NUMERICAL MODELING STRATEGIES FOR HIGH SPEED RAIL STRUCTURAL SYSTEMS

Quarterly Progress Report
For the period ending March 1, 2020

PI: Mohamed Moustafa, Ph.D., P.E.
Graduate Student: Andrew Stephenson

Affiliation: Department of Civil and Environmental Engineering
University of Nevada
Reno, NV

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

Submitted to:
ABC-UTC
Florida International University
Miami, FL

March 2020

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.

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, California started to work on extending the first HSR line that connects the bay area to southern California. Although the construction for the HSR infrastructure started in California in 2017, the project is consistently getting delays and face several hurdles and challenges. Independent of the CA HSR progress, providing guidance on the modeling, analysis, and design of HSR infrastructure and structural systems could be very beneficial to inspire future national and local HSR projects within the United States.

Bridges are key components of the HSR infrastructure and both new construction as well as utilizing existing structure and foundation systems can be used for HSR. The inherent characteristics of HSR raise new problems beyond those found in typical highway construction, so comprehensive numerical approaches on the bridge structure modeling are needed. The focus of this project is to identify the modeling features and special characteristics of HSR bridges and provide guidance and demonstration examples on how to develop such models.

3 Research Approach and Methods

Our approach for this proposed study is twofold: (1) synthesis of existing literature on HSR bridge modeling and numerical simulation; (2) develop detailed finite element models to demonstrate HSR bridge simulation under service loads and extreme events such as earthquakes. OpenSees, an opens source framework developed by the Pacific Earthquake Engineering Center, will be adopted for the finite element computation. Component and system modeling and analysis will be conducted in a collaborative effort between FIU and UNR. The two teams will work together closely where the PI from FIU will be mostly in charge of the substructure modeling, i.e. foundation systems and soil-foundation interaction, and the team at UNR focuses on the superstructure. The specific research objectives include: (1) synergizing available national and international data on HSR bridge configurations and foundation systems; (2) develop numerical modeling guidelines based on previous studies; and (3) provide demonstration case studies for modeling and analysis of HSR bridges.

4 Description of Research Project Tasks

A summary of the proposed research tasks is as follows:

Task 1 – Literature search on HSR bridges and components.

Task 2 – Develop modeling guidelines for HSR bridges with focus on special features such as train-track-structure interaction.

Task 3 – Conduct demonstration analytical case studies of selected HSR bridge models.

Task 4 – 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. The literature review is currently in progress with focus on collecting information on HSR infrastructure around the world.

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 the 276-mile HSR line connecting the 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 a second phase of its national high-speed rail network.

Table 1 - HSR in Operation and Under Construction Worldwide

TABLE 1
High-Speed Rail 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).

Following the rapid growth of high-speed railway transportation and the advancement of railway technology, precise analysis of dynamic interaction for vehicles and bridges has turned into a significant issue. To have a comprehensive knowledge of proper idealization of such systems, modeling techniques for bridge, track and train systems from around the world have been studied and synthesized in their respective sections.

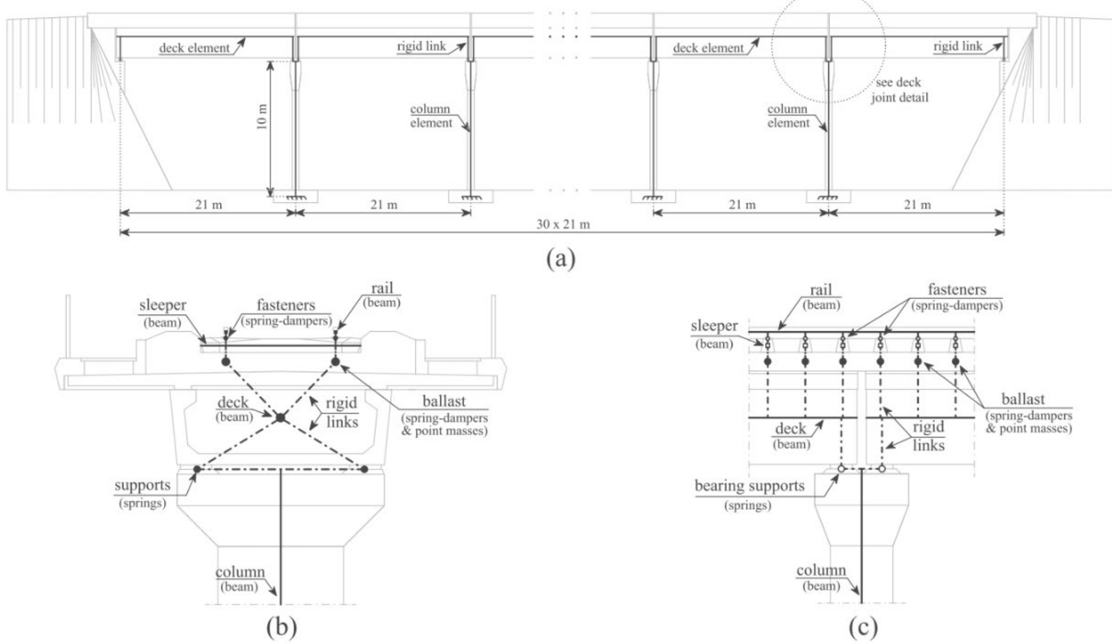
1.1. Bridge Modeling

Bridge models for high-speed rail systems are typically developed using finite element modeling in commercial software such as ANSYS and OpenSees. The main components of the bridge model are the superstructure, substructure and track system. Primarily, the superstructure consists of deck and girder depending on the type of bridge being analyzed, and the substructure consists of abutment, column and bearing. The track system of rail and rail foundation sit on the deck of the superstructure. Although the concept of high-speed rails in the United States infrastructure is new, numerical modeling of bridges are not. Barring the difference in modeling techniques due to structural design, the general numerical modeling of the bridge portion of high-speed rail systems are very similar. The modeling techniques for each component are elaborated in the following sections.

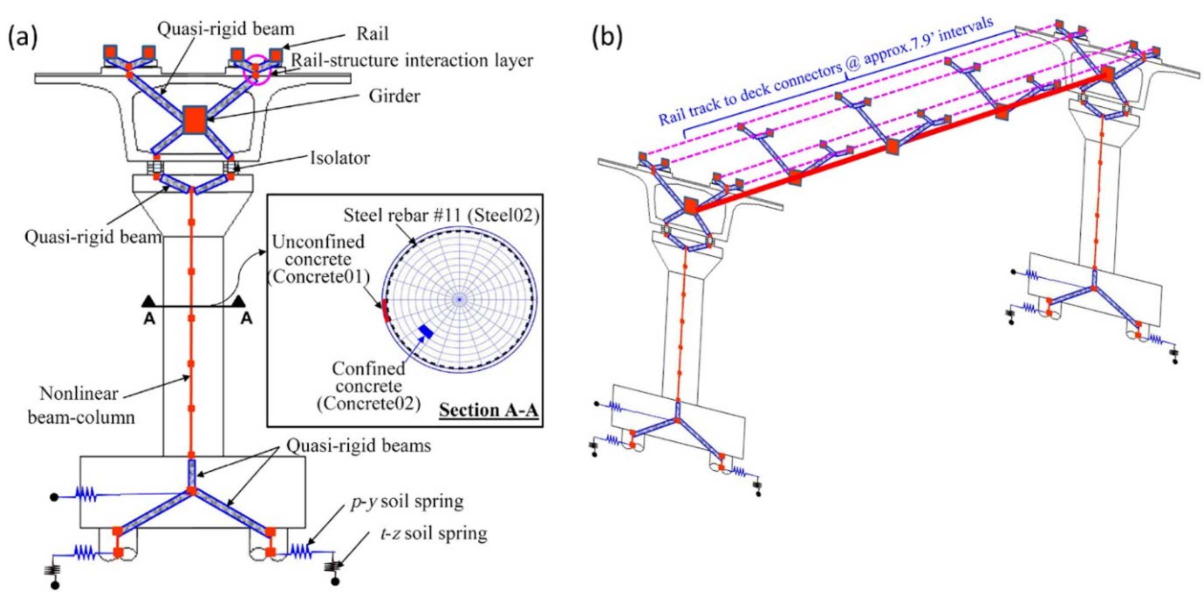
1.1.1. Bridge

The bridge deck and girder can be idealized as a variety of elements depending on the type of bridge system. Beam-column elements are common when modeling concrete box girder bridges because shell elements have higher computational effort and can run into convergence issues in OpenSees.

The most simple and effective way to model a concrete box girder bridge is through linear elastic beam-column elements since they are designed as capacity protected (Fig. 1) (Li et al. 2020, Li and Conte 2016, Montenegro et al. 2015). Rigid connections such as rigid links and quasi rigid elements can be placed between the track and support system to capture the track to deck interactions. A study by Kwark et al. (2004) similarly uses three-dimensional space frame elements constituted by two-nodes, each node with six degrees-of-freedoms (DOF). The girder within each span can be discretized into a number of sections to represent different section properties at the ends of each span (i.e diaphragms) and to accommodate the rail track-to-deck connections. Bridges can also be modelled as an assemblage of three-dimensional beam elements in the elastic domain with six DOFs at each node (Fig. 2) (Lee et al. 2005, Xia et al. 2011). Static condensation of the DOFs, such as Guyan reduction, can be performed to improve computational efficiency.



After Li and Conte (2016)



After Montenegro et al. (2015)

Fig. 1 - Box girder modeled as beam elements

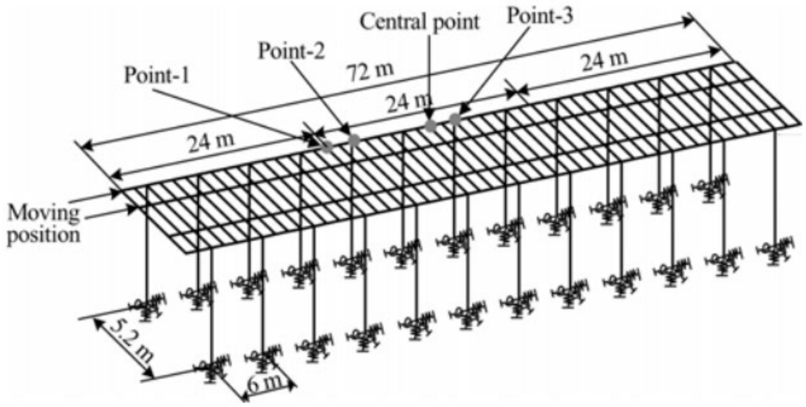


Fig. 3 FEM bridge model

Fig. 2 - Box girder modeled as a frame of beam elements (Xia et al. 2011).

Shell elements can also be used to idealize bridges. Song et al. (2003) utilizes nonconforming flat shell elements (NFS-series) formulated by a linear combination of the nonconforming membrane element with drilling DOF (NMD-series) and the nonconforming plate bending element (NPB-series). NFS elements with six DOFs per node are used to model the box-girder structure (Fig. 3). In-plane and out of-plane deformations are coupled and the consistent mass matrix of the NFS element is lumped at the element joints using the HRZ lumping scheme (Song et al. 2003). When the superstructure and track system are modeled using nonconforming flat shell (NFS) elements, consisting of four nodes with six DOFs per node, it is common engineering practice to use a relatively fine finite element grid in areas of high stress gradients due to abrupt geometrical changes or concentrated loading and a course finite element grid in areas of uniform stress gradients. Transition zones between the fine and coarse grids are modeled using variable-node NFS elements (Song et al. 2003).

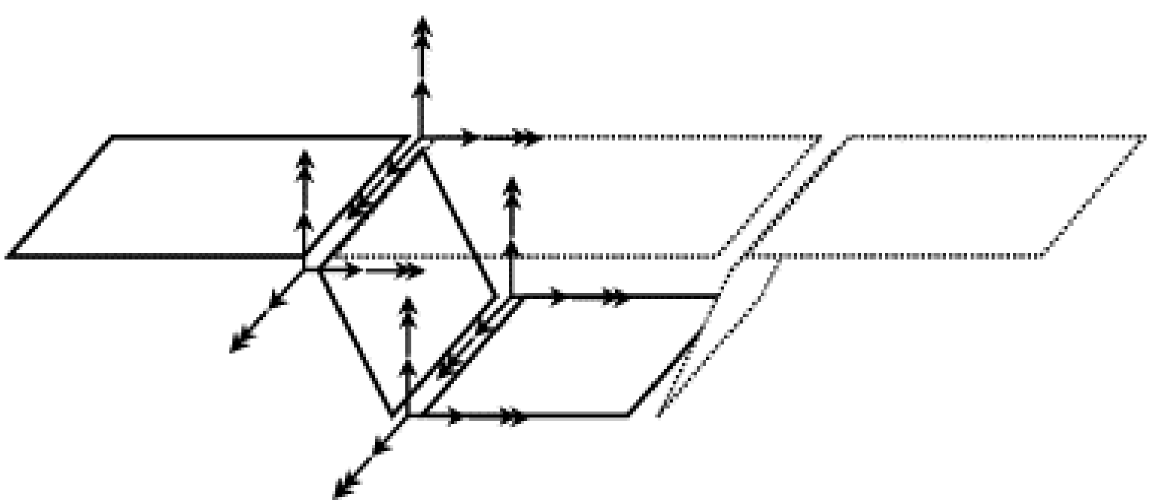


Fig. 3 - Box girder modeled by shell elements (Song et al. 2003).

Another method used to model steel plate girder bridges is with a combination of flat plate elements and beam elements. In Woo Kim et al. 's (2005) study, a steel girder bridge was idealized by modeling the concrete decks as flat plate elements with four nodes and the steel girders, cross beams and guard rails of the bridge as linear elastic beam elements with six DOF nodes. As a similar steel bridge, a steel box girder bridge has been idealized by modeling the concrete deck as a solid element and the steel box as shell elements (Liu et al. 2009). Headed shear studs that connect the concrete deck to the steel boxes are modeled as linear spring elements in the longitudinal direction and coupled in other directions.

1.1.2. Column

Many studies regarding numerical modeling of high-speed rail systems do not include columns in their respective bridge models. This is due to the simplification of the bridge models to simply supported single span bridges. The studies that do include columns typically model such elements with nonlinearity because yielding and damage is expected under strong ground motions.

Bridge columns can be modeled using a number of fiber-based elements such as displacement-based fiber-section beam-column elements (Li and Conte 2016), fiber-based force-based beam finite elements (Kaviani et al. 2012), and three-dimensional elastoplastic fiber elements (Li et al. 2020). Fiber based elements account for material nonlinearity, geometry nonlinearity and bond slip effect of anchoring steel in joints, making it an accurate plastic hinge representation. Integration points should be placed along the length of the element in each column to allow for inelastic behavior at every point. Column cross sections are to be discretized into fibers in polar coordinates as shown in the Section A-A cut, with a specific nonlinear uniaxial material model assigned to each fiber (Fig. 4 and 5), typically unconfined concrete, confined concrete, and steel rebar (Li and Conte 2016, Li et al. 2020, Kaviani et al. 2012). To obtain the behavior of the nonlinear column section, the fiber behavior over the column cross-section is integrated. Potential plastic hinge regions (bottom of column for seismically isolated bridges, and both top and bottom of column for non-isolated bridges) are to be modeled using a single element with length equal to the plastic hinge length, approximated as half the column diameter, to ensure mesh objectivity of the finite element response prediction. The portion of the column-bent embedded in the superstructure is modeled as a rigid element attached to the top of the nonlinear beam-column element. The length of this rigid element is set equal to the distance between the top of the column and the centroid of the soffit-flange of the box-girder.

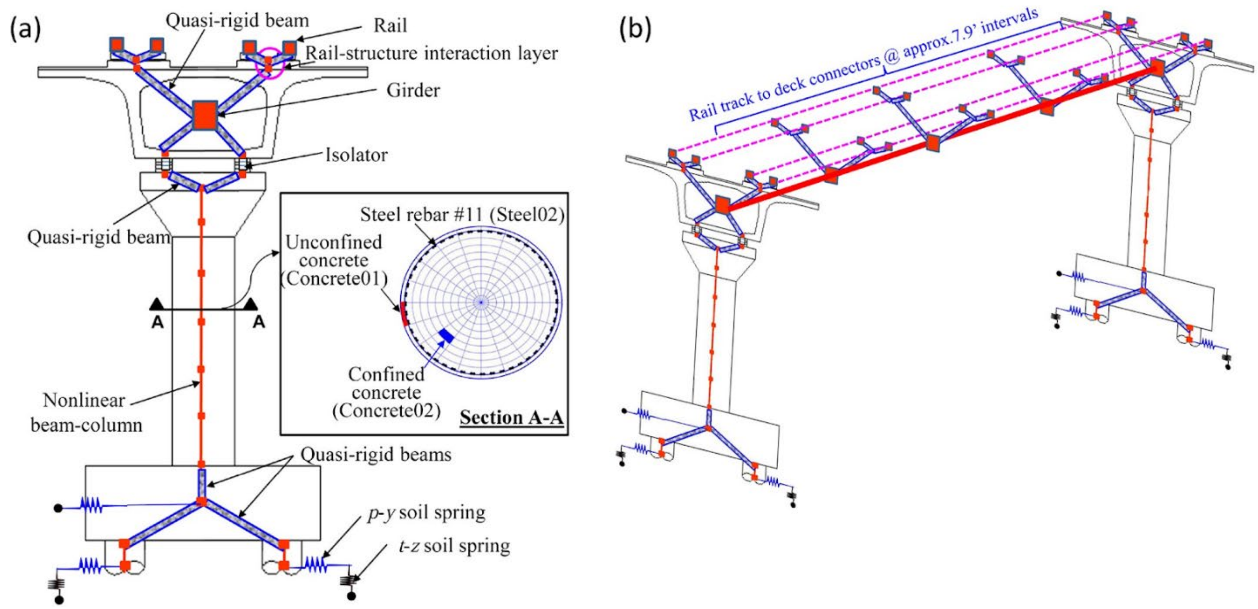


Fig. 4 - Column model schematic (Li and Conte 2016).

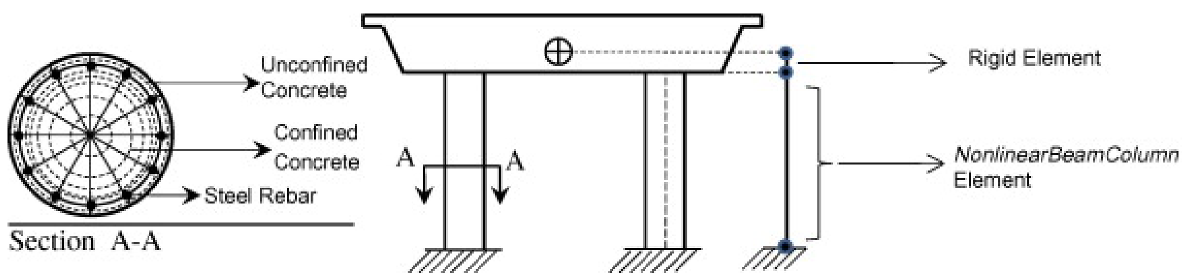


Fig. 5 - Column modeling scheme (Kaviani et al. 2012)

1.1.3. Column Foundation

Column supports can be modeled in an extensive or simplistic method. Li and Conte (2016) have extensively modeled their deep pile foundations using a variety of elements. The schematic is as shown in Figure 6(a), and geometric and material properties are representative of the bridge site considered in their study. The well-established p-y approach is used in modeling the pile foundations and each pile is modeled through displacement-based nonlinear fiber-section beam-column elements. These piles are supported by a series of springs distributed along the length of the pile representing the resistance of the surrounding soil; p-y springs for horizontal resistance and t-z springs for vertical resistance. These springs represent the horizontal and vertical resistance of the surrounding soil, and Q-z springs are placed at the pile tips to represent the vertical soil end-bearing. Pile caps are considered essentially rigid and rigidly connected to the top of each pile, thus modeled as quasi-rigid beam elements to capture the various geometric offsets. Hyperbolic p-y springs are attached to the pile caps to represent the lateral soil resistance.

The elastic effects of column footings, pile structures and the surrounding soil can also be generically modeled by placing longitudinal and transversal ground springs at the bottom of each column (He et al. 2011). Li et al. (2020) have modeled pile foundations as three-dimensional elastoplastic fiber elements, similar to their columns. The fiber elements are divided into 1 m intervals and connected to the soil through three translational and three rotary springs with constant spring values, to simulate the pile-soil interaction.

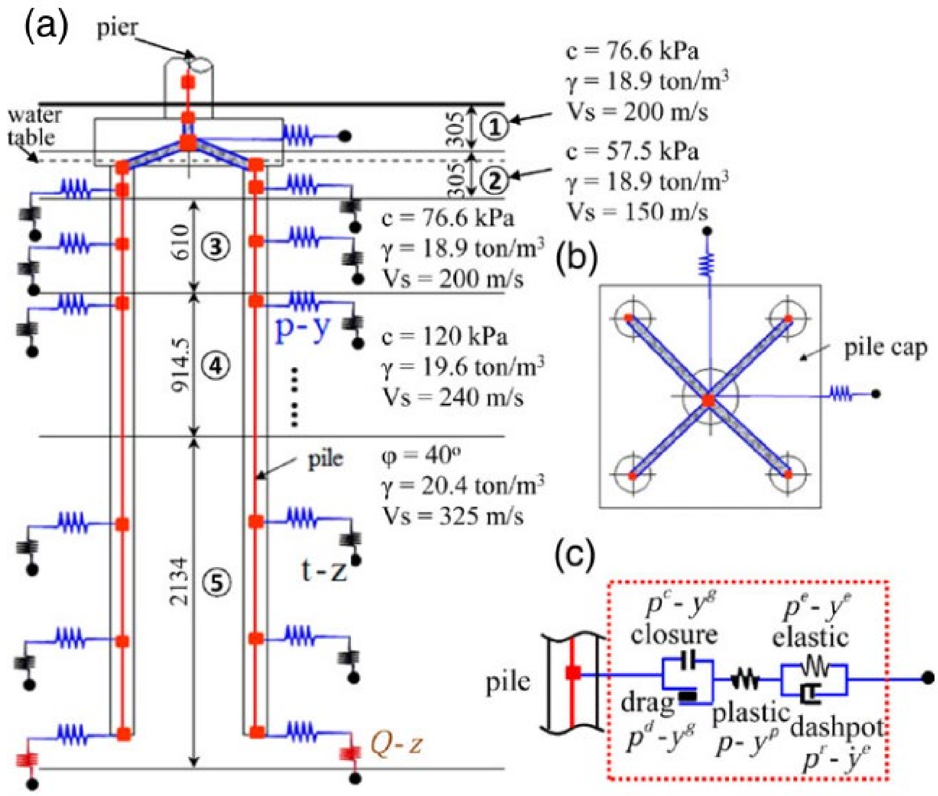


Fig. 6 - Pile foundation model using dynamic p-y approach: (a) schematic view of the FE model, (b) pile cap mode (Li and Conte 2016).

If a bridge is being modeled to observe the response under moderate earthquakes, the columns may be modeled as linear elastic because, in general, columns do not experience significant damage (Montenegro et al. 2015). An alternate methodology by Montenegro et al. (2015) estimates the effective stiffness of the columns performed in the elastic domain, considering reduction in stiffness due to cracking. The material behavior of the columns should be decided based on the magnitude of the excitation applied to the structural model and the overall purpose of the model.

1.1.4. Bearing

A bridge bearing is a component of the bridge placed between the bridge deck and columns. Bearings transfer deck loads to columns and allow specific movements and rotations of the superstructure. Similar to the columns, studies that include bearings are also limited but capture the interaction between bridge decks and columns if modeled. Li and Conte (2016) idealized a generic seismic isolation device with a material of bilinear inelastic force-deformation behavior.

Each bearing is modeled as a zero-length element combined with two uncoupled bilinear inelastic materials for the horizontal behavior: one in the longitudinal direction and the other in the transverse direction of the bridge. Li et al. (2020) similarly idealizes connection components such as the sliding and fixed spherical steel bearings as zero-length nonlinear connection elements. Linear spring-dampers are used to idealize bearing supports in a study by Montenegro et al. (2015) for moderate earthquakes.

1.2. Track System

With the rapid growth of high-speed rail systems around the world, the dynamic interaction between the track and connecting structures has become a significant issue. The track system plays a major role in connecting the train system to the bridge superstructure. Loading from the train system is directly translated to the rail, through the rail foundation consisting of track ballast, railroad ties, fasteners and tie pads, to the bridge deck and downwards. Although, the extent of the components included in the model of the track system depend on the study, the inclusion of rails, ballast and ties are consistent, unless the track system being analyzed is ballastless. Such track systems replace ties and ballast with a rigid construction of concrete or asphalt. The design of ballasted and ballastless rail foundations are elaborated respectively in Sections 1.2.2. and 1.2.3.

1.2.1. Rail

Rails rest on two types of rail foundations: ballasted foundations and ballastless foundations. For both systems, a single track consists of two rails that are designed to behave elastically as a capacity protected element. Therefore, they are modeled as linear elastic beam-column elements, and this method is consistent throughout numerous research studies investigated for this paper (Li et al. 2020, Li and Conte 2016, Liu et al. 2009). The rail model is to be extended past the abutments to the embankments to correctly represent the transition zone.

1.2.2. Ballasted Track System

For ballasted track systems, rails rest on an elastic foundation composed of track ballast and rail ties. Ballast is the crushed material placed on the top layer of a bridge superstructure to allow the embedment and support of railroad ties, also known as sleepers. The ballast is traditionally made of interlocking sharp-edged hard stone to stabilize the track system. Rails are fixed to railroad ties by fasteners, and pads are placed under the ties to act as a damper that reduces fatigue cracking of the fasteners due to impact. Ties are generally rectangular wood or reinforced concrete supports placed transverse to the rail and maintains correct gauge spacing between the rails. Ties are commonly idealized as linear beam finite elements similar to rails, and ballast, fasteners, and pads as linear springs or linear spring dampers.

Fig. 7 - http://www.plasseramerican.com/en/machines-systems/ballast-bed-cleaning.html

An example layout for a track system utilizing ballast by Song et al. (2003) is shown in Figure 8. The Figure demonstrates a simple model with rails and ties as beam elements and ballast as Winkler springs to idealize a two-parameter elastic foundation that models the interaction between the track and the bridge deck. Ties are modeled as beam elements and lay on the ballast, modeled similar to the Winkler foundation consisting of infinite closely spaced linear springs. However, contrary to the traditional Winkler foundation based on the Winkler hypothesis which does not consider interaction of springs, the additional second parameter suggested by Zhaohua and Cook (1983) considers the effects of the interaction between the linear spring-dampers which accurately represents characteristics of practical foundations.

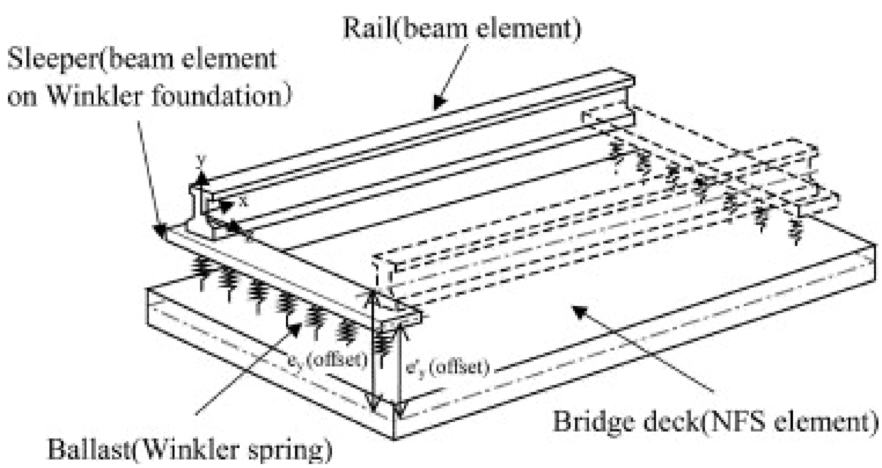


Fig. 8 - Typical track system model layouts (Song et al. 2003).

The deck joint modeled by Montenegro et al. (2015) similarly models rails and ties as beam elements (Fig. 9). Ballast and fasteners are modeled as spring dampers and connections between each component is modeled by rigid links. The decision to model the ballast as springs or spring dampers may affect the overall performance of the model due to energy dissipation and will also require additional data regarding damping coefficients of each element modeled as a spring damper. Such information can be found in previous studies or material testing.

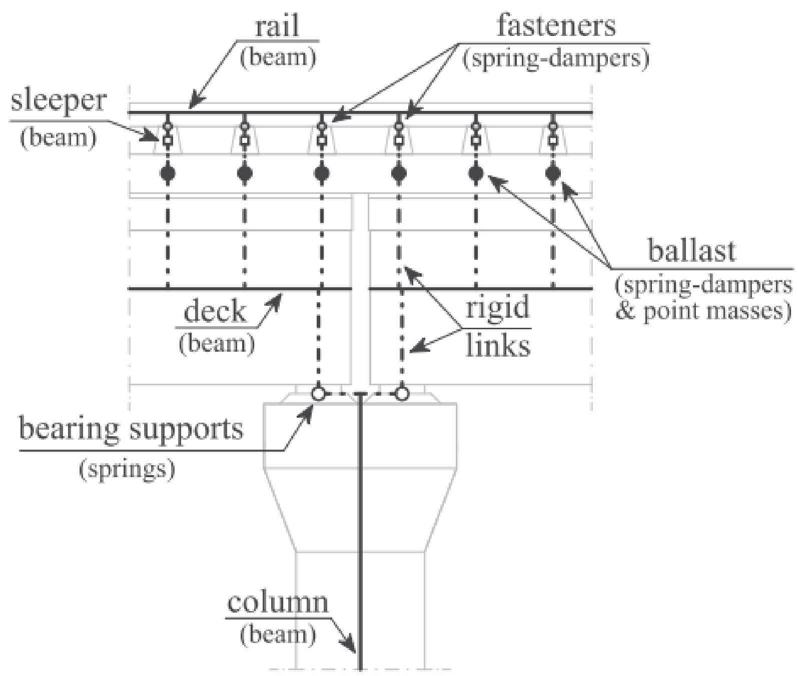


Fig. 9 - Track system scheme with fasteners (Montenegro et al. 2015).

Contrary to the previous methods, Liu et al. (2009) placed springs and dashpots between the rail and sleeper/ballast layer to represent the stiffness and damping for the entire rail system (Fig. 10). The rail is modeled as a beam element, ballast as a solid element, and sleepers (ties) as a mass point element.

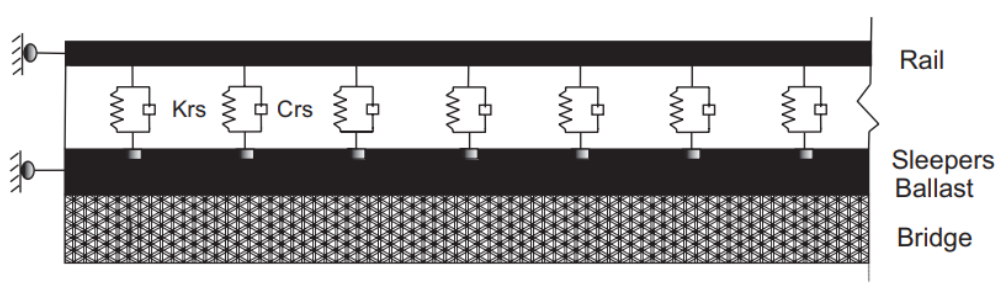


Fig. 10 - Track system scheme (Liu et al. 2009).

1.2.3. Ballastless Track System

As the name suggests, ballastless track systems utilize slabs instead of ballast. The typical design includes continuous welded rails, track plates, base plates, and connecting members (Li et al. 2020, Li and Conte 2016). Connecting members can vary depending on regional design standards. In the study by Li et al. (2020), the China Railway Track System (CRTS) II ballastless track was adopted and includes sliding layers, shear cogging, concrete asphalt (CA) mortar layers, shear reinforcement, fasteners and lateral blocks as connection members. Similarly, the Japanese RCRS slab track utilizes fasteners, track slabs and CA mortar (Fig. 12). The study by Li and Conte (2016) for the California High Speed Rail (CSHR) Authority adopted connecting members of direct fixation fasteners for rail-track slab attachment and cylinder bollards as shear reinforcement to anchor the track slab to the concrete base plate.

Fig. 11 - https://ascelibrary.org/doi/10.1061/%28ASCE%29GM.1943-5622.0001419

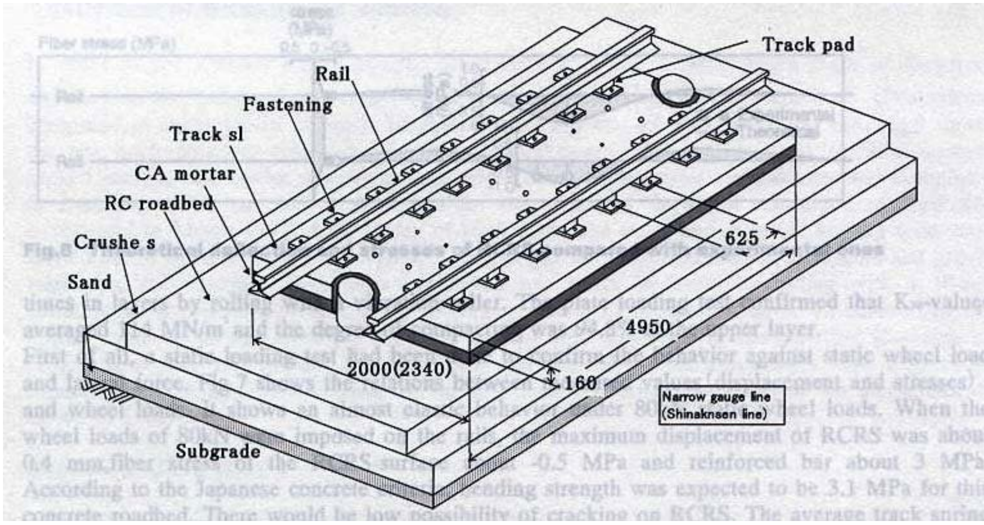


Fig. 12 - Japanese type RCRS slab track on grade (Tayabji and Bilow 2001).

Figure 13(a) demonstrates the modeling schematic of a CSHR ballastless track system by Li and Conte (2016). The rails are connected to the rigid deck through direct fixation fasteners modeled as a series of three elastic and inelastic springs to represent the behavior between the rails and track base. To represent the rail-structure interaction, linear springs are used to model the vertical and transverse stiffness, and an elastic–perfectly–plastic (EPP) spring is used to model the resistance of the track base against the relative longitudinal displacement of the rail track. Additionally, longitudinal boundary springs are modeled at each rail end because of the finite length modeling of the rail extensions to accurately capture seismic response performance. A nonlinear spring model, defined as a single element, denoted as series-parallel (S-P) spring model, was developed to represent the longitudinal boundary spring. A mechanical model was developed to calibrate and validate the rail boundary spring model, and the cyclic hysteresis behavior of the mechanical and S-P model is shown in Figure 13(b). The closeness of the behavior validates the S-P model.

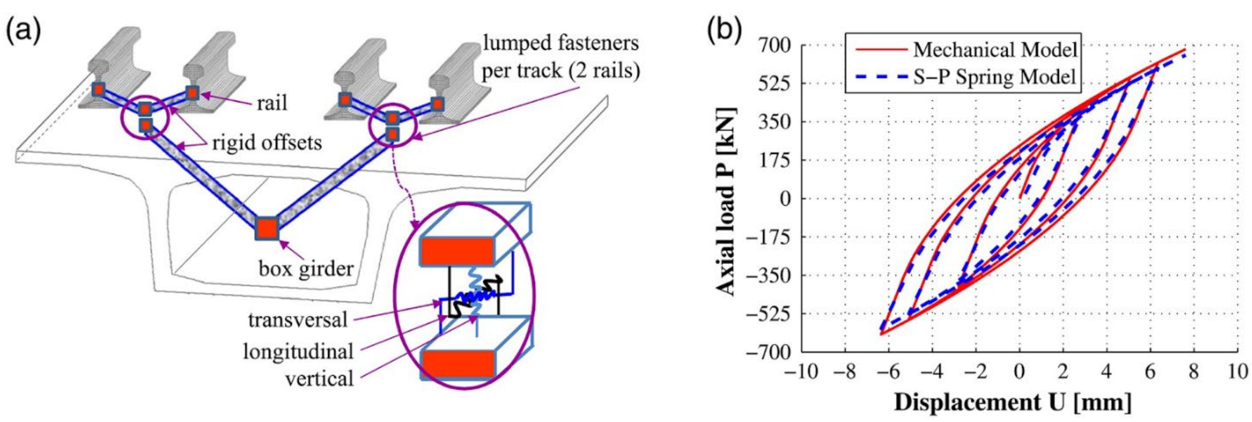


Fig. 13 - Track system scheme with fasteners (a) and longitudinal boundary spring hysteresis loop (b) (Li and Conte 2016).

In the CRTS study by Li et al. (2020), the track plate and base plate are modeled using linear elastic beam-column elements with their respective cross-section parameters because they are designed to behave elastically as capacity protected elements (Fig. 14). The connection components consisting of the sliding layer, CA mortar layer, fastener, shear reinforcement and lateral block are simulated using nonlinear zero-length elements.

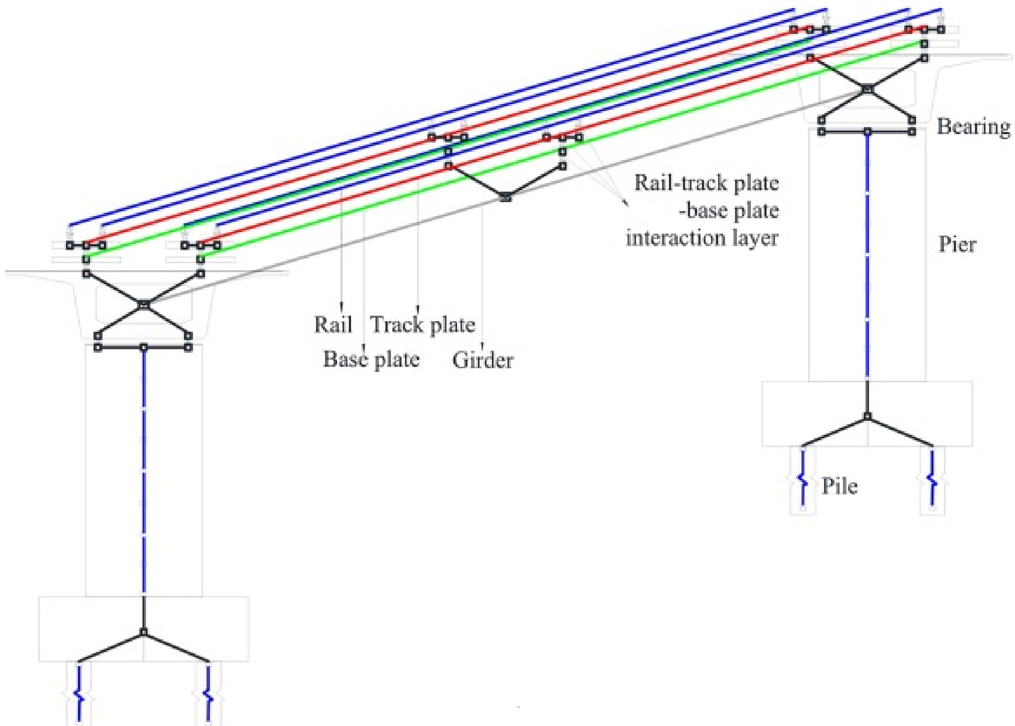


Fig. 14 - Schematic diagram of the ballastless track model (Li et al. 2020)

1.3. Rigid Connections

Connections between bridge elements are typically modeled using rigid components. Linear elastic beam-column elements assigned with exceedingly stiff properties, commonly referred to as quasi-rigid objects can be used to represent the rigid offset between respective element nodes such as the rail and deck. Quasi-rigid objects allow the user to extract the internal forces between the two nodes in connection. The FE model scheme utilizing quasi-rigid beam elements by Li and Conte (2016) is displayed in Figure 15. The figure illustrates the use of quasi-rigid beam elements to connect the centroidal axis of the box girder deck to the track system along a single span. The rigid element also connects the isolation system to the column substructure and box girder deck at the ends of each bridge span.

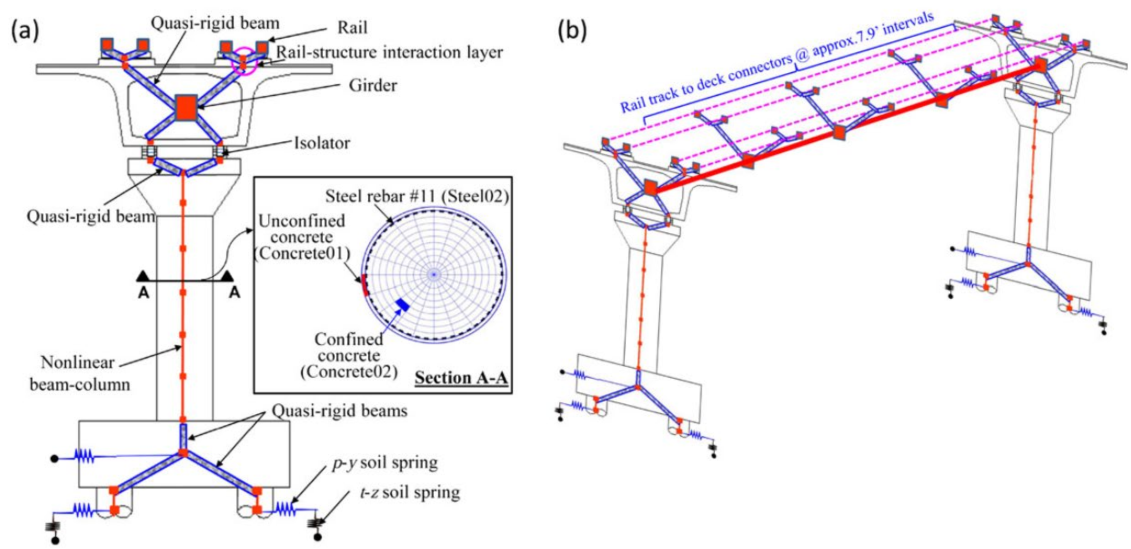


Fig. 15 - Example FE model scheme illustrating connections between each bridge element (Li and Conte 2016).

Another method is to model the connection as rigid links. The advantage of using rigid links is the simplification of the element stiffness matrix. Rigid links allows for the reduction of computational effort but does not allow the user to extract the element force of the bridge between the two nodes connected by the rigid link. A model scheme utilizing rigid links is shown in Figure 16. The placement and use of rigid links are almost identical to quasi-rigid objects mentioned above.

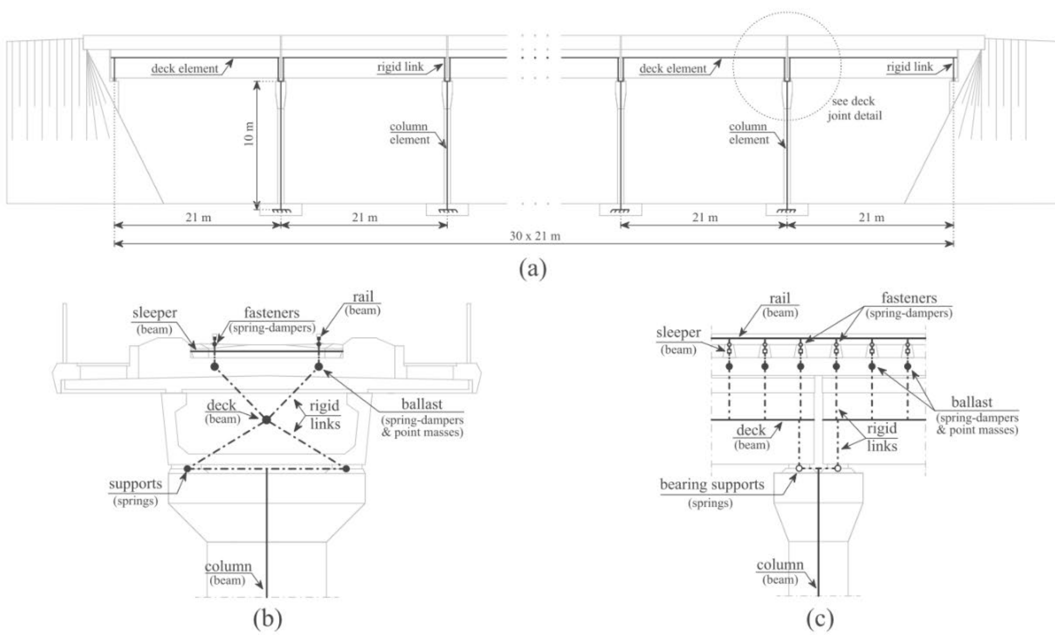


Fig. 16 - Example FE model scheme: a) elevation view b) cross-section c) deck joint (Montenegro et al. 2015).

1.4. Damping

Energy dissipation can be idealized in finite element models through inelastic materials, as mentioned in previous sections, and a method of viscous damping. A Rayleigh damping scheme with a specified damping ratio at two selected modes is commonly used to idealize damping due to vibration, and should be applied to all structural components of the bridge model that are not highly nonlinear zero-length elements (Lee et al. 2005, Li and Conte 2016). A damping ratio of 2% is commonly used (Li and Conte 2016, Montenegro et al. 2015, Song et al. 2003) but a higher value of 3% has also been used (He et al. 2011). They are typically applied to the first transverse and longitudinal mode corresponding to the tangent stiffness matrix of the bridge system after application of the gravity loads.

2. Train Modeling

High-speed train systems are constituted by a traditional vehicle system and an articulated vehicle system. A traditional vehicle system is characterized by two bogies or trucks in the fore and rear parts of the car-body, and each passenger car behaves independently (Fig. 17). Each vehicle has one car-body, two bogies and four wheel sets. An articulated vehicle system connects successive passenger cars by a single bogie frame (Fig. 18(b)); the power car and motorized car at each end of the high-speed train are still supported by their own bogies (Fig. 18(d)). This system restrains the composition of the train but is proven to effectively improve the riding conditions compared to traditional vehicle systems by reducing the vibration generated in each car body (Song et al. 2003).

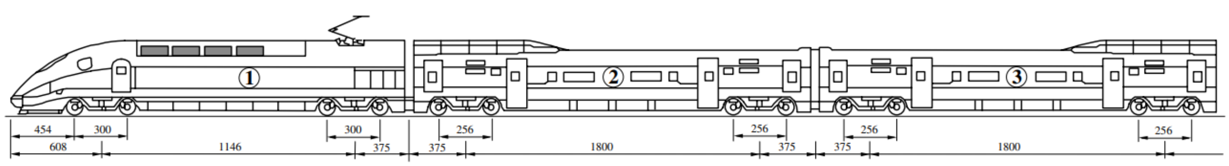


Fig. 17 - China-star high-speed train (Xia and Zhang 2005).

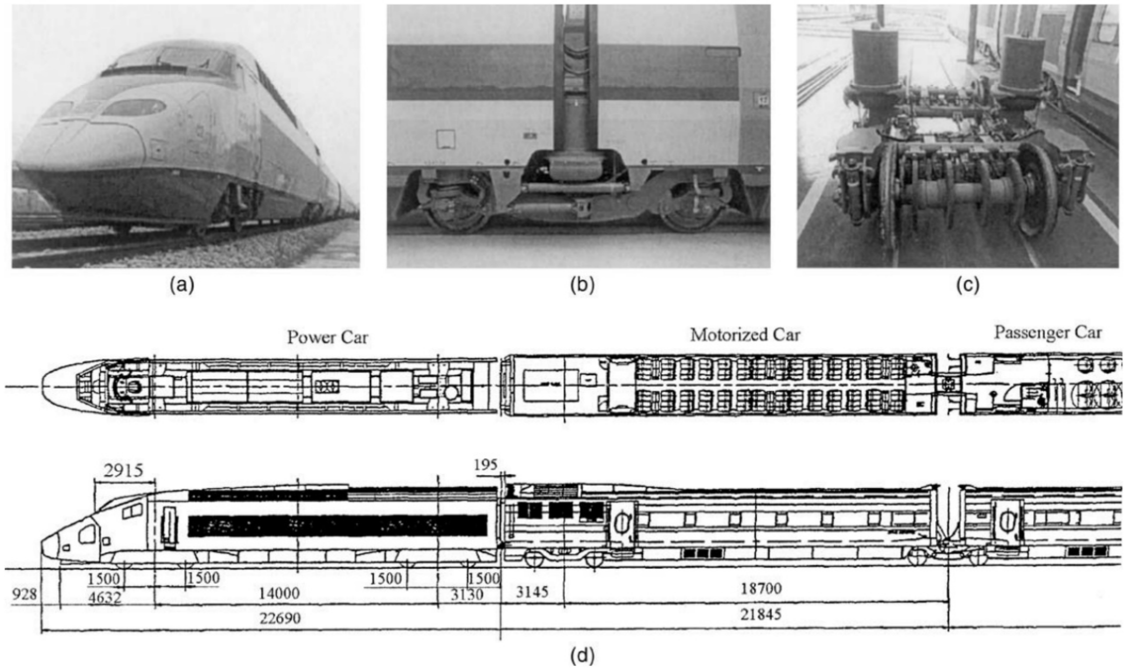


Fig. 18 - Views of the KHST (a) panoramic view, (b) articulated bogie located between the car bodies, (c) articulated bogie and (d) composition of the train (front power car) (Kwark et al. 2004).

The method of modeling high-speed trains are very similar aside from the different types of vehicle systems. The car-body, bogies and wheel-sets in each vehicle are assumed as rigid bodies, neglecting elastic deformation, and connected to each other three-dimensionally by linear springs and dampers (Du et al. 2012, Mao et al. 2016, Xia and Zhang 2005). The car-bodies and bogies are assumed to move along a well-maintained straight track at a constant speed and the wheels and the track always keep in contact, neglecting the influence of the relative motion between the two (Mao et al. 2016, Song et al. 2003, He et. al 2011). The primary and secondary suspension systems of the bogie are typically simplified as an elastic system with linear springs and viscous dampers (Figs. 19, 20, 21).

Another method is to model the car-bodies, bogies, and wheelsets as beam finite elements and the suspension system as a variation of bilinear and multilinear springs in the three directions. Montenegro et al. (2015) have modeled all springs are characterized by bilinear springs, except the one used to model the secondary transversal suspension which follows a multilinear law to simulate the presence of rubber stoppers whose stiffness increases gradually (Fig. 19). Nonlinear springs can be used to model the suspension system but a majority of the studies have simplified the analysis by assuming a linear behavior.

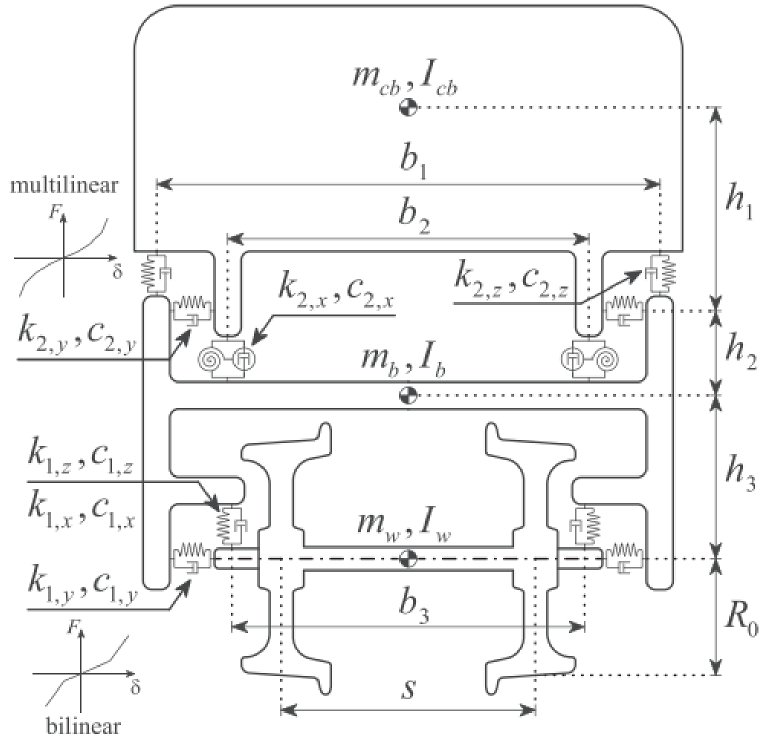


Fig. 19 - Front view of the sprung-mass dynamic car model (Montenegro et al. 2015).

The main difference among studies is the selection of the degrees-of-freedom (DOF) to be concerned in the car-body, bogies, and wheel-sets. Each node has a maximum of six DOFs in finite element modeling but not every DOF is taken into consideration depending on the study. Typically, the displacements taken into consideration in a traditional vehicle system each car-body and each bogie has 5 DOFs: lateral displacement, roll displacement, yaw displacement, vertical displacement, and pitch displacement (Du et al. 2012, Xia et al 2003). The sliding displacement is often omitted because the high-speed train is in motion and not stationary. Although rolling and sliding motions would be excited due to torsional vibrations and track irregularities, these motions are commonly constrained to be zero for efficiency of formulation (Song et al. 2003). On the contrary, Xia and Zhang (2005) and Liu et al. (2009) have included the rolling motion in the concerned DOFs. If the train system is being modeled in a scenario where seismic loading is present, the rolling motion should be accounted for because the seismic loading would heavily excite the rolling motion in the car-bodies and bogies, as the wheel-sets are assumed to stay in contact with the rails. The concerned DOFs for the wheel-sets can be limited to the lateral displacement, vertical displacement, and the roll displacement (Mao et al. 2016). The other DOFs can be neglected because the wheel-set is constantly in rotation and the wheels always stay in contact with the track system.

The assumption of perfect contact between the wheels and the track is commonly represented as the vehicle-track interaction by coupling the displacement DOF relationships between the rail and wheel-set subsystems. A Hertzian contact spring can be placed in-between each wheel and rail to accurately consider the changing contact area caused by the indentation of the rail due to the geometry of the wheel (Connolly et al. 2013, Esveld 2001).

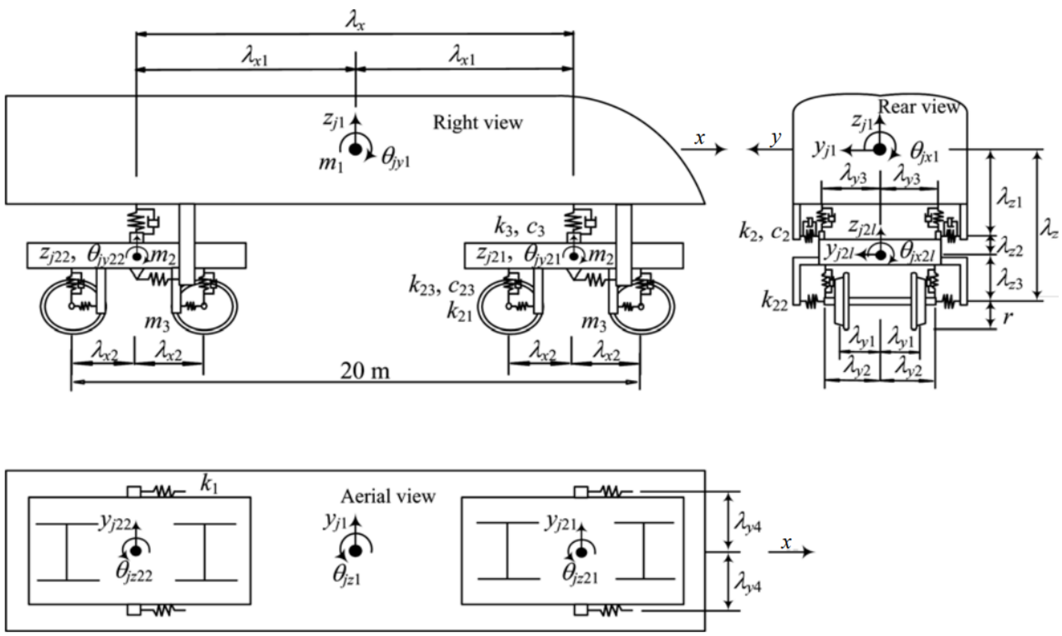


Fig. 20 - Sprung-mass dynamic car model with 15 DOFs (He et al. 2011).

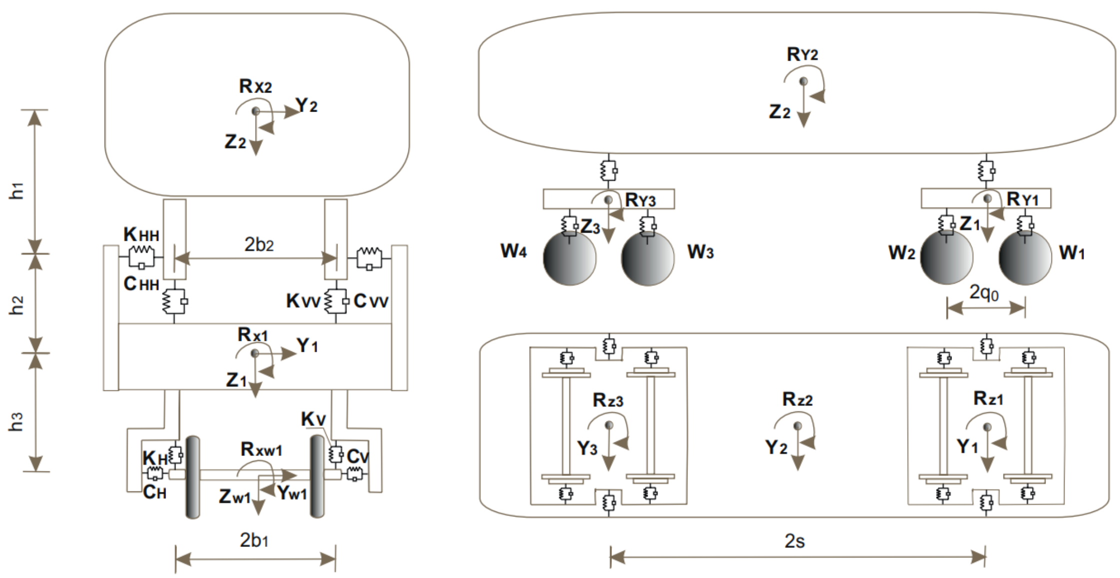


Fig. 21 - Sprung-mass dynamic car model with 27 DOFs (Liu et al. 2009).

For articulated vehicle systems each passenger car no longer behaves independently, and the behavior of each bogie will be affected by the dynamic behavior of the fore and rear car-bodies.

The model by Kwark et al. (2004) individually models the car-bodies, the bogie in between, and the wheels with DOFs as shown in Figure 22. Additional damping due to a central elastic hinge in-between adjacent car-bodies is modeled by transverse springs and dampers (Xia et al. 2003, Kwark et al. 2004). A different method by Song et al. (2003) models the fore and rear car-body behavior as a single joint, and connects the bogie to this joint. The DOFs considered at this joint are bouncing, swaying, pitching and yawing motions. These motions are then condensed into two DOFs as shown in Figure 23. The bogie considers all six DOFs, so each car (two bogies and two joints) has a total of 16 DOFs.

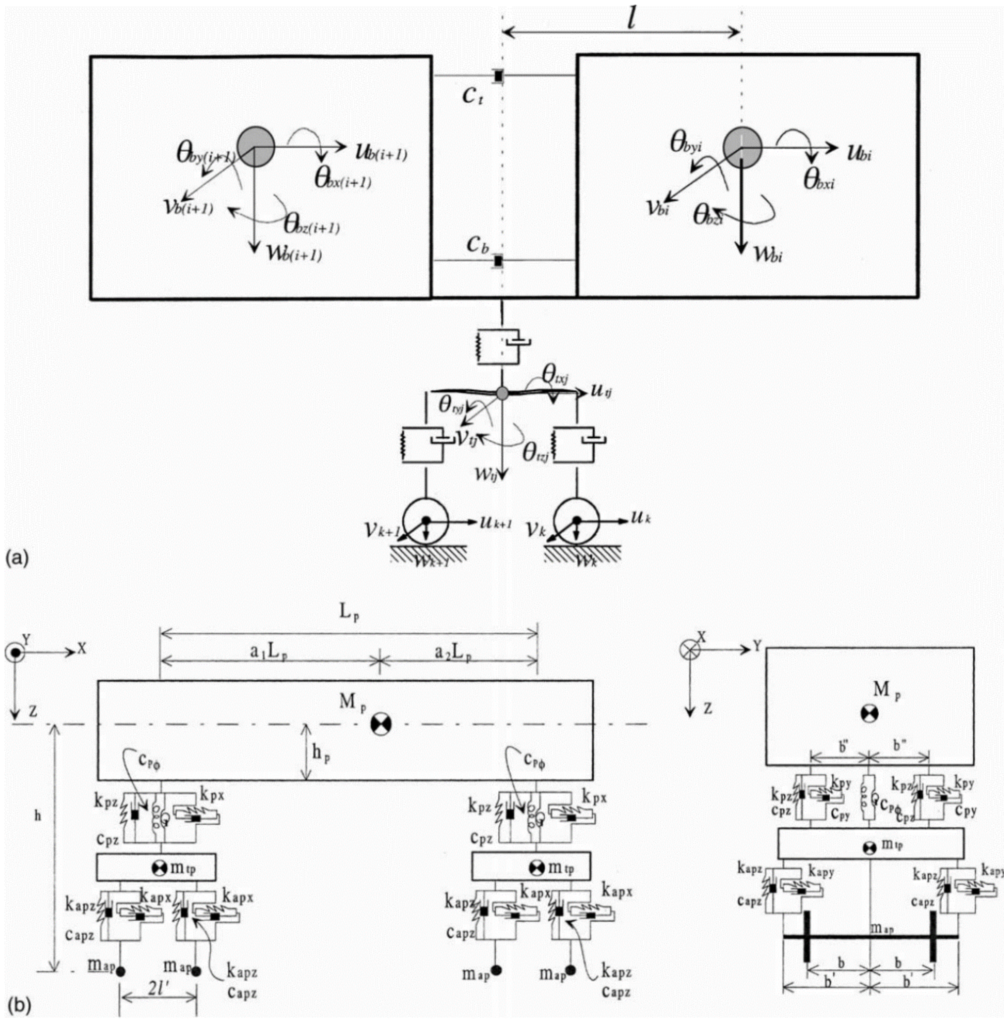


Fig. 22 - Degrees-of-freedom in articulated bogie and adjacent car-body (Kwark et al. 2004).

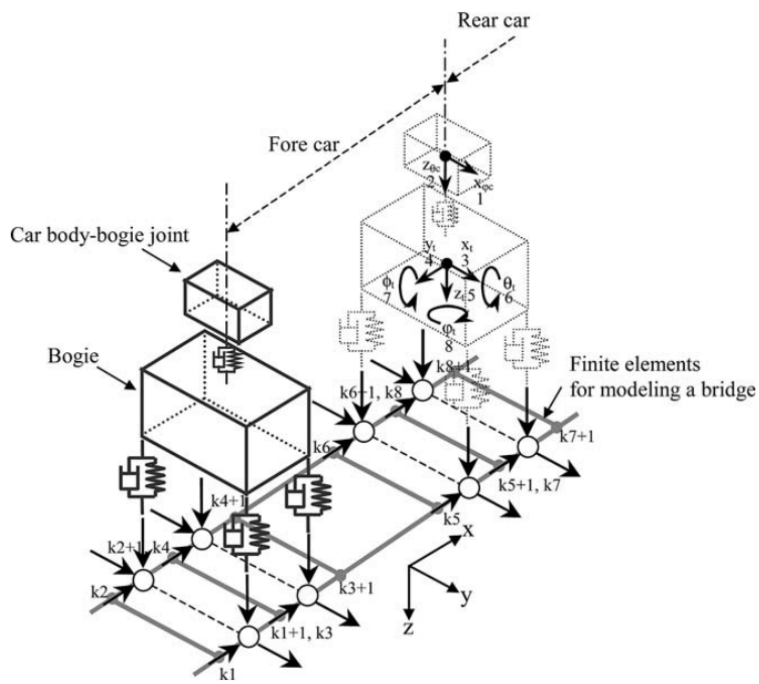


Fig. 23 - Bogie–bridge interaction system model with 16 DOFs (Song et al. 2003).

Task 2 - Develop modeling guidelines for HSR bridges with focus on special features such as train-track-structure interaction.

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 2 is to develop modeling guidelines for HSR bridges. HSR are different from highway bridges not only in design but dynamics response and behavior. Thus, special modeling features of HSR bridges such as train-track-structure interaction need to be considered in representative HSR bridge models that could be reliably used for informing HSR design. Given that HSR is commonly used in several countries as shown above in Table 1, such information on special modeling features of HSR bridges exist and will be compiled as part of developing the modeling guidelines for HSR bridges.

As previously mentioned, this project is collaborative with FIU for providing modeling guidelines of the full HSR bridge systems including foundation systems and substructure. The collaboration is extended to include University of Washington as well through an ABC-UTC initiative to provide design guidelines for HSR bridges as well as the modeling guidelines. So this task is likely to have parallel tasks at FIU and UW.

Task 3 - Conduct demonstration analytical case studies of selected HSR bridge models.

Using the body of literature and detailed modeling guidelines developed in Tasks 1 and 2, selected HSR bridge configurations and prototypes will be used to develop detailed FE models in Opensees and conduct series of nonlinear analysis under various types of loads including earthquakes. The objective of this task is to provide demonstration and step-by-step examples for developing HSR models and conducting numerical simulations.

Task 4 - Summarize the investigation results in the final report.

A final report describing the details of different tasks will be prepared and integrated into a larger report in collaboration with FIU and UW. The report will be used as basis to provide a short guideline on HSR bridge modeling and numerical simulation strategies.

5 Schedule

This project has been extensively delayed over the course of the last 1.5 years because of several major changes in the scope. While the scope and tasks presented herein are believed to be finalized, the expected end date for this project is June 2020, and the progress in the 4 tasks is as follows:

- Task 1 → complete by Nov 2019
- Task 2 → complete by January 2020
- Task 3 → complete by April 2020
- Task 4 → complete by June 2020

The percentage of completion of this project is as follow:

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

6 References

1. Du, X. T., Y. L. Xu, and H. Xia. "Dynamic interaction of bridge–train system under non-uniform seismic ground motion." Earthquake Engineering & Structural Dynamics 41.1 (2012): 139-157.
2. Connolly, D., A. Giannopoulos, and M. C. Forde. "Numerical modelling of ground borne vibrations from high-speed rail lines on embankments." Soil Dynamics and Earthquake Engineering 46 (2013): 13-19.
3. Kaviani, Peyman, Farzin Zareian, and Ertugrul Taciroglu. "Seismic behavior of reinforced concrete bridges with skew-angled seat-type abutments." Engineering Structures 45 (2012): 137-150.
4. Kim, Chul Woo, Mitsuo Kawatani, and Ki Bong Kim. "Three-dimensional dynamic analysis for bridge–vehicle interaction with roadway roughness." Computers & structures 83.19-20 (2005): 1627-1645.
5. Kwark, J. W., et al. "Dynamic behavior of two-span continuous concrete bridges under moving high-speed train." Computers & structures 82.4-5 (2004): 463-474.
6. Lee, Chang Hun, et al. "Dynamic response analysis of monorail bridges under moving trains and riding comfort of trains." Engineering Structures 27.14 (2005): 1999-2013.

7. Li, Haiyan, et al. "Nonlinear random seismic analysis of 3D high-speed railway track-bridge system based on OpenSEES." Structures. Vol. 24. Elsevier, 2020.
8. Li, Yong, and Joel P. Conte. "Effects of seismic isolation on the seismic response of a California high-speed rail prototype bridge with soil-structure and track-structure interactions." Earthquake Engineering & Structural Dynamics 45.15 (2016): 2415-2434.
9. Liu, Kai, et al. "Experimental and numerical analysis of a composite bridge for high-speed trains." Journal of Sound and Vibration 320.1-2 (2009): 201-220.
10. He, Xingwen, et al. "Numerical analysis on seismic response of Shinkansen bridge-train interaction system under moderate earthquakes." Earthquake engineering and engineering vibration 10.1 (2011): 85-97.
11. Mao, Jianfeng, et al. "Random dynamic analysis of a train-bridge coupled system involving random system parameters based on probability density evolution method." Probabilistic Engineering Mechanics 46 (2016): 48-61.
12. Montenegro, P. A., et al. "Running safety assessment of trains moving over bridges subjected to moderate earthquakes." Earthquake Engineering & Structural Dynamics 45.3 (2016): 483-504.
13. Song, Myung-Kwan, Hyuk-Chun Noh, and Chang-Koon Choi. "A new three-dimensional finite element analysis model of high-speed train–bridge interactions." Engineering Structures 25.13 (2003): 1611-1626.
14. Tayabji, Shiraz & Bilow, David. (2001). Concrete Slab Track State of the Practice. Transportation Research Record. 1742. 87-96. 10.3141/1742-11.
15. Xia, He, and Nan Zhang. "Dynamic analysis of railway bridge under high-speed trains." Computers & Structures 83.23-24 (2005): 1891-1901.
16. Xia, He, Nan Zhang, and Guido De Roeck. "Dynamic analysis of high speed railway bridge under articulated trains." Computers & Structures 81.26-27 (2003): 2467-2478.
17. Zhaohua, Feng, and Robert D. Cook. "Beam Elements on Two-Parameter Elastic Foundations." Journal of Engineering Mechanics, vol. 109, no. 6, 1983, pp. 1390-1402.