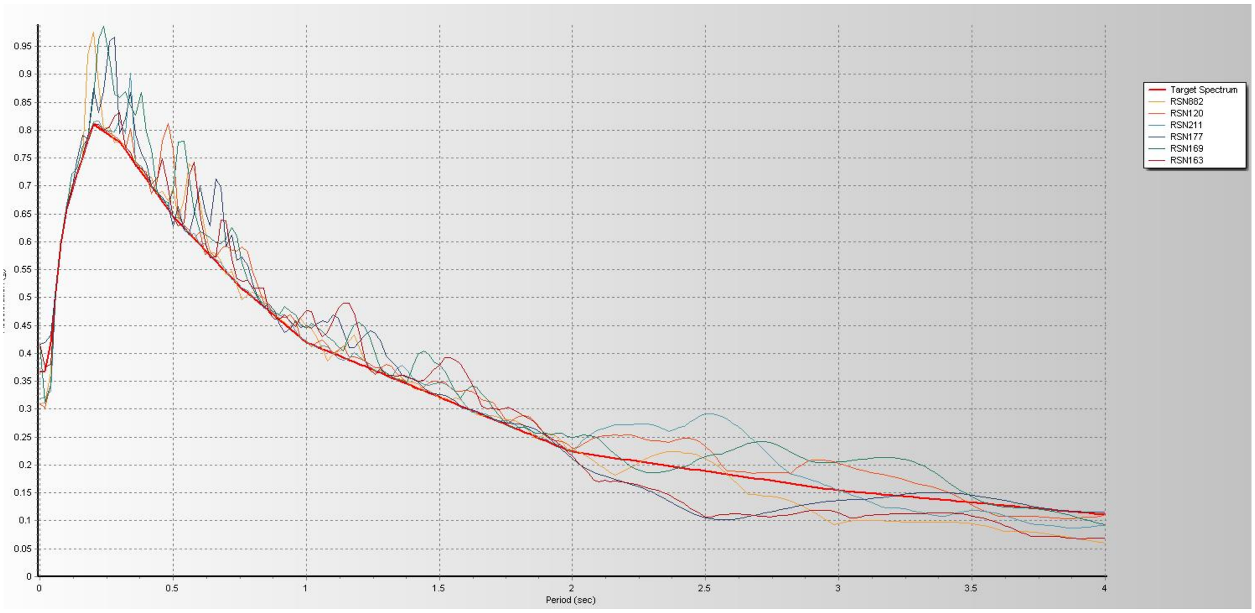

Figure 6: Spectra Target and Spectrally-Matched Motions (Horizontal Component) obtained using Seismomatch 2018

To further study the prototype bridges for numerical modeling, various cross-sections of HSR bridges along alignments described in construction packages one through four were studied. First the bridges were categorized into standard, complex, and non-standard structures bins of varying lengths. Standard structures are those that are not complex structures and comply with the California High-Speed Train Project Guidelines for Standard Aerial Structures. Complex structures are those that have complex response during seismic events or one more of the following: irregular geometry, unusual framing, long spans, lightweight concrete, unusual geologic conditions, proximity to hazardous faults, and regions of severe ground motion. Non-standard structures are those that do not meet the requirements for either standard or complex structures. Grouping the bridges into different categories allows the team to select prototype bridges for analytical studies. The seven categories separating the bridge structures are standard viaducts, non-standard viaducts, underpasses, bridges, trench structure, box culverts, and retaining walls. Furthermore, standard viaducts consist of single-cell prestressed, precast concrete box girders with spans of 100 to 130 feet long. Non-standard viaducts consists of steel trusses, balanced cantilever structures, multi-cell cast-in-place (CIP) box girders used for wide station structures or maintenance tracks or elevated slab structures. Bridges include short structures such as the standard 120-foot PS/PC box girder spans carrying HSR over Tule River and Poso Creek. An example of the classifications is depicted in Table 3. The results of the study demonstrated the most typical cross section to be the standard Caltrans single cell box girder shape depicted in Figure 7. Other prominent structure types include multi-cell box girders, steel u girders, and truss structures.

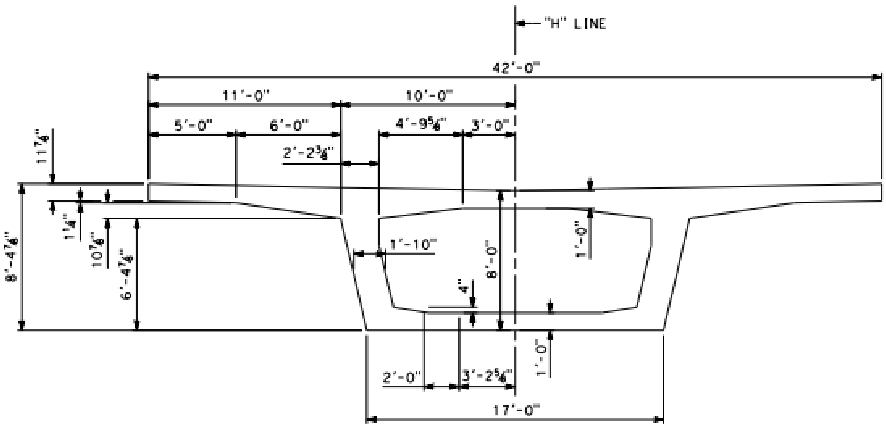

Figure 7: Typical Cross Section Along HSR Route from Madera to Shafter

As a complement to the previous study, a review of existing soil conditions along the planned HSR route from Madera to Shafter was studied using the preliminary geotechnical reports. The boring logs were cross referenced into a Google Earth data file facilitating easy access for future uses. Figure 8 shows a snip of the boring records implemented into Google Earth. Figures 9 through 11 show various CPT and SPT records along the alignments. The soil conditions along the HSR route consisted primarily of sand with interbedded layers of clays, of which is typical in this geologic setting. Categories of soft to stiff soil conditions were interpreted from CPT data by using correlations to N_{60} values. Percentiles were used to quantify the variation and to then select worst case and best scenarios based upon provided data. Figure 12 and 13 depicts the classifications from soft to stiff soil sites for construction packages 2 through 4. Preliminary estimation of drilled pier depths was estimated using available SPT data. The blow counts were used to estimate an effective friction angle and correlated to skin friction using methods described in the FHWA GEC 10. Approximate loading per column was taken at 1,000 kips. The approximate depth of the drilled pier was taken as 45 feet.

Table 3: Classification of the HSR bridges

Bridge Type	Viaduct	Short Length
Standard Bridges	• Fresno Viaduct (11155+36) • Fresno Viaduct (11199+97) • Viaduct Crossing E Conejo Avenue • Viaduct Crossing S Peach Avenue • Kings River Viaduct (1463+58) • Kings River Viaduct (1466+97) • Kings River Viaduct (1489+17) • Kings River Viaduct (1525+33) • Kings River Viaduct (1593+64) • Hanford Viaduct (including Kings/Tulare Regional Station) • Cross Creek Viaduct • SR 43/BNSF Viaduct (2986+36)	• Poso Creek Viaduct • State Route 46 Underpass

<table>
<tr><td></td><td>SR 43/BNSF Viaduct (3026+21)
Wasco Viaduct
Shafter Viaduct</td><td></td></tr>
<tr><td>Complex Bridges</td><td>Fresno Viaduct Golden State Boulevard
Fresno Viaduct South Cedar Avenue
Fresno Viaduct SR 99 Undercrossing
Kings River Viaduct (Steel Truss)
Cole Slough Bridge
Dutch John Cut
Kings River Viaduct (Steel Truss)
Kaweah SR Crossing
Cross Creek Bridge (Steel Truss)</td><td></td></tr>
<tr><td>Non-Standard Bridges</td><td>Conejo Crossover Structure
Hanford Viaduct (including Kings/Tulare Regional Station)
Cross Creek Viaduct (Crossover Beam/Slab Structure)
Cororan Crossover Structure (part of SR 43/BNSF Viaduct)</td><td>Fresno Street Overpass
Tulane Street HST Overpass
Jensen Trench
Whitney Ave/SR 137</td></tr>
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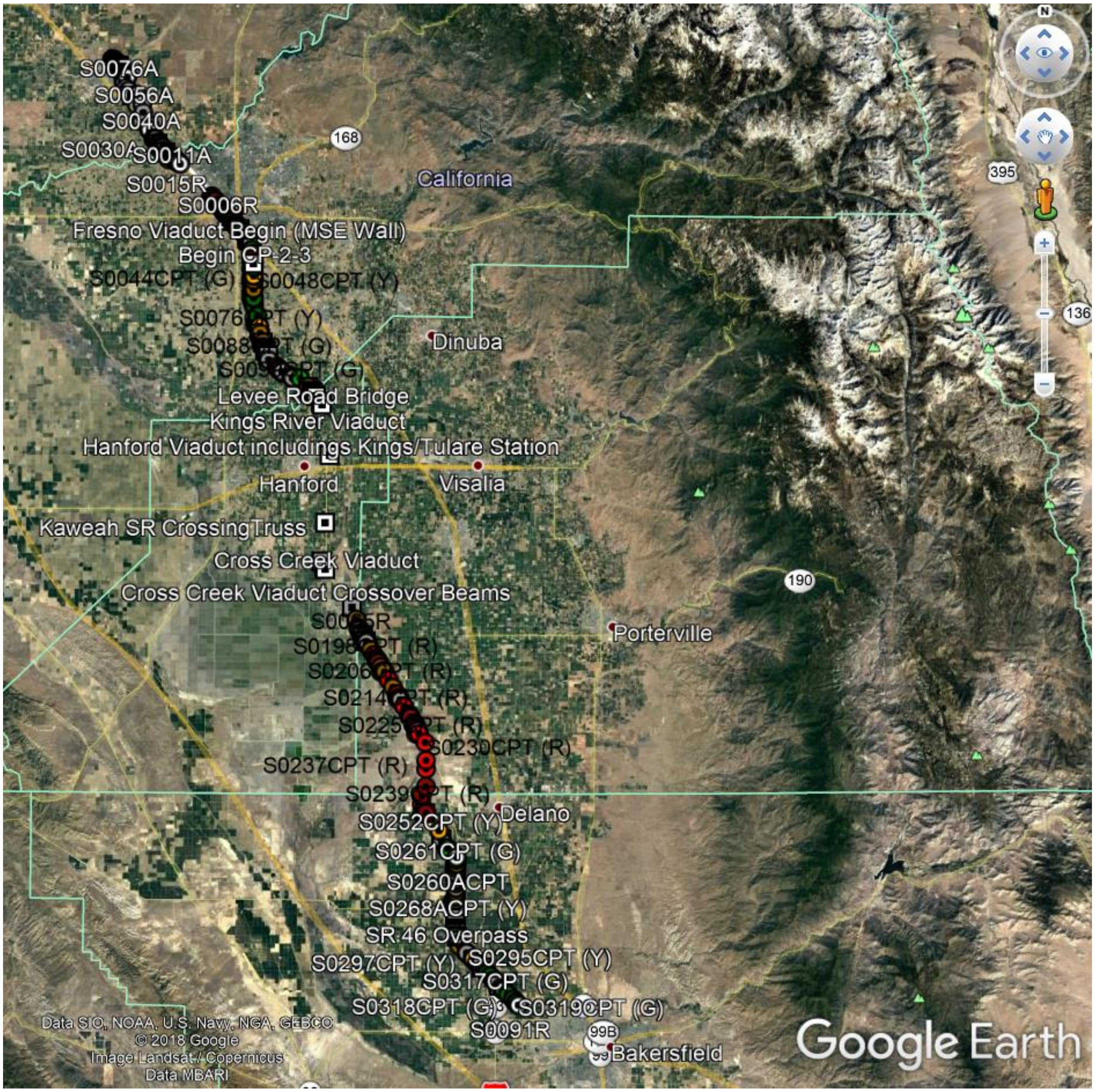

Figure 8:Google Earth Data File of Geotechnical Data

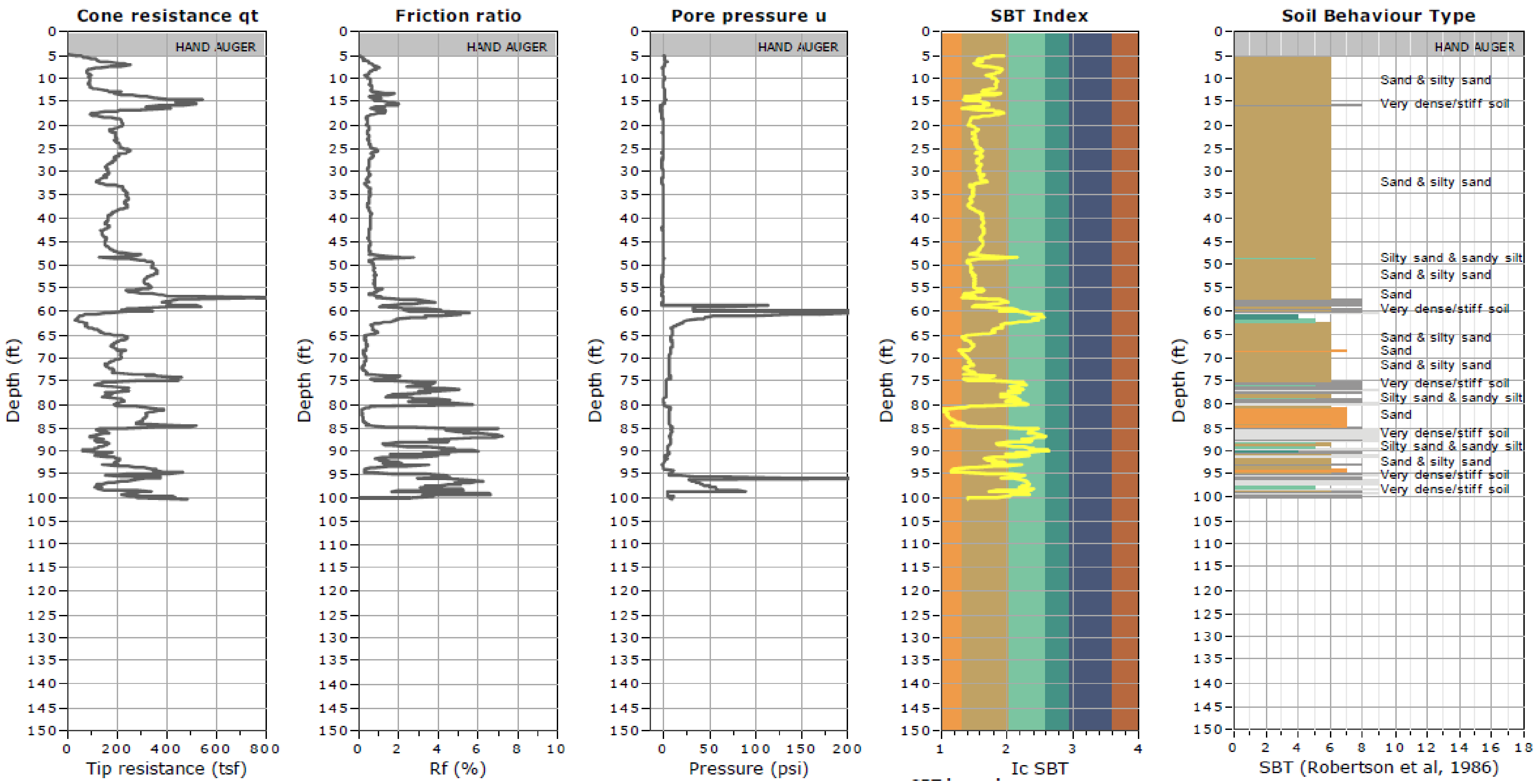

Figure 9: Example CPT Record for Construction Package 1

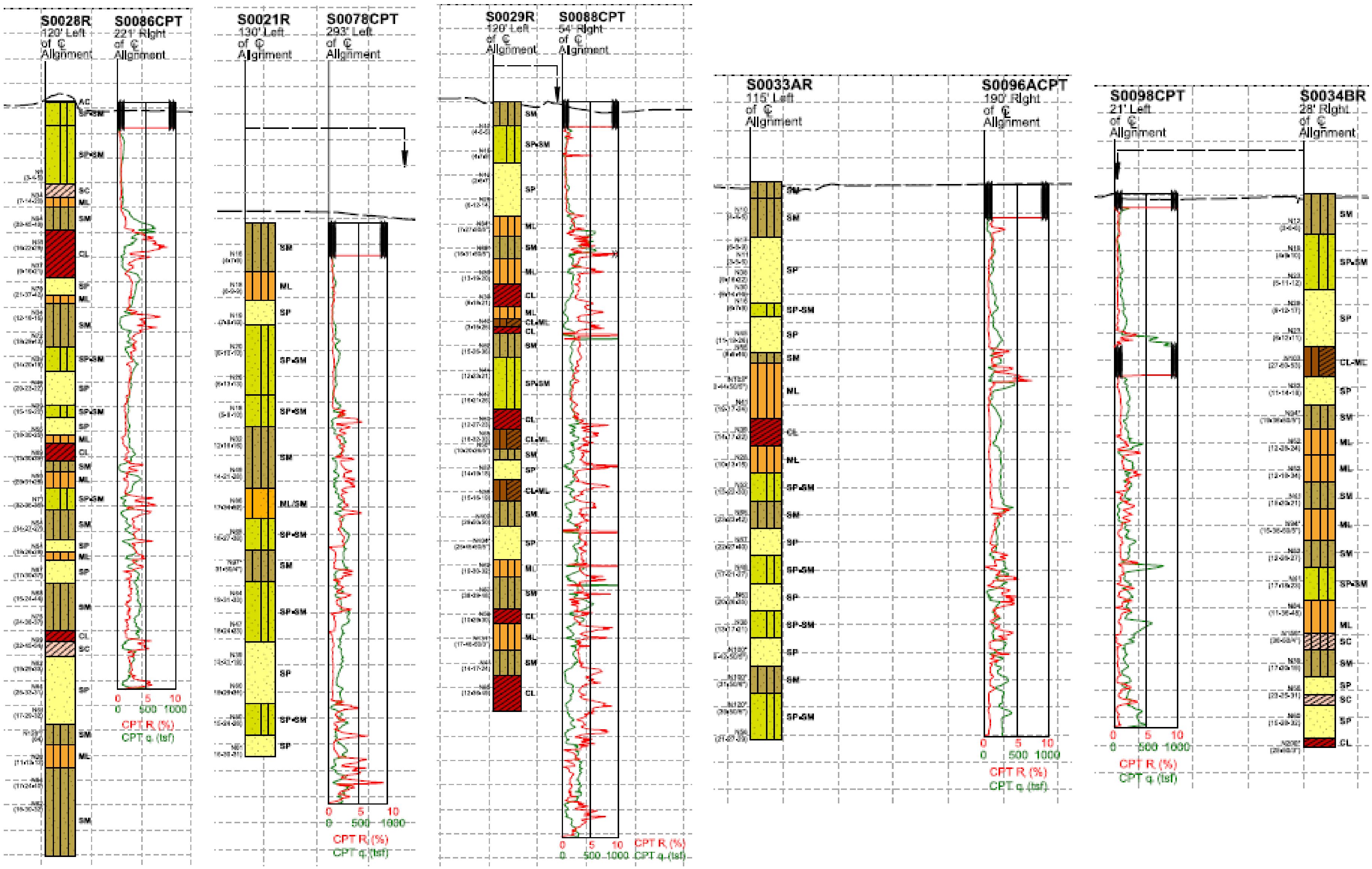

Figure 10: Example CPT and SPT Records for Construction Package 2-3

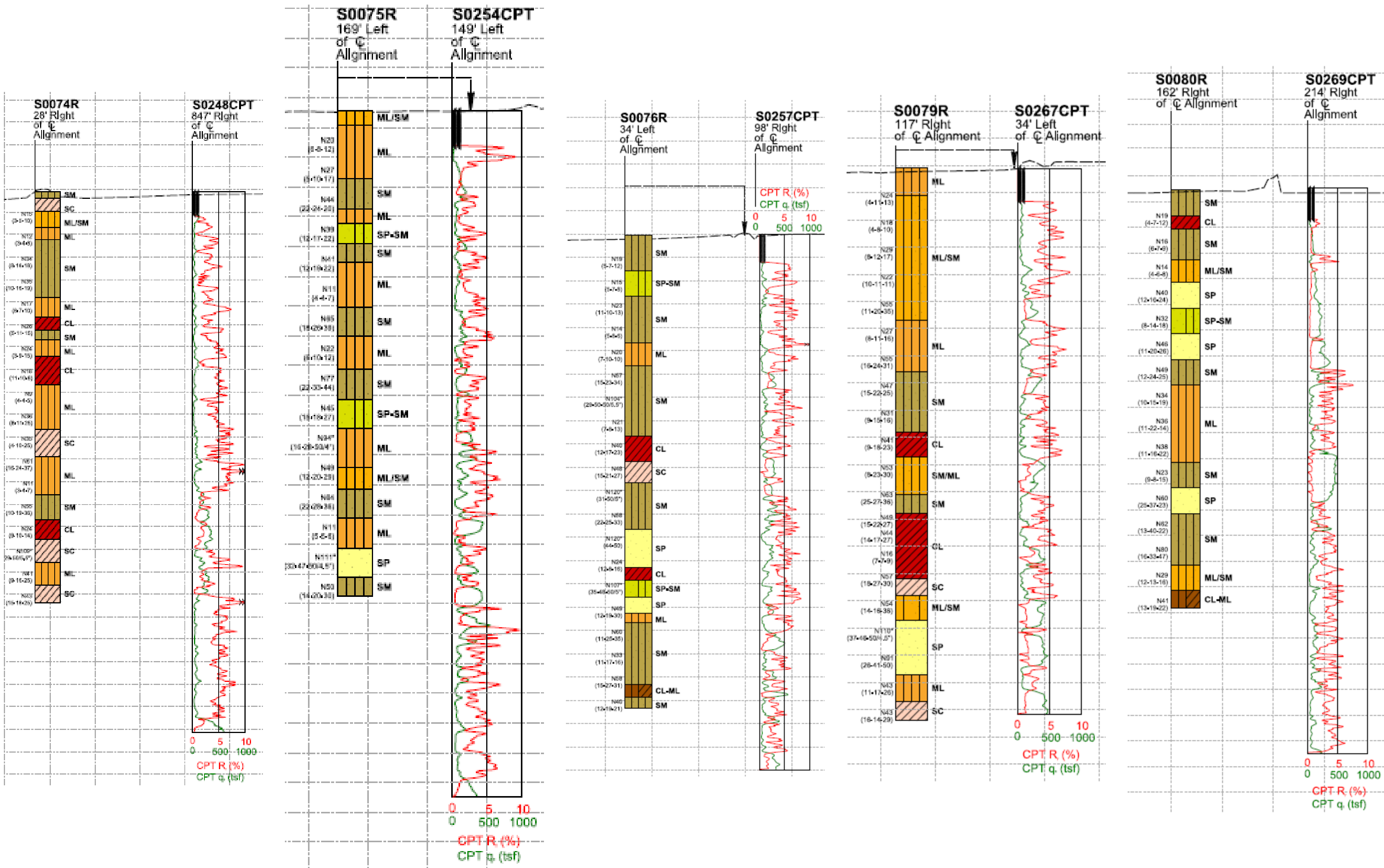

Figure 11: Example CPT and SPT Records for Construction Package 4

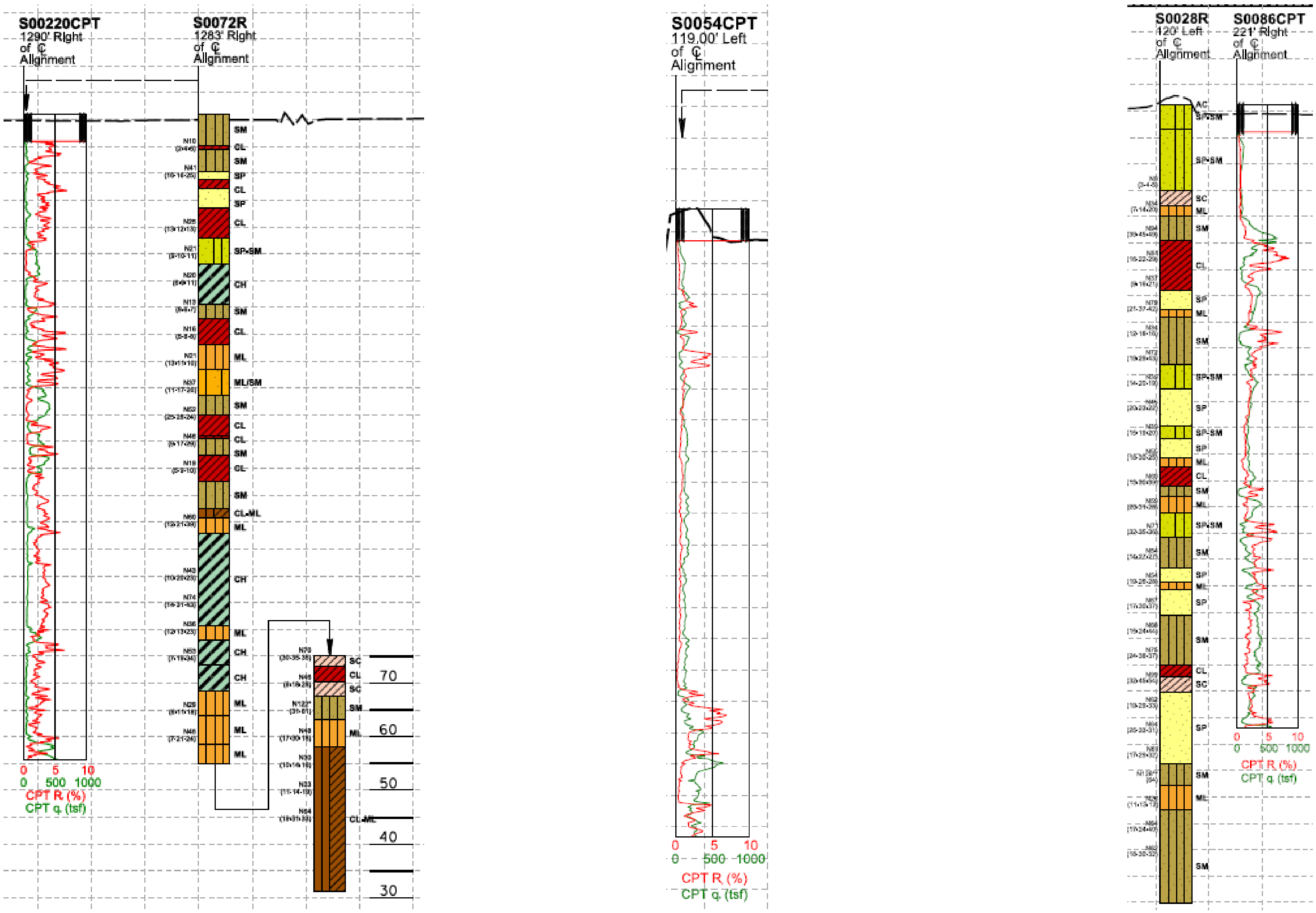

Figure 12: Soft to Stiff Soil Profiles for Construction Package 2-3

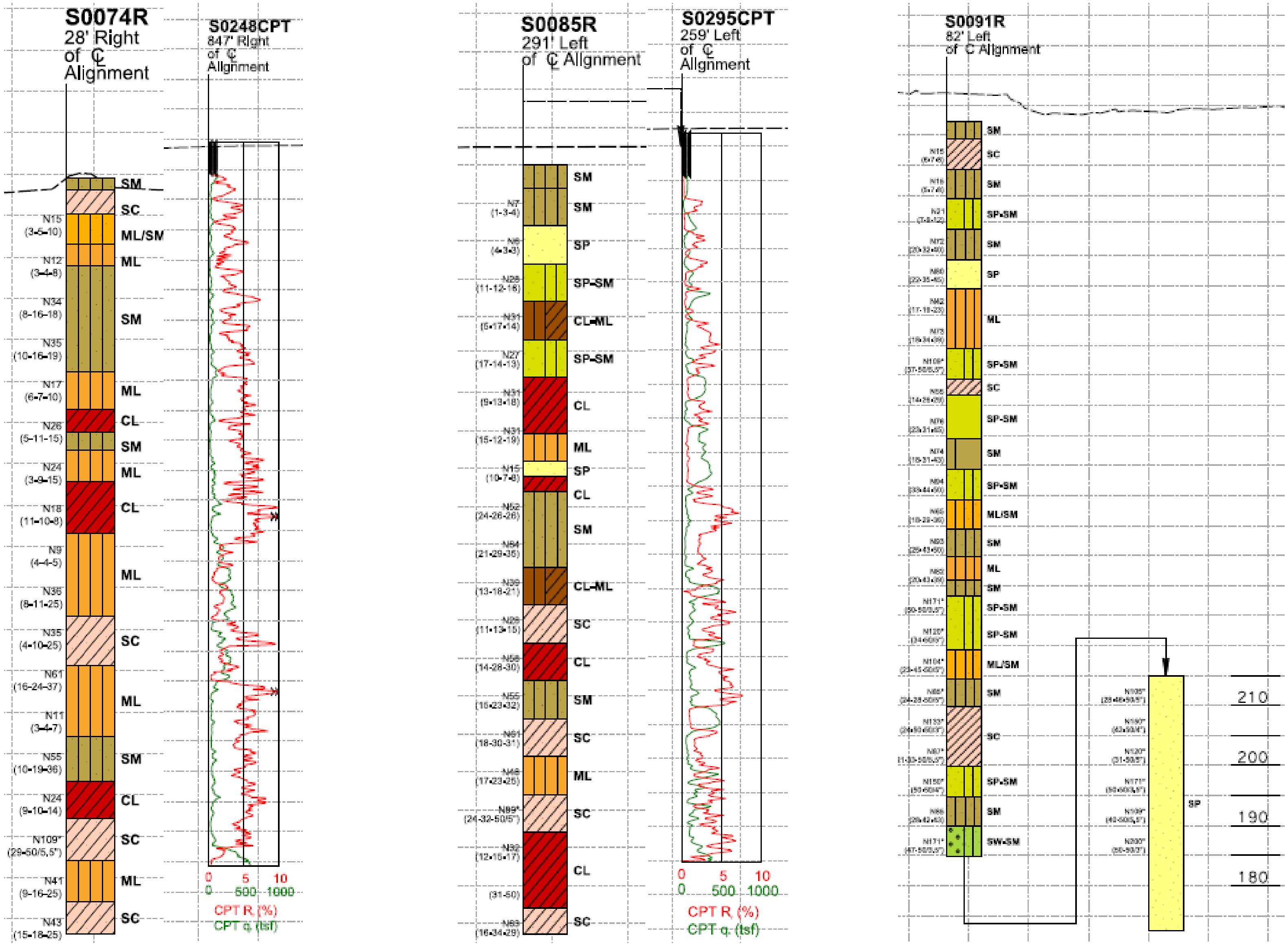

Figure 13: Soft to Stiff Soil Profiles for Construction Package 4

To simulate axel loading from a high-speed rail, an appropriate train loading model was selected. Models from various countries are gathered including AREMA, UIC, IRCT-J, Chinses HSR railway models, and the AREMA Cooper E-50 (Figure 14) was considered as a starting point for the numerical study. This train loading model can later be modified based upon more realistic loading cases in the U.S. or adopt European or Asian standards.

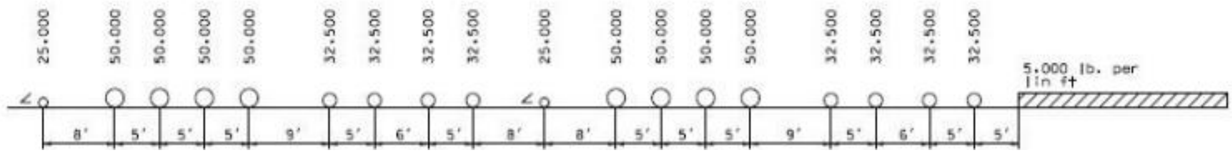

Figure 14: Cooper E-50 Train Loading Model

To model the impact on soil structure interaction on HSR bridge design, this study investigates two distinct modeling approaches that include the direct approach and the sub-structured approach. The direct approach (Figure 15) models the soil, foundation, and structure all within the same simulation referred to as an integrated approach where kinematic and inertia effects are considered within the model directly. The sub-structure (Figure 16) approach is referred to a de-coupled approach where the soil and massless foundation are modeled as simplified springs with factors taking into consideration the inertia effects of the soil.

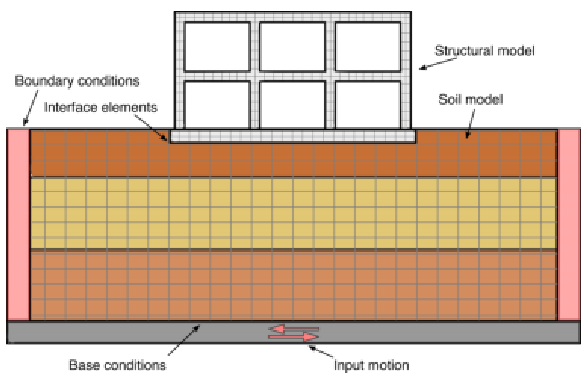

Figure 15: Schematic of a direct approach to modeling SSI

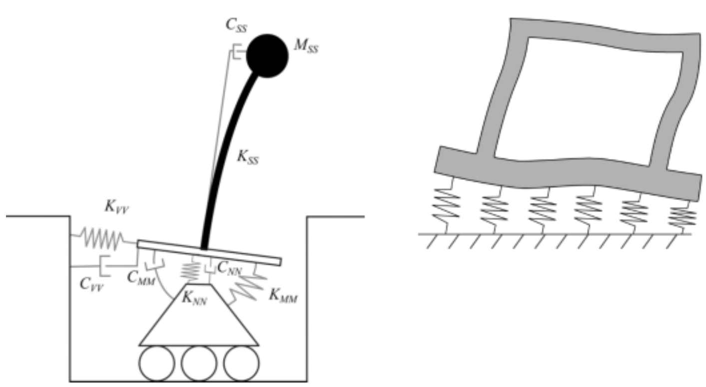

Figure 16: Schematic depicting substructure approach to modeling SSI

To study the impact of train loading on typical high-speed rail bridges an Opensees model modified MSBridge output files was generated. The output file of the program was modified using an integrated development environment called Cypress Editor. The train loading was applied to the model as nodal loads by creating the following subroutine. The position of the vehicle is kept track along the length of the bridge and the loads are applied to the corresponding nodes of its position. The speed is input into the program and a time history analysis is conducted with each step corresponding to a load being instantaneously applied, solved, removed, and reapplied in the following step. With this approach, combined seismic and moving live load can be modeled. The results of our first modeling attempt against the Borrego earthquake is shown below in Figures 17 and 18.

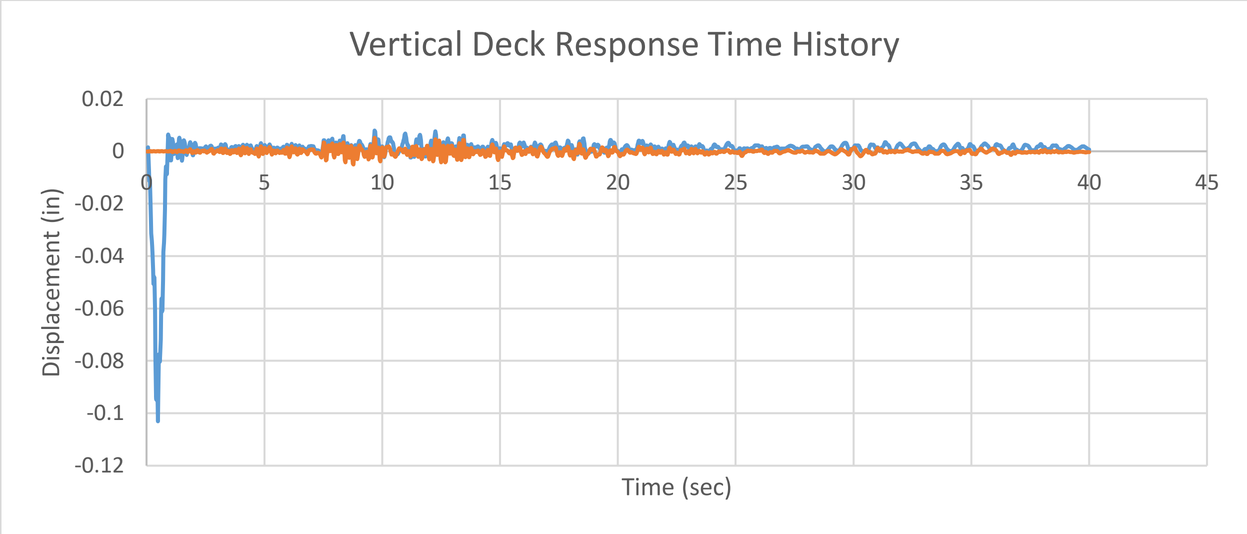

Figure 17: Vertical Deck Response Time History of Preliminary Opensees Model

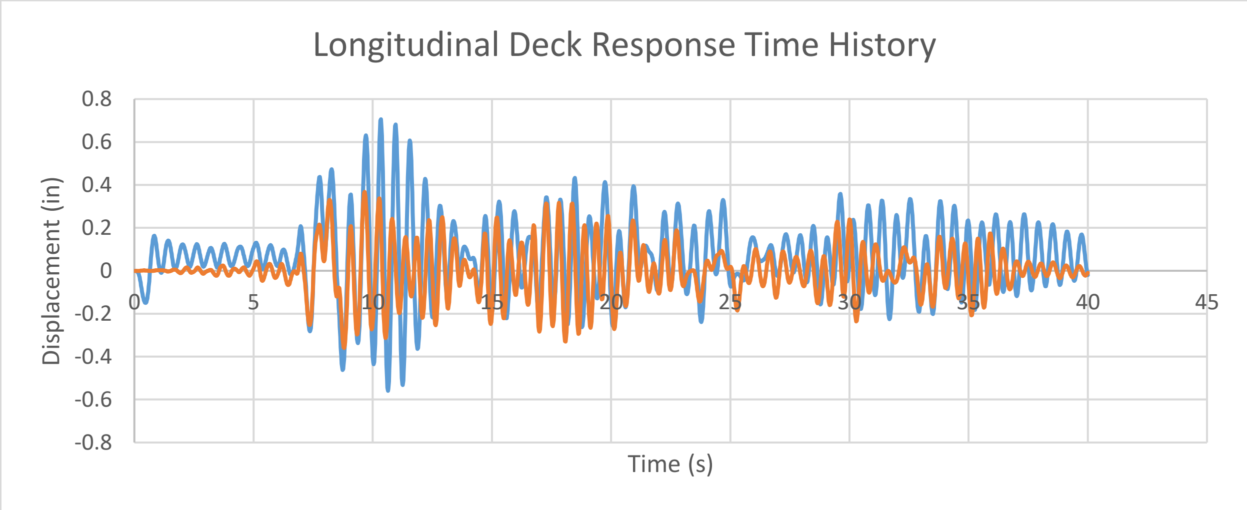

Figure 18: Longitudinal Deck Response Time History of Preliminary Opensees Model

Future direction of this project will involve the validation of Opensees model against published references and any available software to the team.

Task 5 - Conduct analytical studies of the bridge model

Using the detailed component and full system models that will be developed in Tasks 2 through 4, extensive nonlinear time history analysis will be conducted. The objective of such analysis and this task is to investigate the seismic response of potential HSR bridges retrofitted with innovative foundation systems and micropiles. To better gage the efficiency of the retrofit or the effect of new proposed foundation systems, comparative analysis will be conducted. This is to compare the structural and seismic response of bridge models with conventional foundation systems to the new retrofitted system. The response will be determined based on damage in structural components such as columns or failure in the foundation system such as yielding in the soil. Displacement demands will be determined and compared as needed to serviceability requirements from design codes or performance-based design guidelines for HSR. One other potential way of comparing the seismic response is to develop fragility curves for the bridges with conventional and innovative foundation systems across the different damage states. The final method for presenting the analysis data can be decided through discussions and consultation with the project advisory panel. No further development has been done on this task to date.

Task 6 - Summarize the investigation results in the final report

A final report describing the details of different tasks will be prepared and submitted to the ABC-UTC steering committee for review and comments. Upon addressing the review comments, the report will be finalized and made widely available for dissemination.

5 Expected Results and Specific Deliverables

5.1 Tentative ABC-UTC Modeling Guideline

One format to disseminate the results from this project is to develop an ABC guideline to apply the innovative foundation systems for HSR. The guideline will also include preliminary design and detailing guidelines for the foundation systems.

5.2 A five-minute Video Summarizing the Project

Another format to disseminate the results from this project and contribute to workforce development and outreach is to develop a video and presentation slides to summarize the project. A webinar format can be used to publish and make available such videos or presentations.

5.3 Final Report and Publications

A comprehensive report will be developed to summarize the design and modeling approaches as well as all the analysis results. The produced analytical datasets could also be published using existing or new cyber infrastructure or data platforms if a unified research repository is employed by ABC-UTC for the research center projects. Publications in peer-reviewed journals and conference presentations will also be considered for delivering project results.

6 Schedule

Progress of tasks in this project is shown in the table below.

Task	Year 1				Year 2	
	Q1	Q2	Q3	Q4	Q1	Q2
1. Literature search	X					
2. Innovative conceptual design		X	X			
3. Component modeling			X	X	X	
4. HSR bridge modeling		X	X			
5. Conduct component /system analysis				X	X	X
6. Final report & dissemination						X

Work performed or in progress

Work to be performed

Item	% Completed
Percentage of Completion of this project to Date	25

7 References

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