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STRONG MOTION INSTRUMENTATION PLAN FOR THE UTAH DEPARTMENT OF TRANSPORTATION

Prepared For:

Utah Department of Transportation Research and Development Division

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16. Abstract

The State of Utah, and its people have invested a considerable amount of money to construct and maintain the infrastructure and bridges in the state. This entire transportation network is at risk in the event of an earthquake. To protect Utah's bridges from a strong motion event site and bridge behavior must be better understood. Instrumenting bridges to collect data during such an event is of great importance.

Strong motion data collection can cost tens of thousands of dollars for initiation installation and even more for routine maintenance. As such, Utah faces the challenge of deciding which bridges to instrument to achieve optimal data collection but at the lowest cost possible.

An analysis was performed on some of Utah's bridges to further understand bridge behavior in a strong motion event and to design an optimal instrumentation plan. This knowledge can be applied to other bridges which assists in knowing which bridges to instrument and in which configuration the instruments should be installed.

A weighted decision tree was developed using several criteria, which allows a person or organization to quickly evaluate any number of bridges (side-by-side) to see which of the bridges actually merits instrumentation.

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1.0 INTRODUCTION

The highway transportation system in Utah is important to Utah's economy and future growth potential. Highways provide arteries of transportation for people and goods needed for the support of the economy and the day-to-day living of Utah's population. Due to its importance, a large investment has been made to create and maintain a highway infrastructure by the State of Utah, its people, and the federal government. To help protect and maintain the highway system in Utah, a strong motion instrumentation plan is suggested to monitor bridge motion and possible damage that may occur in a seismic event.

Accurately monitoring bridge movements during a large earthquake is helpful to advance our understanding of how these massive structures are affected by seismic input. Bridges of different structure types react differently to the same seismic wave patterns. Dynamic soil-structure interaction can be studied and theories can be verified or disproved based on the actual readings. Before strong motion sensors were placed at ground sites or on civil structures, theories were based on very little data. Therefore, the data collected from large earthquakes with these sensors are invaluable to the seismic engineering community. (Hipley and Huang 2009)

Strong motion instrumentation includes the installation of various sensors to record movement in any desired direction. Using data gathered in such studies, it is possible to locate areas of damage in structures as bridges and their supporting systems including foundations, abutments, columns, bents, and hinges. Data gathered in seismic events can also be used to design better structures in the future.

By conducting a site-specific study, it is possible to model a structure's reaction to ground excitation. This provides the possibility to optimize possible locations for strong motion instrumentation. Following certain guidelines, representative structures can be selected and modeled to encompass multiple structures throughout the state. This makes it possible to use the same plan to implement instrumentation on structures throughout the state.

2.0 EXECUTIVE SUMMARY

The State of Utah, its people, and the federal government have invested considerable resources in constructing Utah's highways and bridges. In order to protect Utah's infrastructure, including bridges, it is important to record strong motion in the event of seismic activity. This plan includes strategically placed accelerometers to record the motion on bridges in a seismic event. This data can then be used to detect areas of possible damage on the bridge as well as determine the structures' response. This data can also be used to construct better bridges in the future. An investment into strong motion instrumentation can be compared to an investment in a "black box" on an airplane. An airplane may perform its entire life without a mishap, but if one does occur, it's expected that the "black box" can give key insight on exactly what happened to cause the failure. Strong motion instrumentation is also valuable in determining structural behavior in an seismic event and structural failure.

In order to determine which structures should be instrumented and modeled there are many criteria that should be considered. Geographic location, proximity to other instrumented bridges, bridge importance, bridge type and complexity are some of the criteria that should be considered when choosing a structure to be instrumented and modeled. An algorithm to evaluate the qualifications of a bridge based on these criteria can be used to assist in strong motion instrumentation.

To define a strong motion instrumentation plan, it is useful to first create a model of the structure in question to predict possible reactions to seismic excitation. Mathematical models can be created using software to represent the structure. SAP2000 (SAP) is a finite element program created by Computers and Structures, Inc. (CSI) that can be used to model structures; allowing the user to input member sizes as well as structural properties to help define the model.

Ground motion can also be modeled and predicted. A model for a typical earthquake in a given area can be determined based on soil properties and proximity to faults. Free-field geotechnical instrumentation should also be placed in the area near each structure in question to measure the exact ground acceleration that is applied to the structure.

Using SAP, ground motions can be applied to the representative models and calculated or expected displacements can be determined. The models are useful in determining possible locations of maximum displacement where instrumentation could gather the best information.

Without actual data such models and their reaction to seismic excitation are merely theories of the actual reaction. Using the predicted displacements determined by the mathematical model it is possible to develop a strong motion instrumentation plan. A list of guidelines for instrumentation selection and specific placement can also be created for future instrumentation of other similar bridges is possible.

3.0 BRIDGE SELECTION CONSIDERATIONS FOR INSTRUMENTATION

In an ideal situation, every bridge structure would be instrumented for strong motion. However, this is just not feasible. A selection process with detailed identifiers is discussed below. The selection consideration includes five main categories, which are called identifiers, with each identifier having its own sub-identifiers, which provide a more detailed selection within the identifier.

3.1 IDENTIFIER: PROXIMITY

The geographic location is the most important identifier. There are two Identifiers to help determine if a bridge is worthy of instrumentation. The first is proximity to identified sources and the other is proximity to another instrumented bridge. In order to collect valuable data that leads to a better understanding of bridge behavior during a strong motion event, it is important to have instrumented bridges close to an identified source but relatively distant from another instrumented bridge.

The values used in the decision tree were chosen because, in a strong motion event, 100% of the collapsed bridges were located within three miles (5km) of the surface fault rupture zone and all remaining damaged bridges were within ten miles (16km). (Rojahn & Raggett, 1981)

It is recommended that instrumented bridges be fairly distant from each other. If two bridges are instrumented and are close to each other the collected data has a higher chance of being redundant and therefore useless. This is why more points are awarded to bridges that are further from other instrumented bridges.

3.2 IDENTIFIER: IMPORTANCE

The importance of a bridge, which can be determine by analyzing a few different indicators, will help to determine if it merits instrumentation. The first indicator is the average daily traffic (ADT), the next is the viable alternative route path, and the final is the current bridge value.

The amount of traffic a bridge experiences each day is a good indicator of the bridges overall importance. The ADT report is easily accessible and a quick way to analyze a bridge for instrumentation. ADT reports also give values for the average daily truck traffic (ADTT). For this quick analysis, only the ADT is used to compare bridges for instrumentation, however, if further analysis is needed, the ADTT will be another good manner to further analyze a bridge's importance factor.

The viable alternative route path is also a good indicator as to a bridge's importance. Some of Utah's routes depend on bridges to cross common geographic boundaries such as valleys and/or rivers. If one of these bridges were to fail then traffic would need to be rerouted. In some cases a bridge failure can add hundreds of miles to traveling routes for commuters, commerce and shipments.

The final sub-identifier for importance is the current value of the bridge. Current values are used because although the state may have considerably invested in a bridge, it may not currently be of particular value. Current bridge value can be determined based on the initial cost of the bridge with certain key characteristics taken into account, such as historical value, remaining life span and significant deterioration, leading to structural decay.

3.3 IDENTIFIER: STRUCTURAL FORM

In the beginning of the process of collecting data from structures during a strong motion event, it is important to collect data from simpler structures to lay a good foundation of strong motion behavior knowledge and gradually move toward more complex structures as our understanding increases. Several sub-identifiers can help us determine just how simple a bridge is. They are: skew, curvature, number of spans, number of girders and other considerations for simplicity.

The indicators are fairly obvious in the idea that the more complex it is, the lower the score that it receives. So, a bridge with no skew, no curvature, one span, and two girders would score at the top, whereas a bridge with a lot of skew, a lot of curvature, and many spans and girders would score very poorly on a test to be instrumented.

The list of sub-identifiers which classify a bridge level of simplicity could go on and on. The more important indicators are those previously discussed as a part of the importance factor, but other characteristics such as girder types, prefab components versus cast-in-place components, pre/post tensioning attributes, uniqueness of structural type or material, historical value, etc. are also taken into consideration in the selection process. Although these characteristics individually contribute to a bridge's complexity, they are less adequate indicators as to the value of whether or not to instrument bridges for strong motion. As a result, these less important characteristics are lumped together in the sub-identifier titled, *Other considerations for simplicity.* The bridges which are overall simple, intermediate or complex can be categorized and receive a score.

3.4 IDENTIFIER: LOCAL SOIL

A bridge's foundation soil can greatly affect how it will behave in a strong motion event. Because every foundational soil profile is different, it is important to simplify the soil types and make an attempt to evenly distribute instrumentation among these simplified soil types.

Chapter 20 of *Minimum Design Loads for Buildings and Other Structures, ASCE 7-05*, more commonly referred to as 'ASCE 7' specifies specific parameters and equations to simplify soil profiles and categorize them into an A to F ranking, where A is "hard rock" and F is "soils requiring site response analysis in accordance with Section 21.1". These parameters should be utilized in the decision tree process. (American Society of Civil Engineers, 2005)

As more bridges become instrumented, local soil will become less of an issue as there will be many soil types with instrumented bridges built upon the.

3.5 IDENTIFIER: AGE

The final identifier is the bridge's age. This is especially obvious because it is not logical to spend valuable finances for instrumentation of a bridge that is at the end of its lifespan.

4.0 DECISION TREE PROCESS

4.1 GENERAL OVERVIEW

A decision tree with weighted point-values for the different identifiers and sub-identifiers and corresponding criteria can be used to help select which structures should be instrumented among the candidates. The final score of a bridge is a quantifiable representation of its merit for instrumentation. These scores can be quickly compared with the scores of other possible bridges. A screenshot of a blank decision tree can be seen in the image below.

Identifier	Sub-Identifier	criteria	weight	Points	Weighted Score
Proximity	*to Identified Sources (miles)*	Select One			Selection Needed
		0<x<3	*5*	3	
		3<x<10		1	
		x>10		0	
	to another instrumented bridge (miles)	Select One			Selection Needed
		x>10	*2*	3	
		3<x<10		1	
		0<x<3		0	
Importance	*Average Daily Traffic*	Select One			Selection Needed
		ADT >3000	*4*	3	
		ADT <3000		1	
	Viable Alternative Route (Lifeline Importance)(L=additional travel miles)	Select One			Selection Needed
		L>100	*2*	3	
		20<L<100		1	
		0<L<20		0	
	Current Bridge Value	Select One			Selection Needed
		Value>$3M	*1*	3	
		Value<$3M		1	
Structural Form*	*skew*	Select One			Selection Needed
		0°<s<2°	*1*	3	
		2°<s<15°		1	
		15°<s		0	
	Curvature (R=curve radius (in feet))	Select One			Selection Needed
		5000<R<∞	*1*	3	
		1000<R<5000		1	
		R<1000		0	
	Number of spans	Select One			Selection Needed
		1	*1*	3	
		2		1	
		3+		0	
	Number of girders	Select One			Selection Needed
		2	*1*	3	
		3-5		1	
		6+		0	
	Other considerations for simplicity: ie. Girder Types, prefab components v cast-in-place components, pre/post tensioning, uniqueness of structural type or material, historical value, etc	Select One			Selection Needed
		simple	*1*	3	
		intermediate		1	
		complex		0	
Local Soil	*other bridges in program with same soil type (types A - F)*	Select One			Selection Needed
		0	*1*	3	
		1-2		1	
		3+		0	
Age	*years in service*	Select One			Selection Needed
		new	*1*	3	
		1-10		1	
		11+		0	
		Maximum possible points:		63	0
		Minimun possible points:		5	

*These values will apply throughout the beginning of the instrumentation process but will gradually shift to apply higher point values to more complex bridge structures and lower point values to simpler bridge structures

Structure ID: **"Blank Decision Tree"**

Total Percentage Score: **0.0%**

Figure 1: Blank Decision Tree

The weighted score that a bridge receives is achieved by multiplying the sub-identifier's weight with the points received for the bridge's corresponding criteria classification. For example, if a bridge were 2.3 miles away from an identified source, it would be classified into the 0<x<3 criteria, and as such qualify for the associated three points. The weighted score for the proximity of such a bridge to a known seismic source would then be five multiplied by three, which is fifteen points.

The weights are associated with each sub-identifier and can be modified to favor different identifiers as the project (or knowledge of bridge behavior in strong motion events) evolves. The decision tree is currently setup to favor bridges close to known seismic sources, far from other instrumented bridges, simpler bridges, and bridges with higher daily traffic but, as stated, can change as more data and a better understanding of bridge-strong motion behavior is acquired. This will allow for high quality data collection in the primary stages, when little is known of strong motion behavior, and in later stages, when more detailed and specific data is required.

The variables and units of measurement are listed within each sub-identifier on the decision tree.

4.2 EXAMPLES

Three hypothetical cases will be a demonstration to illustrate the usefulness of the decision tree in aiding the selection of bridges for instrumentation. These cases follow and are in order starting with highly qualified, followed by somewhat qualified and finishing with poorly qualified, where the qualification refers to eligibility for instrumentation.

4.2.1 HIGHLY QUALIFIED BRIDGE

A six span interstate bridge is made of steel and is located along the Wasatch Front.

The first sub-identifier on the decision tree is 'proximity to identified source'. We know that the bridge is located along the Wasatch front and is two and a half miles from a strong motion source. We then select, '0<x<3' miles and the decision tree gives our bridge fifteen points by multiplying the weight (5) by the point value (3).

The next sub-identifier on the decision tree is 'proximity to another instrumented bridge.' We know that the strong motion project is just in the beginning and that the nearest instrumented bridge is twenty-five miles away. The criteria, ‘x>10’ is selected. The weighted score is then the weight multiplied by the points to receive 6 (2*3=6).

Continuing in this fashion, the remainder of the decision tree can be completed, requiring only minimal research. The rest of the highly qualified bridge’s decision tree results can be seen in the image below.

Identifier	Sub-Identifier	criteria	weight	Points	Weighted Score
Proximity	*to Identified Sources (miles)*	Select One 0<x<3 3<x<10 x>10	*5*	 3 1 0	15
	to another instrumented bridge (miles)	Select One x>10 3<x<10 0<x<3	*2*	 3 1 0	6
Importance	*Average Daily Traffic*	Select One ADT >3000 ADT <3000	*4*	 3 1	12
	Viable Alternative Route (Lifeline Importance)(L=additional travel miles)	Select One L>100 20<L<100 0<L<20	*2*	 3 1 0	0
	Current Bridge Value	Select One Value>$3M Value<$3M	*1*	 3 1	3
Structural Form*	*skew*	Select One 0°<s<2° 2°<s<15° 15°<s	*1*	 3 1 0	1
	Curvature (R=curve radius (in feet))	Select One 5000<R<∞ 1000<R<5000 R<1000	*1*	 3 1 0	3
	Number of spans	Select One 1 2 3+	*1*	 3 1 0	0
	Number of girders	Select One 2 3-5 6+	*1*	 3 1 0	0
	Other considerations for simplicity: ie. Girder Types, prefab components v cast-in-place components, pre/post tensioning, uniqueness of structural type or material, historical value, etc	Select One simple intermediate complex	*1*	 3 1 0	0
Local Soil	*other bridges in program with same soil type (types A - F)*	Select One 0 1-2 3+	*1*	 3 1 0	0
Age	*years in service*	Select One new 1-10 11+	*1*	 3 1 0	1
		Maximum possible points:		63	41
		Minimun possible points:		5	

*These values will apply throughout the beginning of the instrumentation process but will gradually shift to apply higher point values to more complex bridge structures and lower point values to simpler bridge structures

Structure ID: "Highly Qualified Bridge"
Total Percentage Score: 65.1%

Figure 2: Hypothetical Decision Tree Results of Highly Qualified Bridge

The highly qualified bridge receives an overall total score of forty-one points out of the sixty-three possible. Although the structure is fairly complex, it can be seen that the proximity to known sources and other instrumented bridges dominates its qualifications over the complexity.

4.2.2 SOMEWHAT QUALIFIED BRIDGE

The somewhat qualified bridge is a two-span bridge made of pre-stress concrete on a state highway near Moab, Utah.

After a couple of minutes of research, the decision tree can be completed as shown below.

Identifier	Sub-Identifier	criteria	weight	Points	Weighted Score
Proximity	*to Identified Sources (miles)*	Select One 0<x<3 3<x<10 x>10	*5*	3 1 0	0
	to another instrumented bridge (miles)	Select One x>10 3<x<10 0<x<3	*2*	3 1 0	6
Importance	*Average Daily Traffic*	Select One ADT >3000 ADT <3000	*4*	3 1	4
	Viable Alternative Route (Lifeline Importance)(L=additional travel miles)	Select One L>100 20<L<100 0<L<20	*2*	3 1 0	6
	Current Bridge Value	Select One Value>$3M Value<$3M	*1*	3 1	1
Structural Form*	*skew*	Select One 0°<s<2° 2°<s<15° 15°<s	*1*	3 1 0	3
	Curvature (R=curve radius (in feet))	Select One 5000<R<∞ 1000<R<5000 R<1000	*1*	3 1 0	3
	Number of spans	Select One 1 2 3+	*1*	3 1 0	3
	Number of girders	Select One 2 3-5 6+	*1*	3 1 0	3
	Other considerations for simplicity: ie. Girder Types, prefab components v cast-in-place components, pre/post tensioning, uniqueness of structural type or material, historical value, etc	Select One simple intermediate complex	*1*	3 1 0	3
Local Soil	*other bridges in program with same soil type (types A - F)*	Select One 0 1-2 3+	*1*	3 1 0	3
Age	*years in service*	Select One new 1-10 11+	*1*	3 1 0	0
		Maximum possible points:		63	35
		Minimun possible points:		5	

*These values will apply throughout the beginning of the instrumentation process but will gradually shift to apply higher point values to more complex bridge structures and lower point values to simpler bridge structures

Structure ID: **"Somewhat Qualified**
Total Percentage Score: **55.6%**

Figure 3: Hypothetical Decision Tree Results of Somewhat Qualified Bridge

The bridge scored very high in terms of simplicity but poor in terms of location. The bridge received a mediocre score.

4.2.3 POORLY QUALIFIED BRIDGE

Identifier	Sub-Identifier	criteria	weight	Points	Weighted Score
Proximity	*to Identified Sources (miles)*	Select One			0
		0<x<3	*5*	3	
		3<x<10		1	
		x>10		0	
	to another instrumented bridge (miles)	Select One			2
		x>10	*2*	3	
		3<x<10		1	
		0<x<3		0	
Importance	*Average Daily Traffic*	Select One			4
		ADT >3000	*4*	3	
		ADT <3000		1	
	Viable Alternative Route (Lifeline Importance)(L=additional travel miles)	Select One			2
		L>100	*2*	3	
		20<L<100		1	
		0<L<20		0	
	Current Bridge Value	Select One			1
		Value>$3M	*1*	3	
		Value<$3M		1	
Structural Form*	*skew*	Select One			1
		0°<s<2°	*1*	3	
		2°<s<15°		1	
		15°<s		0	
	Curvature (R=curve radius (in feet))	Select One			1
		5000<R<∞	*1*	3	
		1000<R<5000		1	
		R<1000		0	
	Number of spans	Select One			1
		1	*1*	3	
		2		1	
		3+		0	
	Number of girders	Select One			1
		2	*1*	3	
		3-5		1	
		6+		0	
	Other considerations for simplicity: ie. Girder Types, prefab components v cast-in-place components, pre/post tensioning, uniqueness of structural type or material, historical value, etc	Select One			1
		simple	*1*	3	
		intermediate		1	
		complex		0	
Local Soil	*other bridges in program with same soil type (types A - F)*	Select One			3
		0	*1*	3	
		1-2		1	
		3+		0	
Age	*years in service*	Select One			0
		new	*1*	3	
		1-10		1	
		11+		0	
		Maximum possible points:		63	17
		Minimun possible points:		5	

*These values will apply throughout the beginning of the instrumentation process but will gradually shift to apply higher point values to more complex bridge structures and lower point values to simpler bridge structures

Structure ID: "Poorly Qualified Bridge"
Total Percentage Score: 27.0%

Figure 4: Hypothetical Decision Tree Results of Poorly Qualified Bridge

5.0 DEMONSTRATION INSTRUMENTATION FOR TWO UDOT STRUCTURES

Suppose bridges F-774 and C-986 have been selected for instrumentation. The proposed instrumentation plan is illustrated below.

5.1 BRIDGE F-774

F-774 is a bridge on interstate 15 (I-15) crossing Beck Street, Warm Springs Road and several lines of rail, near Rose Park, Utah. The instrumentation plan can be seen in the figure below illustrating the plan view and elevation view. The plan calls for a total of thirty sensors (which can be seen on the plan as indicated by a circle and cross-hairs), including the triaxial, free-field sensors (one vertical, one horizontal and one transverse) located away from the structure to act as a control for data collection.

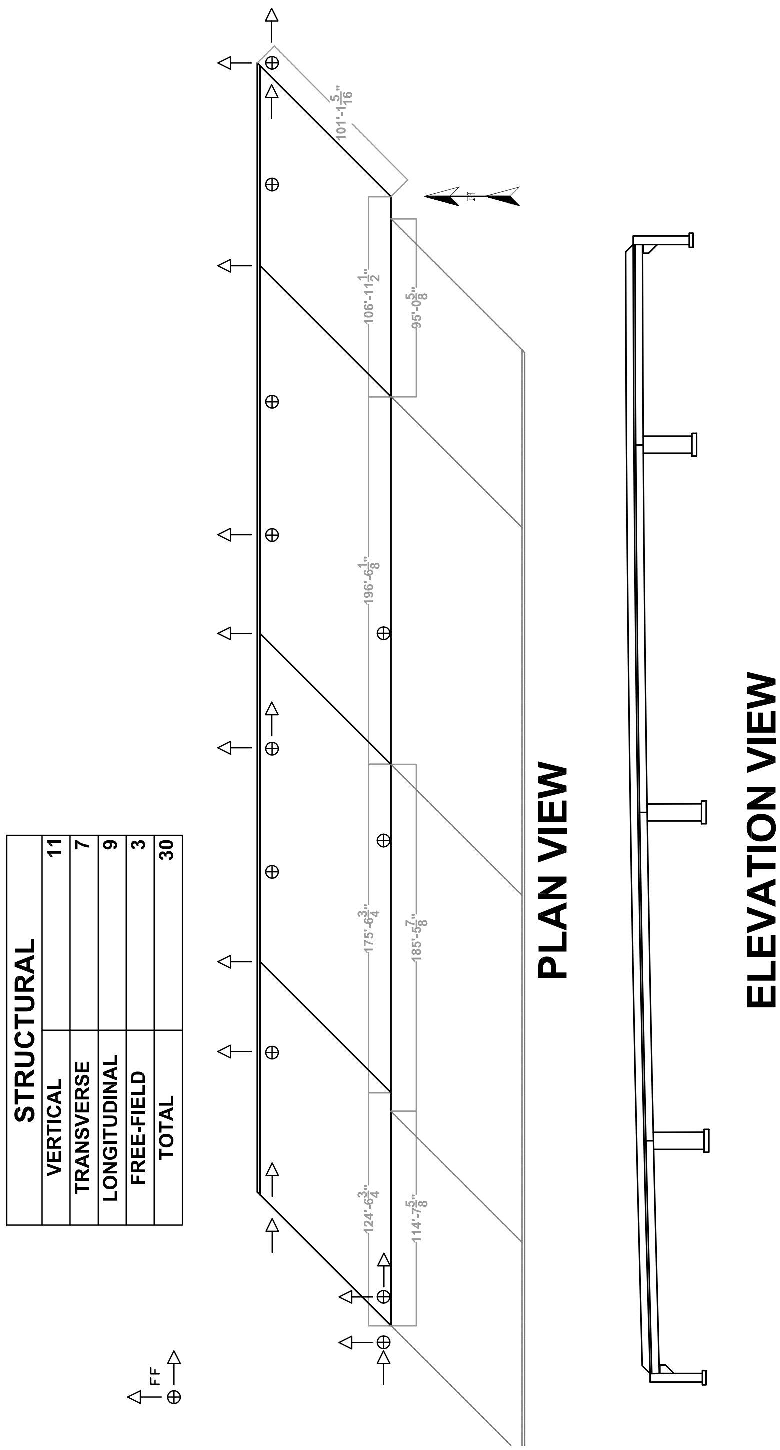

Figure 5: Proposed Instrumentation plan of Bridge F-774; Plan and Elevation Views

5.2 BRIDGE C-986

C-986 is a on Layton Parkway, crossing I-15 and located in Layton City, Utah. The instrumentation plan can be seen in the figure below. The plan calls for a total of twenty-two sensors (which can be seen on the plan as indicated by a circle and cross-hairs), including the triaxial, free-field sensors (one vertical, one horizontal and one transverse) located away from the structure to act as a control for data collection.

STRUCTURAL	
VERTICAL	11
TRANSVERSE	4
LONGITUDINAL	4
FREE-FIELD	3
TOTAL	22

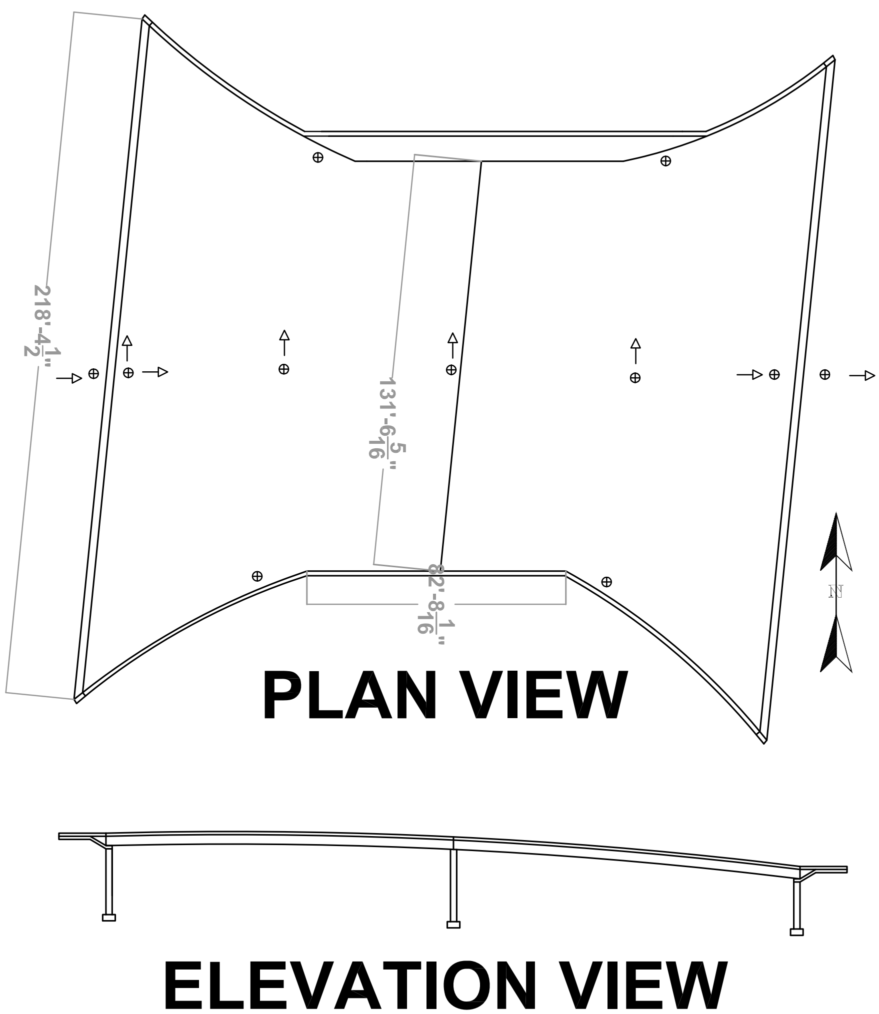

Figure 6: Proposed Instrumentation of Bridge C-986

6.0 GENERAL GUIDELINES

Bridge sites should be chosen throughout the state to take advantage of the probability of having a known seismic source near the location. Having a widely dispersed array of sites is advantageous for the shotgun approach and therefore captures the best and widest array of collected data.

Another criterion for bridge site determination is the use of studies sponsored by the Utah Geological Survey (UGS) and the United States Geological Survey (USGS) that include mapping of earthquake faults in Utah. Bridges should be chosen to be as near to the major faults as possible. Some locations along the faults have a higher probability of experiencing a large quake.

Various structure types should be chosen for instrumentation to learn about all common UDOT bridge types. Steel girder, truss structure, pre-cast concrete girder, etc. should be instrumented. Various substructure types could also be selected for strong motion studies. Pier wall, multi-column bent and single column bent bridges should all be monitored. In the large metropolitan areas, various bridge types should be chosen at the same interchange to study different structures having similar seismic input.

In addition to understanding the structural mode shapes for the global bridge model, studies of different components of the bridge are also important. These studies include the opening and closing of in-span hinges, the movements over abutments, the top and bottom relative movement of the columns, and so on. (Hipley and Huang 2009)

6.1 Regional Considerations

When selecting a structure for modeling and instrumentation, many factors should be considered. It is recommended that the structures be near a populated area, relatively near other instrumented structures and near a fault line.

Two bridges were selected in conjunction with UDOT for an instrumentation study. The bridges that were selected for the study are the C-865 Bridge that is part of the north interchange of the Legacy Parkway and the F-669 bridge which spans over the Legacy Parkway on west State Street in Farmington. The C-865 bridge spans a section of the northbound connection of the Legacy Parkway to northbound I-15.

Farmington, Utah is part of the Wasatch metropolitan area. With Layton and Ogden to the north and Centerville, Bountiful, and Salt Lake to the south, this section of roadway is used heavily. The two bridges selected in this area are used heavily and make good candidates for bridge modeling.

Utah State University is currently conducting a study on a nearby bridge. There are already accelerometers placed on the twenty-first South bridge near I-15 in Salt Lake City, roughly twenty miles away from the selected Legacy Parkway bridge site locations. Data collected during a seismic event from these sites would be useful in structure response studies due to their proximity to each other.

The bridges are near the Wasatch fault line. Figure 7 illustrates the proximity of the I-15 bridges to each other and to the fault. The figure shows several locations along the Wasatch Fault as well as the location of the selected bridges relative to the fault.

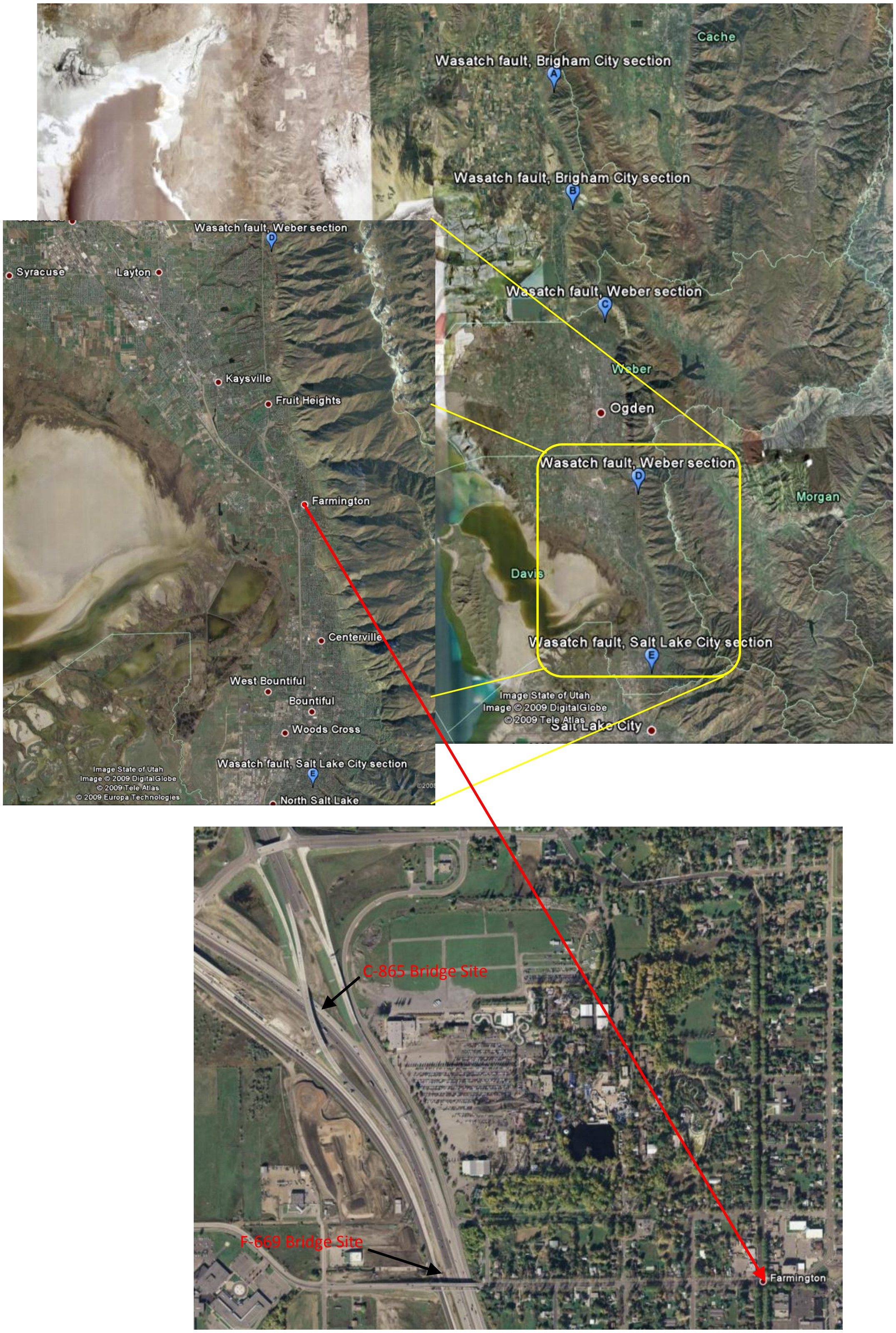

Figure 7: Bridge Site Location

6.2 Site and Geotechnical Considerations

The intermediate portions of the profiles for the North and South interchanges of Legacy Parkway compiled in the appendices to this report are based on deep well logs available in the area. The South interchange of Legacy Parkway is located in one of the deepest sediment basins along the Wasatch Front with depth to bedrock ranging from 840 meters to 900 meters according to the constrained inversion of gravity data by Radkins (1990). Radkins also reports the depth of the boundary between unconsolidated sediments and semi-consolidated sediments, as estimated by Arnow (1981), at approximately 700 meters. This represents an exceedingly deep soil profile when compared to other sites in the adjacent Salt Lake and Davis Counties where sediment depths probably do not exceed 200 meters.

The soils in the North interchange are shallower than those found in the South interchange. In the North interchange, semi-consolidated sediments are encountered at about 250 meters below the surface (Radkins 1990); depth to bedrock is estimated at about 700 meters below the surface.

Values of Vs30 were measured for the North and South interchanges of Legacy Parkway of 191 and 188 m/s, respectively. For comparison purposes, EQL and NL soil properties were modeled in soils from the surface to a depth of 250 meters for the North interchange and from the surface to a depth of 700 meters for the South interchange. One case was done using equivalent linear (EQL) properties for these depth intervals and then the analysis was repeated using nonlinear (NL) properties at these intervals. The semi-consolidated sediments were modeled to a depth of two kilometers for both locations.

Both the NL and EQL cases were based on using modified hyperbolic soil parameters, which is a user specified option in Deepsoil software. When this option is used, modified hyperbolic soil parameters are used to provide continuous functions for the shear modulus degradation and damping curves but the analysis is still done using the EQL method. The modified hyperbolic soil parameters were obtained by matching the appropriate EQL modulus degradation and damping curves.

6.3 Structural Considerations

Two bridge types were chosen for the study; a steel-girder and a concrete-girder bridge. The C-865 bridge is a steel-girder bridge that spans 209 meters and has a width of twelve meters. The superstructure is a multi-jointed, multi-span steel girder bridge supported by three single-column bents and two abutments. There are six hinges (expansion joints) in the superstructure that separate the bridge structure into seven frame structures of different lengths and different numbers of spans. The substructure consists of three single-column bents. The typical column section is octagonal in shape (two-and-a half meters by two-and-a half meters) and the column height ranges from ten to fifteen meters. The column footings are each supported by thirty-two steel pipe piles filled with reinforced concrete.

The F-669 Bridge is a concrete-girder bridge that spans 100 meters with a width of twenty-three meters. The superstructure is a multi-jointed, multi-span concrete girder bridge supported by two, three-column bents and two abutments. The typical column section is octagonal in shape (one and seven eighths by one and seven eighths meters) and the column height is 5.8 meters. The column footings are each supported by thirty-two steel pipe piles filled with reinforced concrete. By modeling differing structure types with near proximity to each other, information can be gathered on multiple bridge types in response to the same excitation.

Another study is being conducted on the F-669 Bridge by Utah State University and some instrumentation already exists on the bridge. Current instrumentation includes strain gages. These strain gages also may be useful to determine the response of the structure to seismic excitation. Readings are taken from the stain gages every two seconds and can be used to measure the strain on the bridge during a seismic event. Using the strain information in conjunction with the accelerometer data will give more insight into the reaction of the bridge. Instrumentation can be placed on the C-865 bridge without causing major disruption to the flow of traffic and no disruption to the local rail lines. An aerial view of each bridge and their relative locations to one another can be seen in Figure 8. Plan views of the C-865 Bridge and the F-669 bridge can be seen as Figures 9 and 10 respectively.

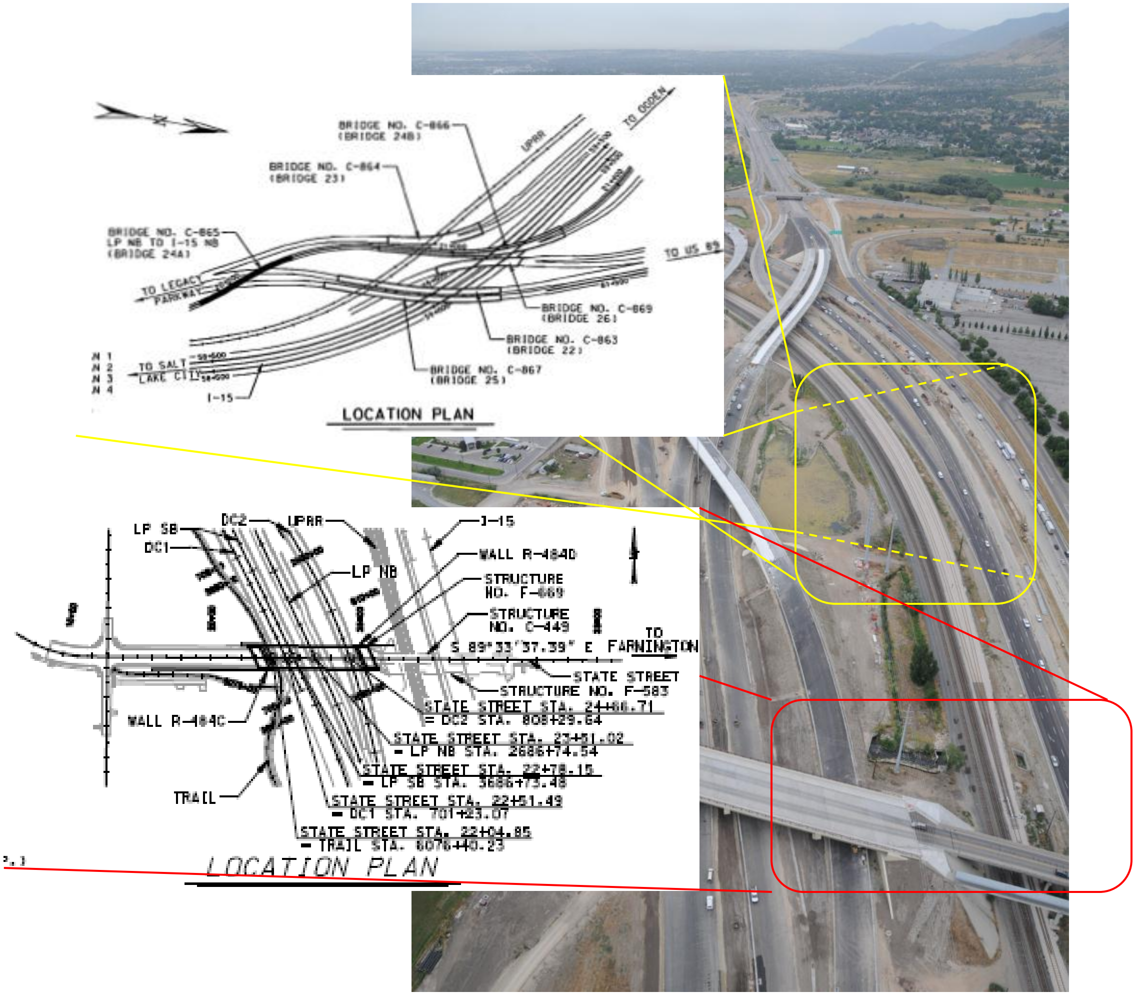

Figure 8: C-865 and F-669 Bridges, Ariel View
Figure 9: C-865 Bridge, Plan View
Figure 10: F-669 Bridge, Plan View

7.0 DETAILS, SPECIFICATIONS, AND GUIDELINES FOR INCLUSION IN FUTURE UDOT PROJECTS

Accelerometers can be placed on a bridge during construction or they may be retrofitted to the structure at a later time. Since the two bridges that were selected for study have already been constructed, the accelerometers must be retrofitted. One suggested manufacturer of strong motion accelerometers is Kinemetrics. The following is a description of the suggested sensor types taken directly from the Kinemetrics website (Kinemetrics, 2008):

> The EpiSensor ES-U: The EpiSensor is a uniaxial accelerometer optimized for earthquake recording applications. Inside the waterproof, anodized-aluminum housing is one EpiSensor force balance accelerometer module. The EpiSensor has

user-selectable full-scale recording ranges of ±4g, ±2g, ±1g, ±1/2g or ±1/4g. Its bandwidth of DC to 200 Hz is a significant improvement over earlier generations of sensors. The output voltage levels are user-selectable at either ±2.5V or ±10V single-ended, or ±5V or ± 20V differential. The EpiSensor is normally powered with a ±12V or ±15V external DC power source. It is optionally available with a single +12V supply option. The EpiSensor ES-U is shown here as Figure 11.

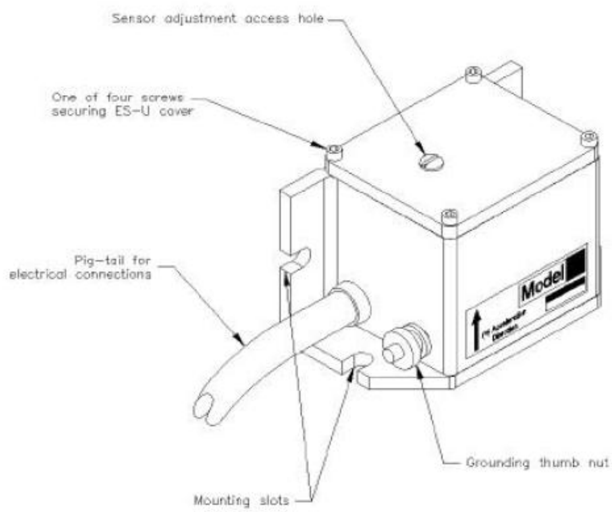

Figure 11: EpiSensor ES-U, uniaxial accelerometer

The EpiSensor FBA ES-T: The EpiSensor is a triaxial accelerometer optimized for earthquake recording applications. Inside the waterproof, anodized-aluminum housing are three orthogonally mounted, low-noise EpiSensor force balance accelerometer modules. The EpiSensor has user-selectable full-scale recording ranges of ±4g, ±2g, ±1g, ±1/2g or ±1/4g. The EpiSensor bandwidth of DC to 200 Hz is a significant improvement over earlier generations of sensors. The output voltage levels are user-selectable at either ±2.5V or ±10V single-ended, or ±5V or ± 20V differential. The EpiSensor is normally powered with a ±12V external DC power source. It is optionally available with a single +12V supply option. The ES-T can be seen here as Figure 12.

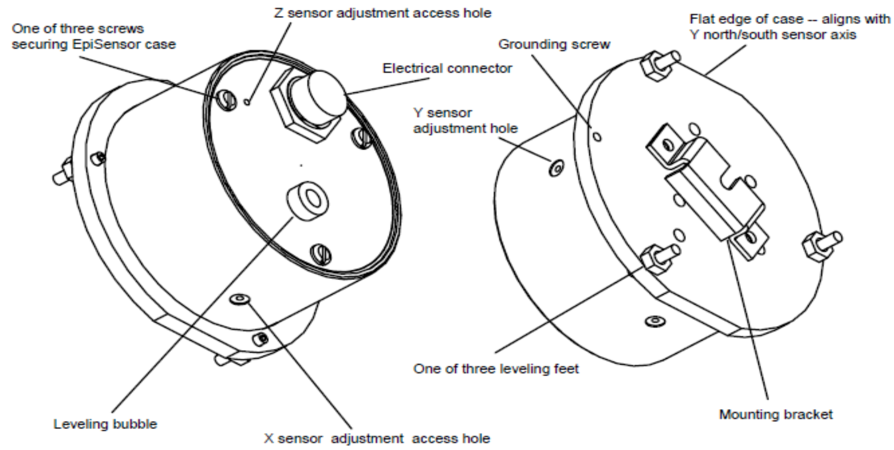

Figure 12: EpiSensor FBA ES-T, triaxial sensor

These sensors can be attached directly to the concrete by following the installation guidelines provided in the users' manual of the EpiSensor. Some locations for installation of the EpiSensors are indicated here in figure 13.

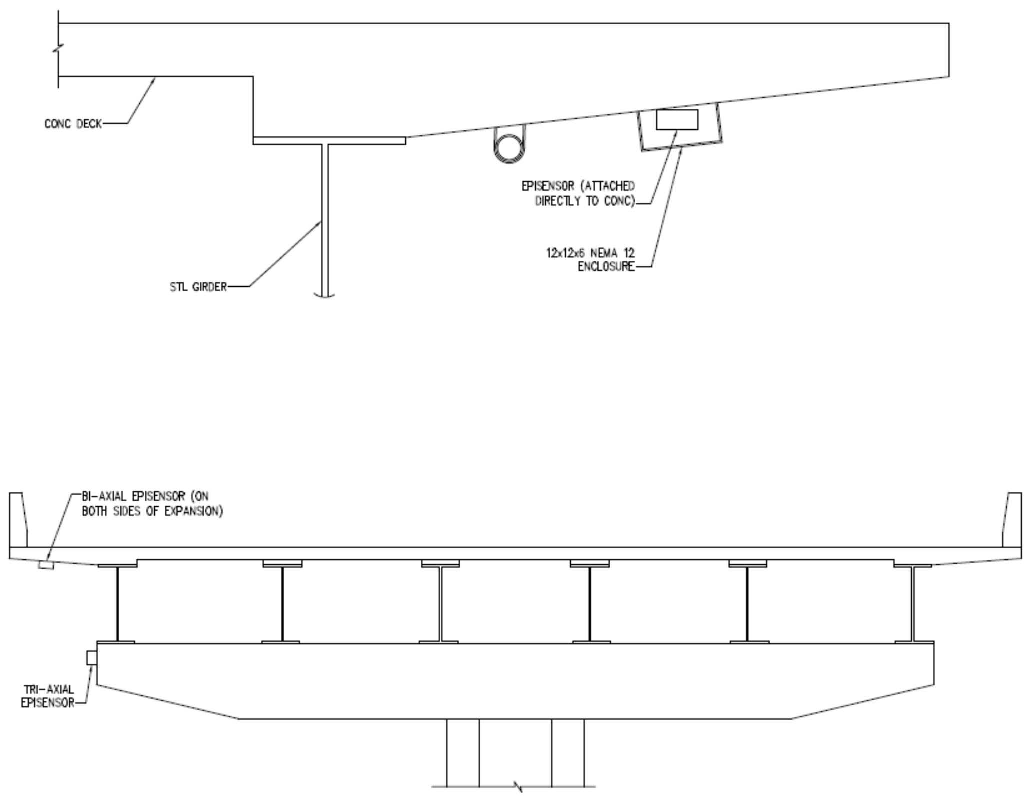

Figure 13: Instrumentation Installation Locations

8.0 MODELING AND ANALYSIS

8.1 Regional Considerations

The South interchange of the Legacy Parkway connecting to I-215 is located approximately two kilometers west of the Wasatch mountain range near the Salt Lake - Davis County line. The North interchange of the Legacy Parkway connecting to I-15 and Highway 89 is located approximately two kilometers west of the Wasatch Range in Farmington, Utah.

8.2 Site and Geotechnical Considerations

Ground response analyses were performed at the South and North interchanges of the Legacy Parkway to evaluate the potential ground shaking resulting from rupture of the Weber-Davis County segment of the Wasatch fault. The evaluations for this event were done using both EQL and NL methods so that a comparison of the techniques could be made. Additional rupture events were evaluated for the North interchange of the Legacy Parkway that include: rupture on the Salt Lake City and Brigham City segments of the Wasatch fault and a 475-year return period event. These analyses were done using NL site response methods and upper, mean and lower bound soil profiles.

One-dimensional site response analyses for the North and South interchanges of Legacy Parkway were performed using the EQL and NL codes implemented in Deepsoil. In order to more closely compare the EQL and NL codes, the modified hyperbolic model was used for shear modulus degradation and damping formulations for both analyses. Figures 14 to 17 show the site response results for a rupture of the Weber segment of the Wasatch fault zone for the North and South interchanges of Legacy Parkway. NL site response results for alternative rupture scenarios along the Wasatch fault zone (Salt Lake City segment, Brigham City segment, and 475-year return period) are included for comparison in Figures 18 to 20.

The EQL spectral values are generally greater than the NL spectra for both interchanges (Figures 14 through 20). Both the EQL and NL spectra for the Legacy Parkway exhibit a significant shift in the predominant period. They range from approximately 0.2 seconds in the input rock target spectrum, to approximately 0.5 seconds in the New Generation

Attenuation (NGA) spectrum to between 0.9 seconds and 1.4 seconds in the EQL and NL spectra.

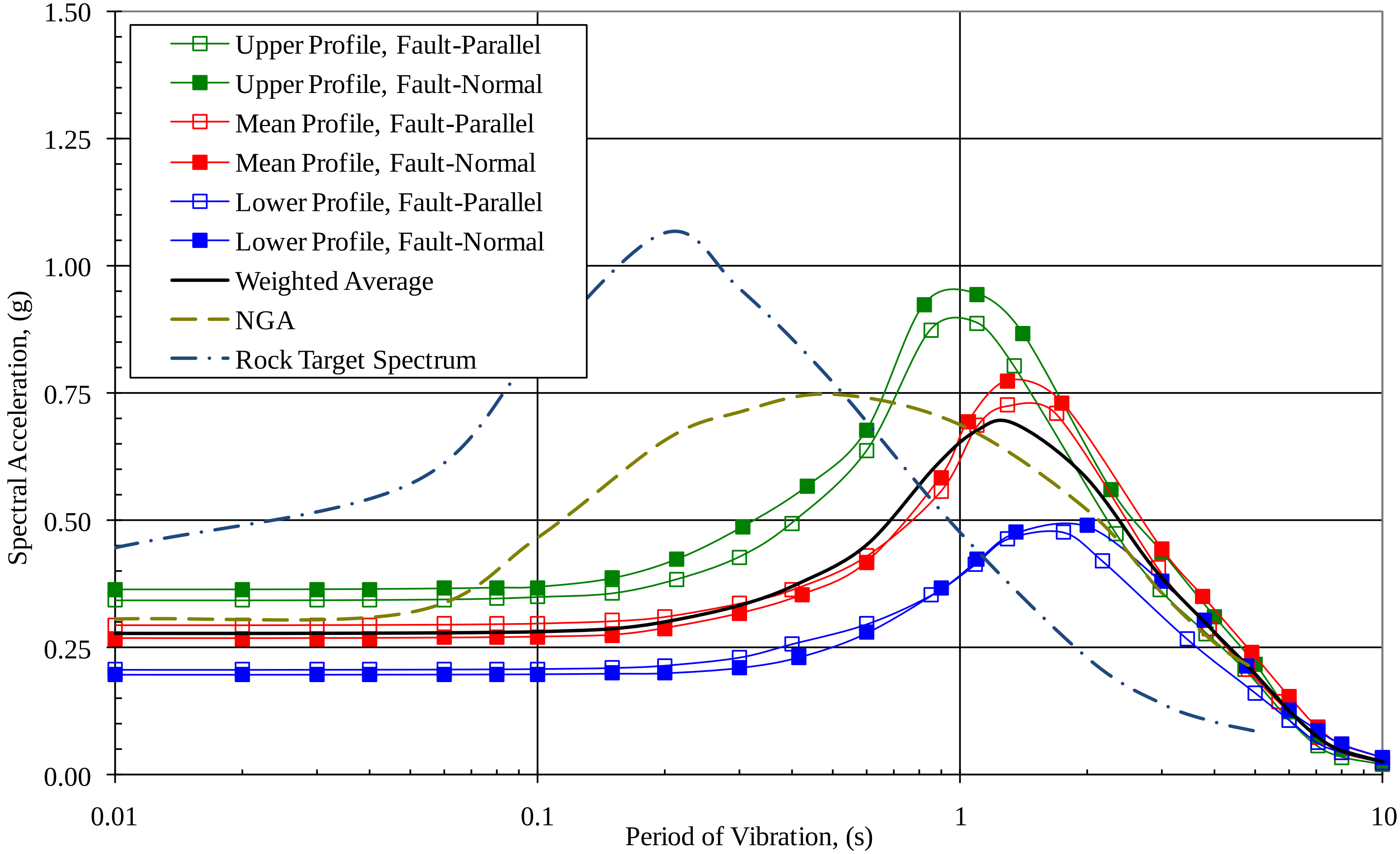

Figure 14: Results of the EQL site response analysis for the South Interchange of Legacy Parkway for the rupture of the Weber Segment

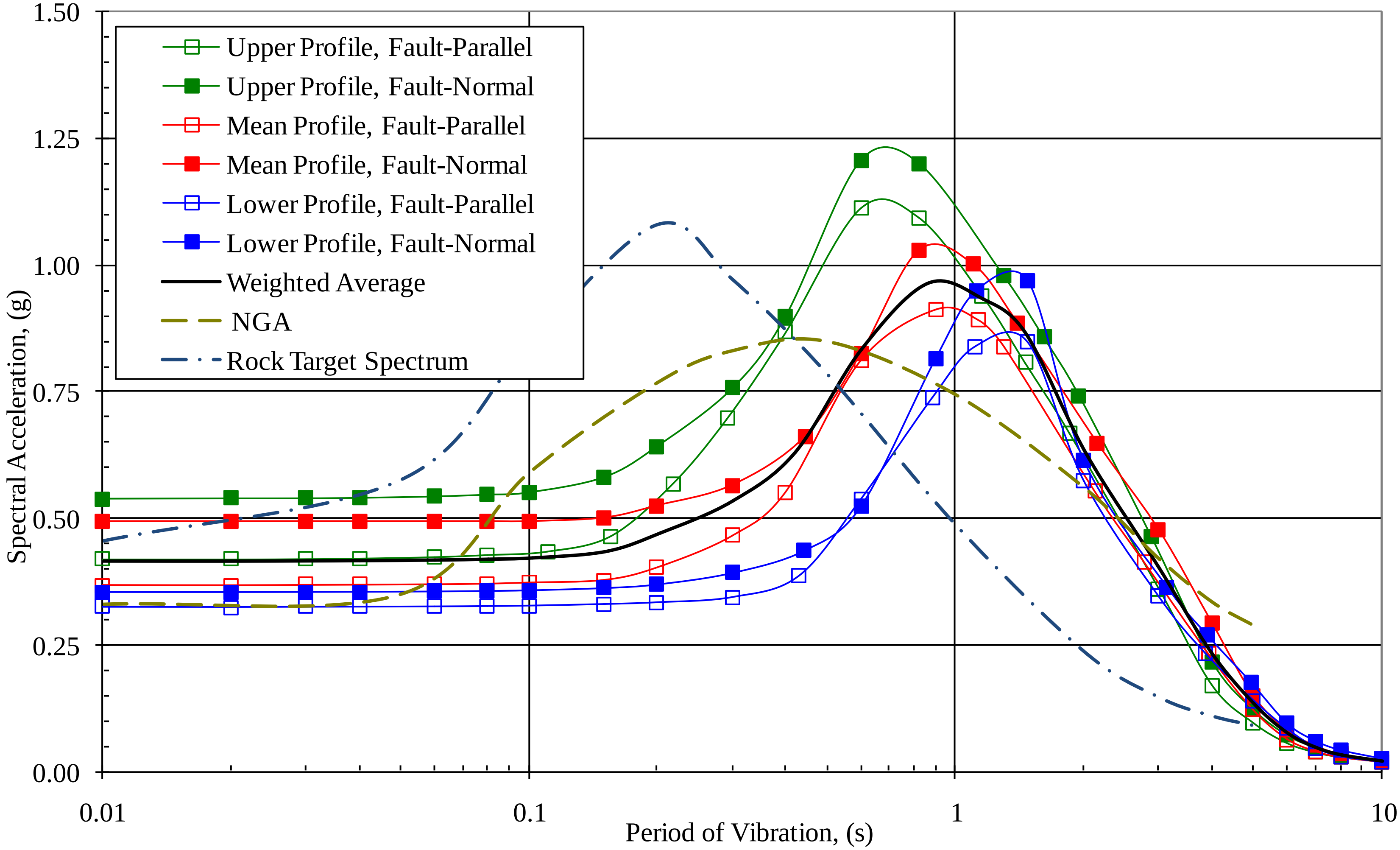

Figure 15: Results of the EQL site response analysis for the North Interchange of Legacy Parkway for the rupture of the Weber Segment

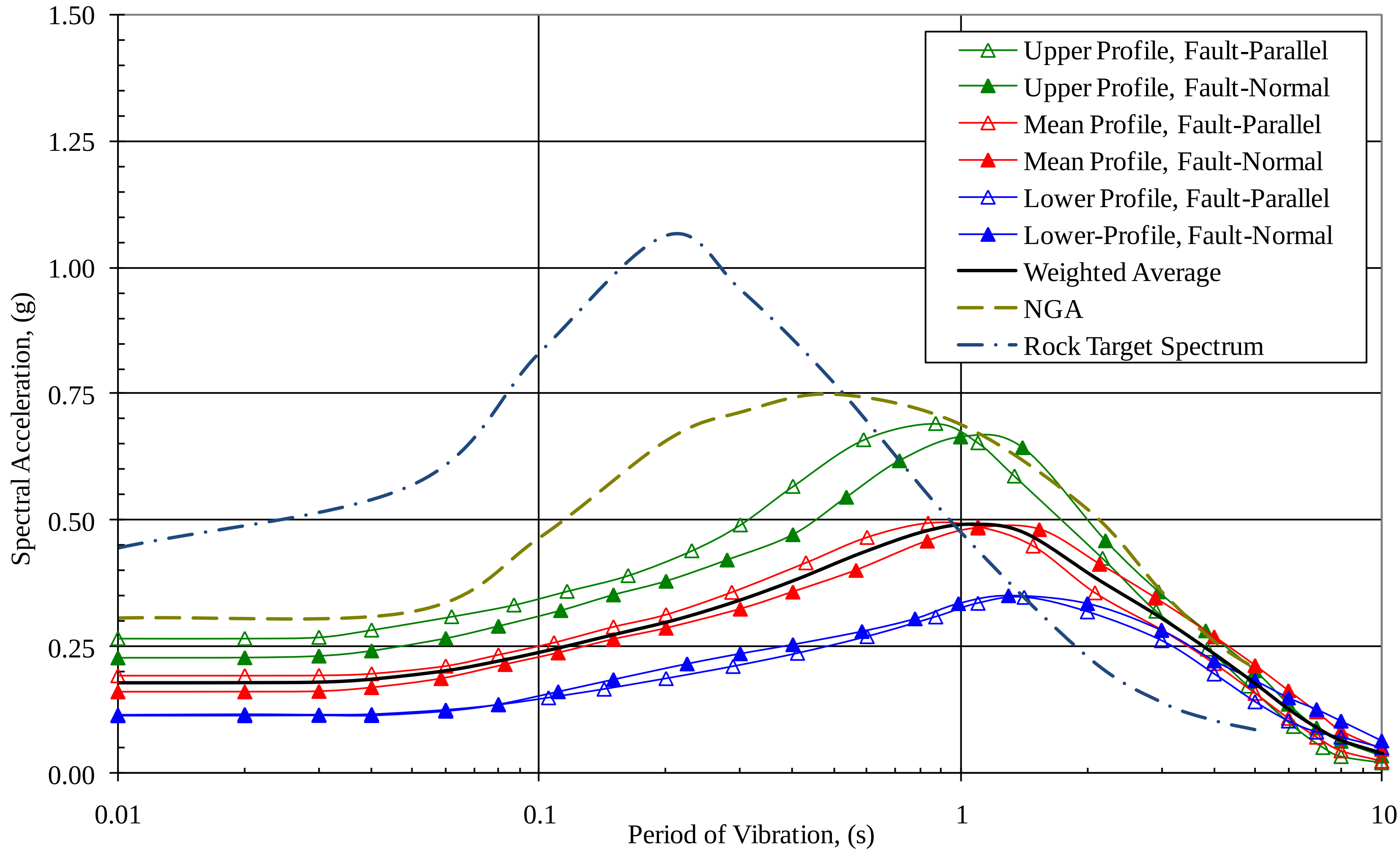

Figure 16: Results of the NL site response analysis for the South Interchange of Legacy Parkway for the rupture of the Weber Segment

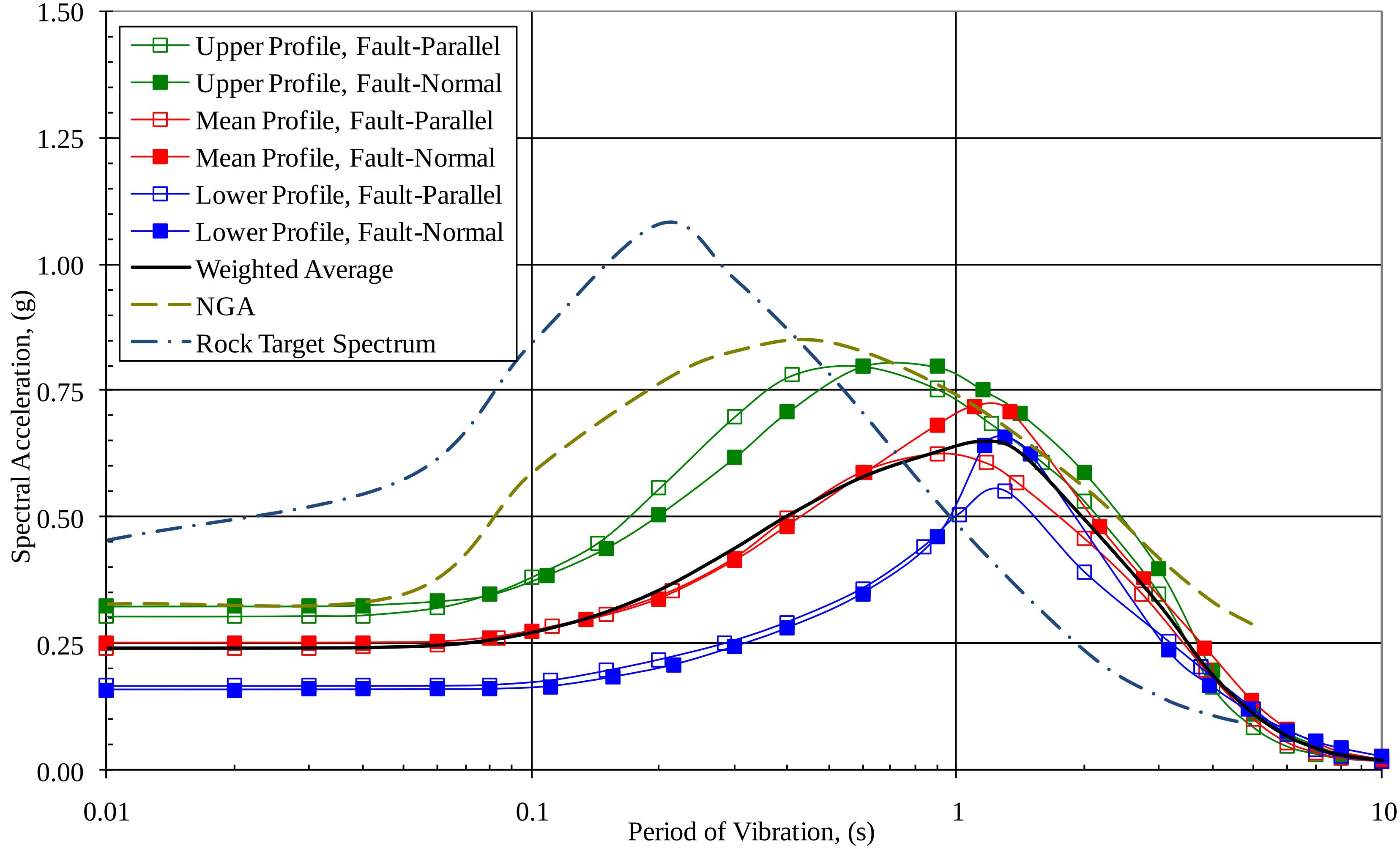

Figure 17: Results of the NL site response analysis for the North Interchange of Legacy Parkway for the rupture of the Weber Segment

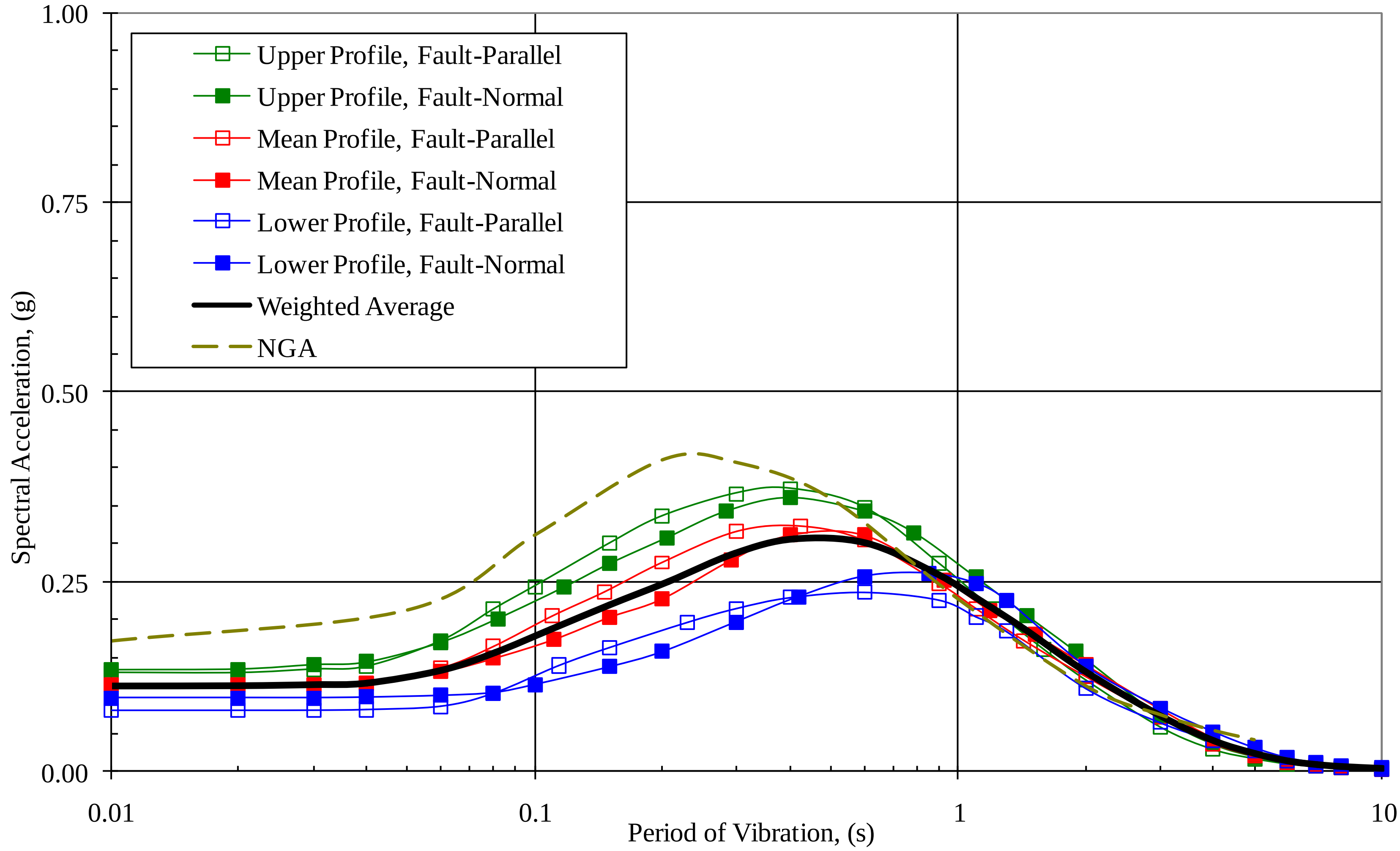

Figure 18: Results of the NL site response analysis for the North Interchange of Legacy Parkway for the rupture of the Salt Lake City Segment

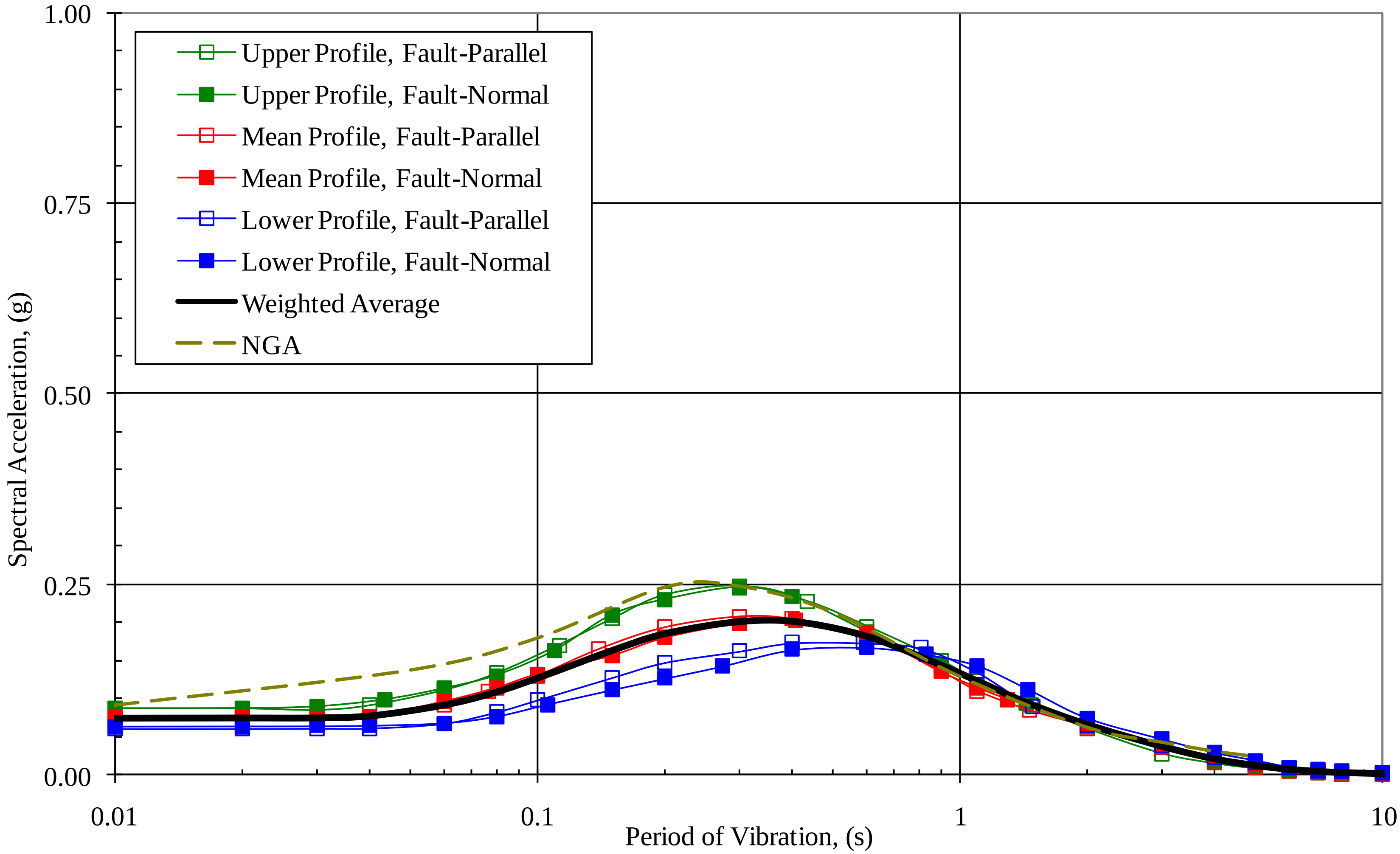

Figure 19: Results of the NL site response analysis for the North Interchange of Legacy Parkway for the rupture of the Brigham City Segment

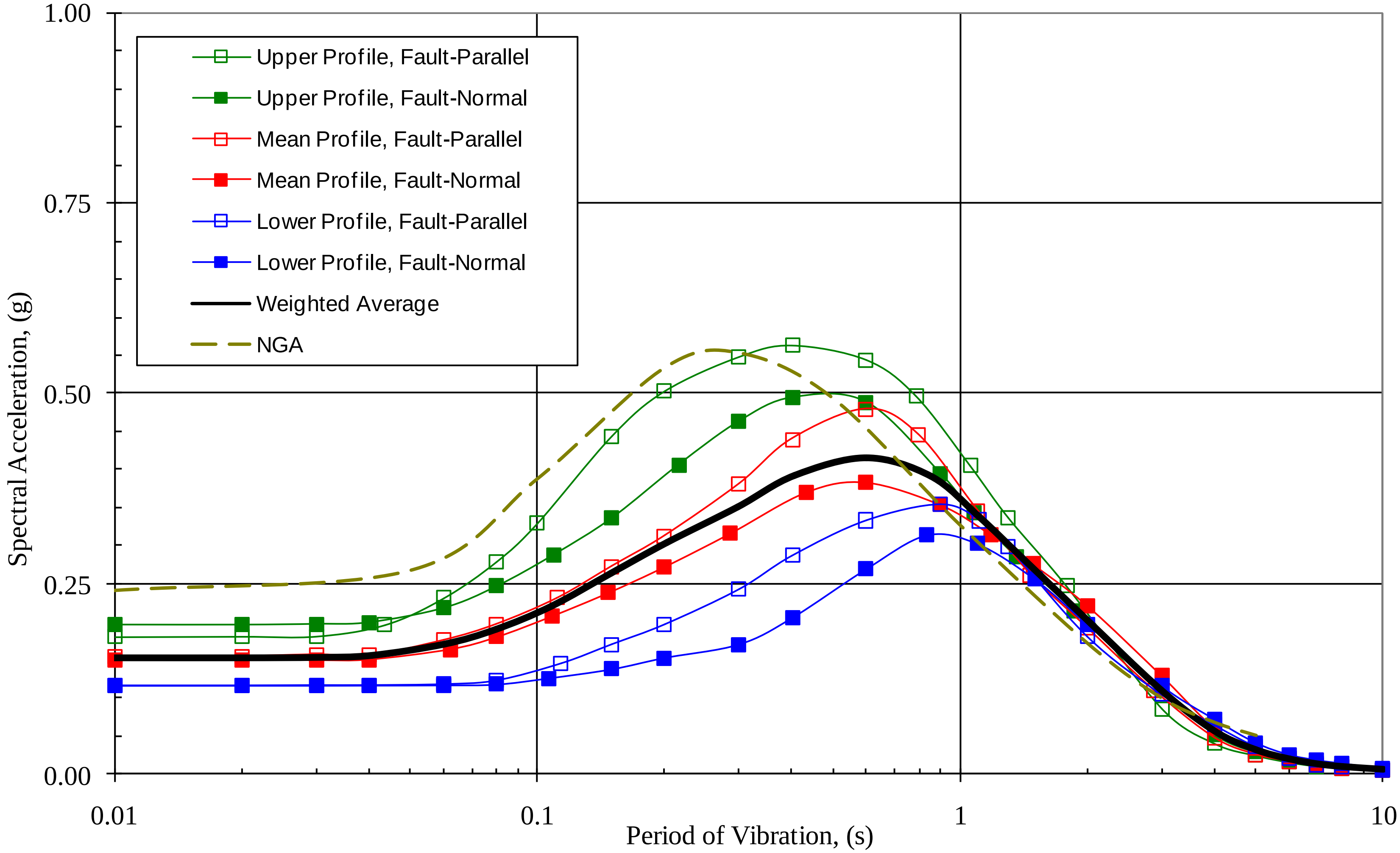

Figure 20: Result of the NL site response analysis for the North Interchange of Legacy Parkway for the 475-year return period scenario

8.3 Structural Considerations

The finite element program SAP2000 was selected to create a representative, mathematical model of the two selected bridges. These models are created by constructing a wire-mesh model by connecting nodes using line and area elements. Node spacing and location depend on desired accuracy. Nodes and structural elements should be placed to represent the structure. In other words, members of the structure should be represented graphically by nodes connected with the wire mesh. The size and material properties of structural members can be assigned to the wire mesh as will be discussed later.

Construction documents were obtained from UDOT for the C-865 and the F-669 bridges and used to create simple models of each bridge. SAP representations of each bridge can be seen as Figures 21 and 22 respectively.

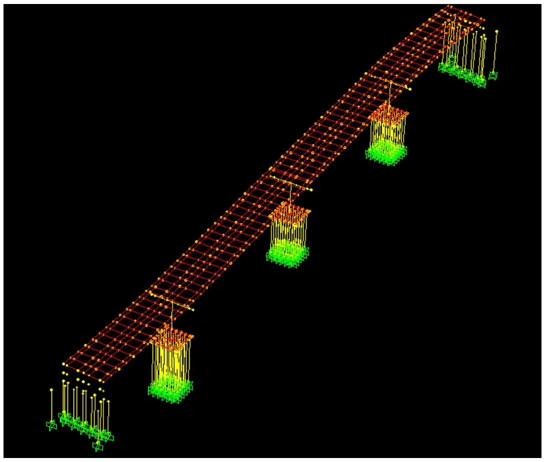

Figure 21: C-865 (Wire Mesh)

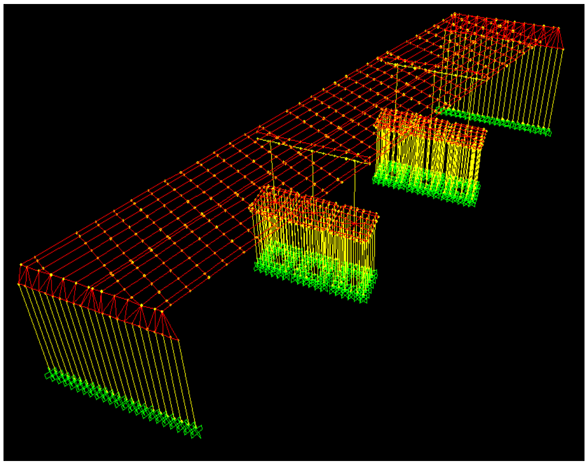

Figure 22: F-669 (Wire Mesh)

The previous figures show the discretized wire mesh bridges. Node spacing varies throughout each bridge depending on the member sizes, locations, and connections. There was a node placed roughly at ten-foot intervals throughout the deck and for the girder spans in the longitudinal direction. The deck nodes are spaced according to the girder spacing in the transverse direction. Nodes were placed in the deck/girder-beam spans at locations where the bends would intersect with the deck. These deck nodes were then offset vertically to create the bent nodes. Joint constraints were assigned between the bent nodes and the corresponding deck nodes to represent the deck girder/bent cap interaction. The offset nodes are constrained to one another and fixed in each direction relative to eachother but free to rotate about the line created by the bent cap.

Pile-cap node locations at the ground level were created so that the pile cap and the pile tops would share the same nodes. In order to better represent the pile-top/pile-cap interaction, a moment release was assigned in each direction at the top of each pile line element. This allows for the rotation of the pile tops relative to the pile cap but does not release the pile cap in translation. Each pile tip was fixed at the base and a stiffness was determined for each pile to represent the soil stiffness. Since steel pipe piles with a concrete core were used, the pile stiffness was determined by creating a concrete/steel composite material with an equivalent stiffness. The piles are considered to be nearly rigid due to the soil interaction. The pile stiffness is such that acceleration due to earthquake excitation is applied to the pile caps and transferred into the bridge structure rather than being absorbed into the piles.

Line elements representing the structural members of the structure are used to connect the nodes. Section properties can be assigned to the line elements allowing for differing structural memebers such as girder beams, bents, columns, and piles. The section properties of area, compressive strength and modulus of elasticity were assigned to each structural member according to the construction documents.

Shell elements were used to create the concrete deck and pile caps. In SAP, area elements represent a solid surface and can be used to check in-plane, out-of-plane, and combined forces. Each shell element is modeled as a thin concrete shell with the same thickness and concrete compressive strength as required on the construction plans.

Each line on the model represents an actual structural member in the bridge. Structural member elements were sized and structural properties were assigned to each member according to the construction plans. A representative model of each bridge can be seen in the following two figures, noted here as Figures 23 and 24.

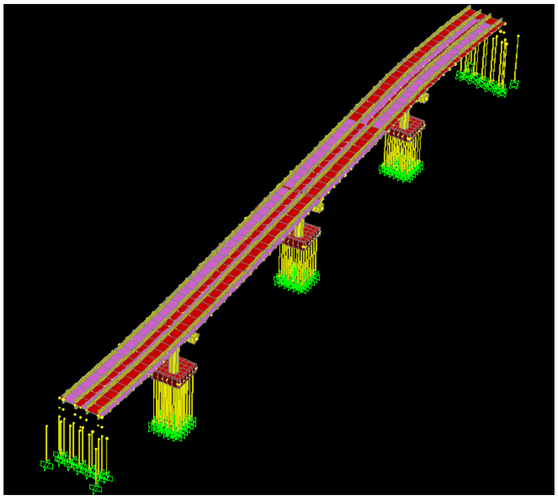

Figure 23: C-865 (Extruded View)

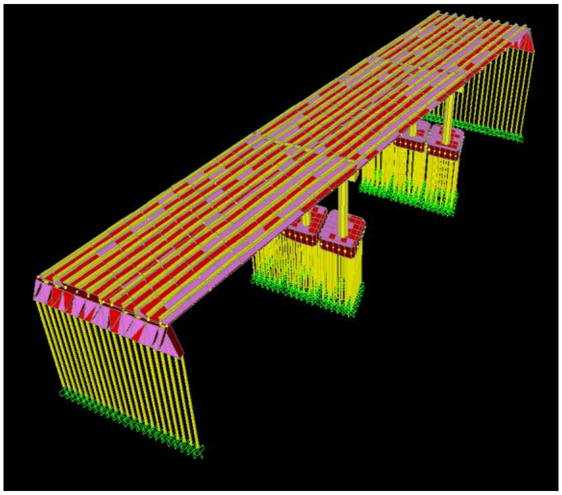

Figure 24: F-669 (Extruded View)

Here, each element is extruded to see how the members and shell elements are represented by the wire mesh. The deck girders can be seen here, showing that the deck and girders share the same nodes. The concrete columns, pile caps and piles can be seen below the deck.

8.3.1 The C-865 Bridge

In order to determine a structural response to a determined ground motion, mode shapes and frequencies must be determined. Using SAP, the first ten principle modes and their respective frequencies were determined for each bridge. A graph showing the percent of mass participation for each mode in each global direction is shown here as Figure 25. A summary of the mode shapes, direction, and frequencies can be seen as Table 1.

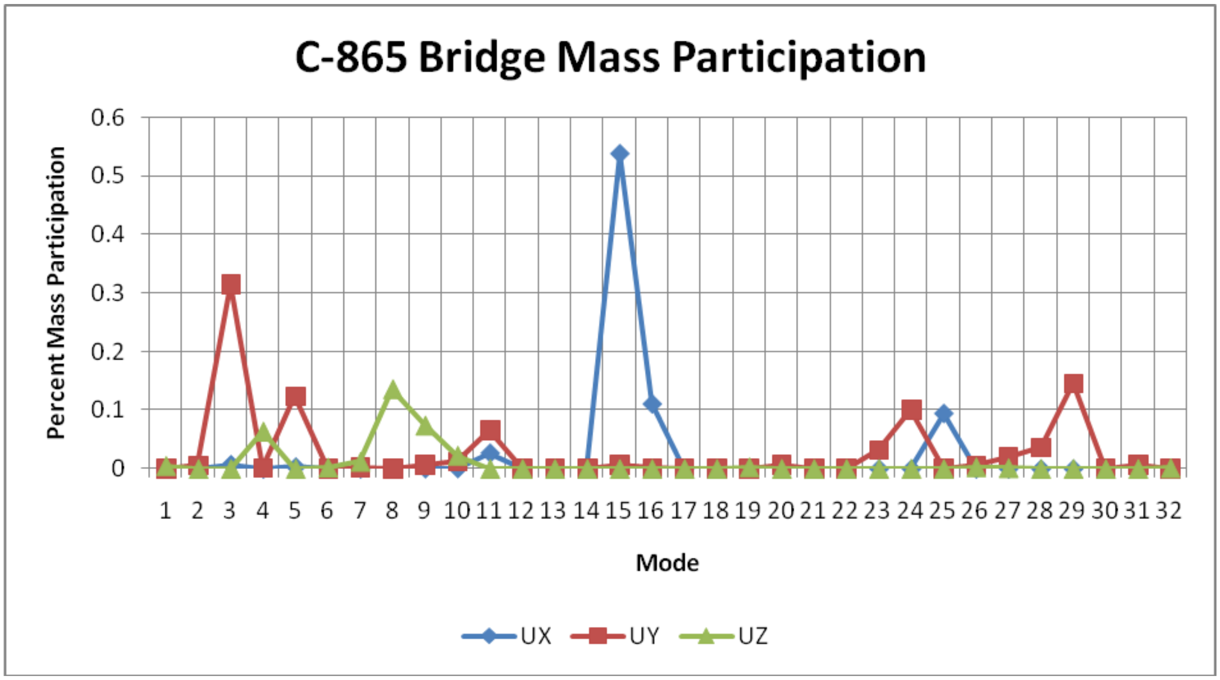

Figure 25: Mass Participation for Each Mode

Table 1: Principle Modal Shapes

Mode	Direction	Period	Frequency
3	Trans	0.7232	1.382839
4	Vert	0.6396	1.5635505
5	Trans	0.5672	1.7629533
8	Vert	0.3883	2.5755937
11	Trans	0.2664	3.7541765
11	Long	0.2664	3.7541765
15	Long	0.2459	4.0665284
24	Trans	0.1523	6.5677131
25	Long	0.1389	7.1978694
29	Trans	0.1243	8.0424642

8.3.2 The F-669 Bridge

A similar procedure was followed to determine the mass participation of each mode for the F-669 Bridge. A graph of mass participation for each mode can be seen as Figure 26. A summary of the mode shapes, direction, and frequencies can be seen as Table 2.

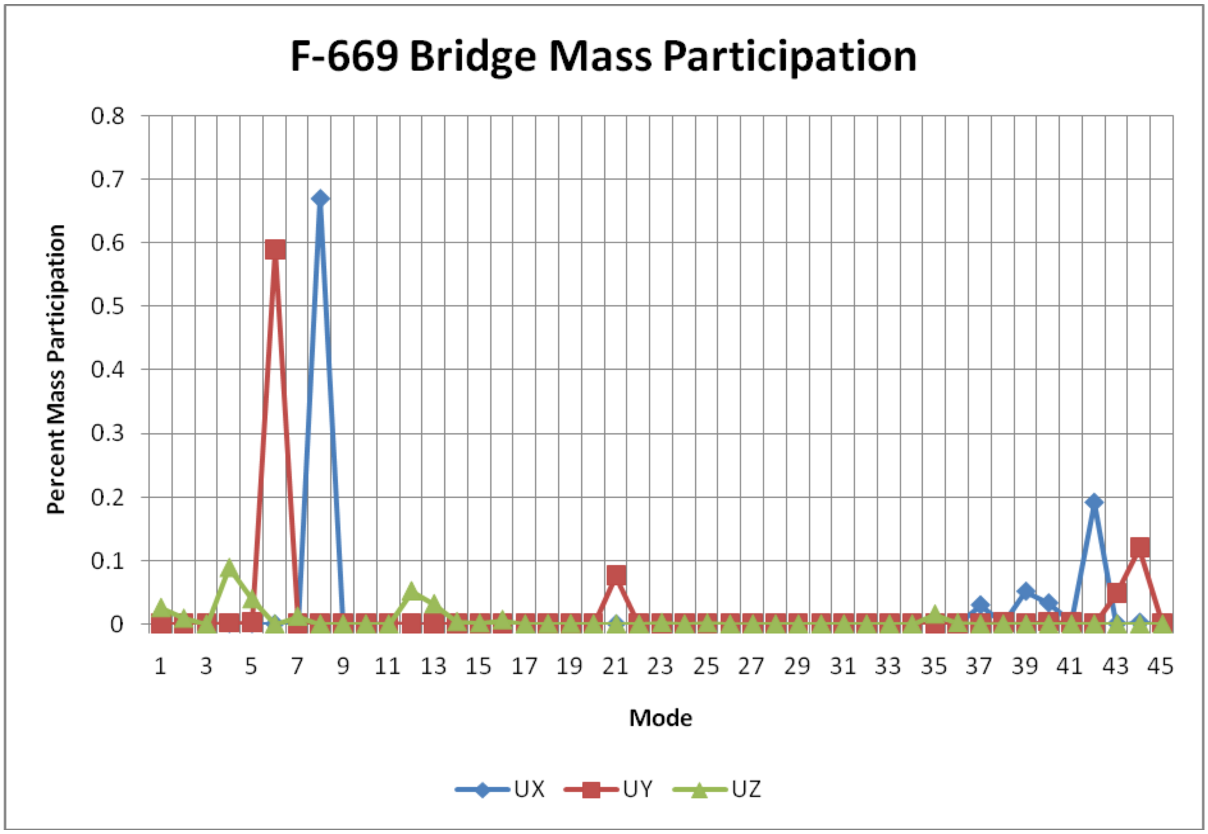

Figure 26: Mass Participation for Each Mode

Table 2: Principle Modal Shapes

Mode	Direction	Period	Frequency
4	Vert	0.3502	2.8553481
6	Trans	0.3036	3.2938076
8	Long	0.2638	3.7911817
12	Vert	0.1924	5.1977754
21	Trans	0.1415	7.0661391
37	Long	0.0781	12.805737
39	Long	0.0774	12.916559
42	Long	0.0773	12.936611
44	Trans	0.0772	12.94666

All of these modes were used in the excitation analysis to insure that at least ten of the major participating modes were included in the structural analysis.

9.0 SITE SPECIFIC INSTRUMENTATION DESIGN

9.1 Site and Geotechnical Considerations

Downhole and free-field Instrumentation of UDOT bridge sites can provide valuable information on the ground response of the soil system. Downhole accelerometer arrays allow seismic energy and deformation to be monitored as it propagates vertically through the soil media. Propagation of waves through soft, layered strata can have an important influence on the wave propagation. Unfortunately, these effects are poorly understood because of the dearth of downhole arrays, and further instrumentation and research is needed in this area. Because the North interchange of Legacy Highway is located within a kilometer of the Wasatch fault zone, a successful recording of a large magnitude event using a downhole, free-field and bridge seismic array will provide priceless data to the earthquake research community.

The design of a downhole array should be conducted in connection with a site response analysis and formal predictions of the expected free-field response at the instrumentation site. During the site response analysis, inspection of the vertical propagation of seismic response may also indicate areas of high impedance contrast between major geologic sediment beds. Accelerometers should be placed above and below such high impedance interfaces in the site-specific profile. One free-field accelerometer at the surface with a minimum of three additional accelerometers at depth is adequate to capture the effects of the local sedimentary soil layers on the transmission of seismic energy.

The spectral results and interpreted profile from the site response analysis can be used to determine instrument locations in the site-specific profile. Table 3 shows the shallow interpreted profile for the North interchange of Legacy Highway that was developed during the site response analysis.

Among the best indicators of the high contrast boundaries are impedance contrast (reflection coefficient), shear wave velocity, and the results of the site response analysis. Figure 27 shows the recommended instrument locations, the shallow shear wave velocity profile, peak ground acceleration (PGA) profile from the results of the site response analysis, the geologic interpretation of major sediment beds based on cone penetration testing (CPT) and boring data. Figure 27 shows the measured data and predicted results to enable easy placement of the instruments.

Table 3: Shallow interpreted profile for North Interchange of Legacy Highway

Soil Type	**Total Unit Weight**	**Density**	**Shear Wave Velocity**	**Depth**	**Impedance**	**Reflection Coefficient**
(-)	**(kN/m^3)**	**(kg/m^3)**	**(m/s)**	**(m)**	**(kΩ)**	**(-)**
Silty Sand	19	979	160	4	157	0.077
Gravel	21	1142	160	7	183	-0.072
Lean Clay	20	989	160	9	158	-0.016
Silty Sand	19	958	160	12	153	0.292
Gravel	22	1244	225	13	280	-0.008
Silty Sand	22	1223	225	15	275	0.008
Gravel	22	1244	225	20	280	-0.284
Fat Clay	20	1040	150	22	156	0.229
Gravel	22	1244	200	25	249	-0.0427
Clayey Sand	21	1142	200	30	228	-

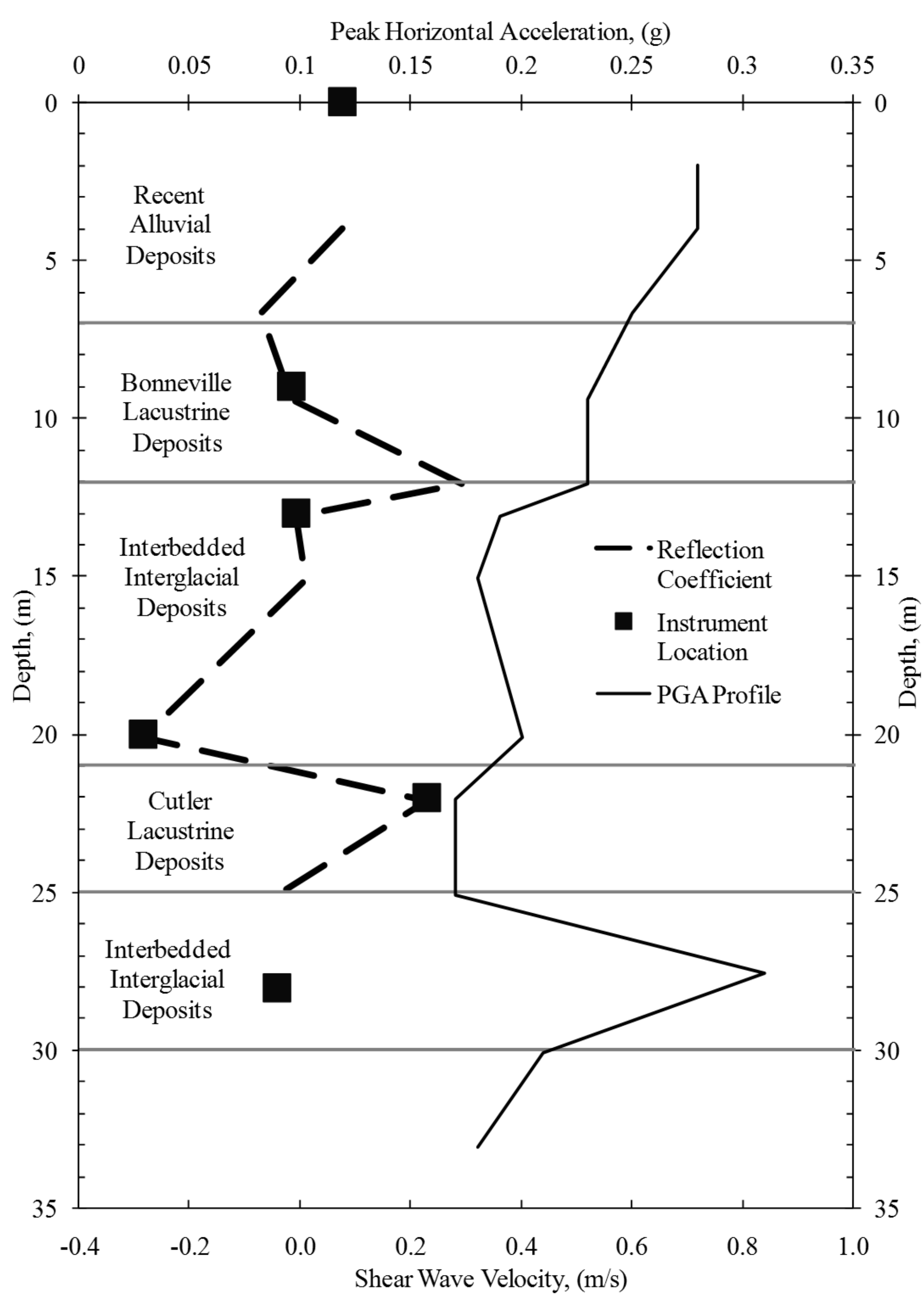

Figure 27: Recommended borehole accelerometer placement, shallow shear-wave velocity profile, peak horizontal acceleration (PGA) profile, and geologic interpretation of soil layering for North Interchange of Legacy Parkway

We recommend that a free-field accelerometer be placed at the surface, a second in the lean clay layer of the Bonneville lacustrine deposits, a third and fourth in the gravel layers of the interbedded interglacial deposits, a fifth in the fat clay layer in the Cutler lacustrine deposits, and a possibly a sixth located in the clayey sand layer in the lower interbedded interglacial deposits. These locations meet the criteria described above and are expected to provide valuable data in the case of a seismic event in the area.

9.2 Structural Considerations

Using the ground motions that were provided by the University of Utah, a structural response can be determined for each bridge. Each acceleration has a transverse and a longitudinal component. To determine the maximum displacement that could occur during an earthquake, the accelerations were applied one in the transverse direction and the other in the longitudinal direction. The accelerations were then switched and applied again to the model. Using SAP, a displacement verses time curve can be plotted for any node in the structure. An example of one of these curves can be seen as Figure 28. This graph corresponds to joint 381, a point at the outer limit of the deck at the midpoint of the longest span of the C-865 bridge.

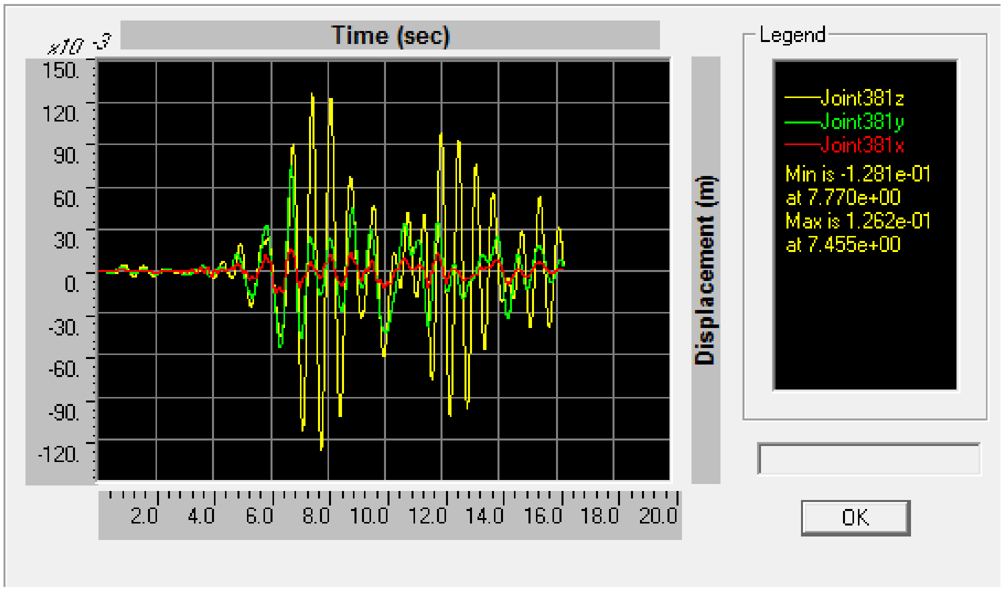

Figure 28: Longitudinal Time-Displacement

The response of the same node to the same earthquake with the accelerations applied in different directions can be seen as Figure 30.

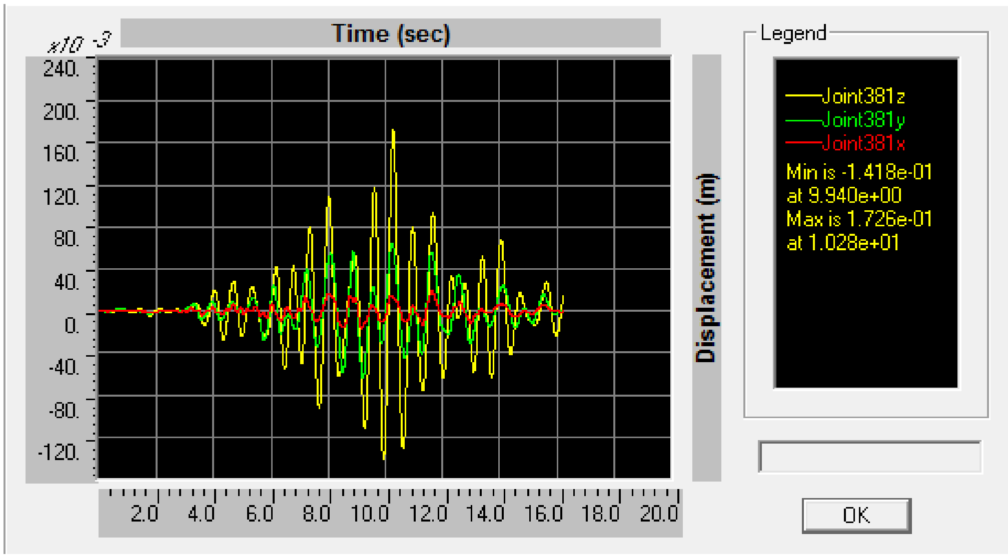

Figure 29: Transverse Time-Displacement

As can be seen when comparing the figures, the response of the structure varies when the accelerations are applied in different directions.

9.2.1 The C-865 Bridge

By locating the areas of maximum displacement while the accelerations are applied in each direction, locations of concern, or places of maximum displacement can be pinpointed. In order to do this, a maximum envelope of displacements can be created using SAP. Figures 24 and 31 show the nodes of the C-865 Bridge in their maximum displacements with seismic acceleration applied in both directions as described previously.

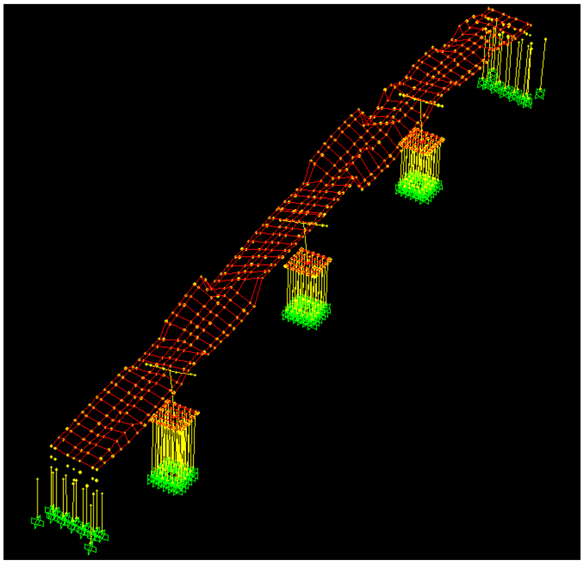

Figure 30: C-865 Bridge (Long. Gazli Excitation)

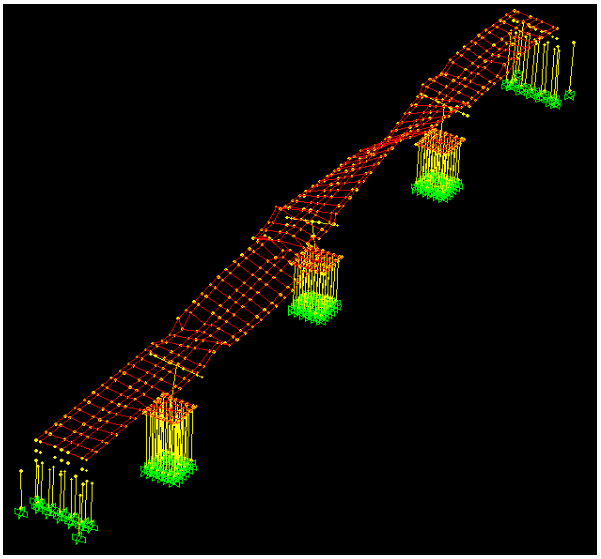

Figure 31: C-865 Bridge (Trans. Gazli Excitation)

Discontinuity of the deck occurs in these figures because of the maximum envelope. The maximum displacement in these sections occur at the upward motion for one node and on the downward motion for the next node, thus there is a discontinuity in the figure. This does not reflect the actual reaction of the structure. These figures can be used in SAP to find areas of maximum displacement during a given seismic excitation. The deformed shape of the deck and columns can also be seen. Each excitation was checked in each direction.

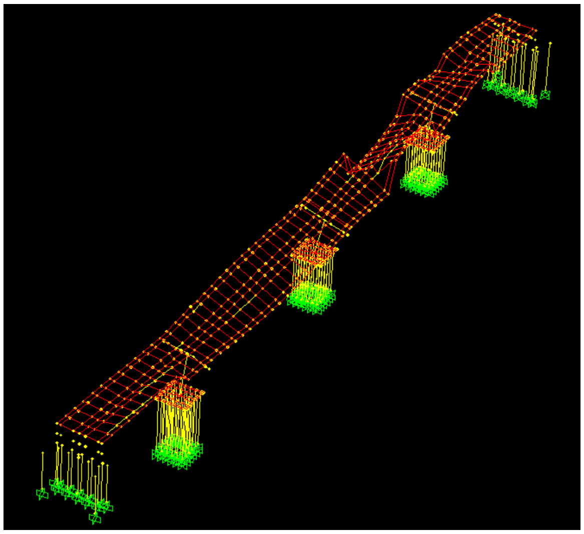

Figure 32: C-865 Bridge (Long. Irpinia Excitation)

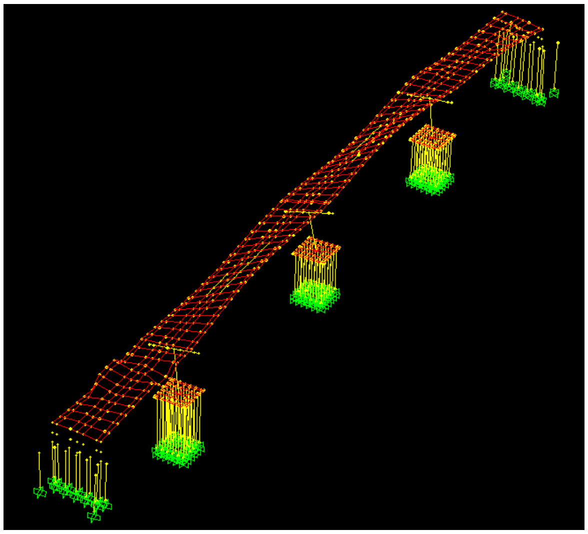

Figure 33: C-865 (Trans. Irpinia Excitation)

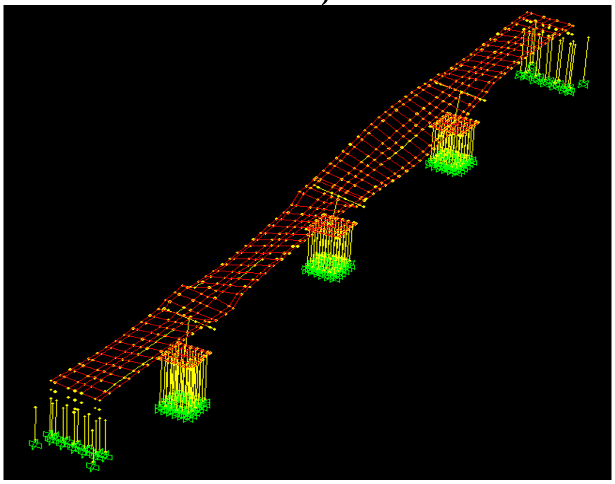

Figure 34: C-865 Bridge (Long. Loma Excitation)

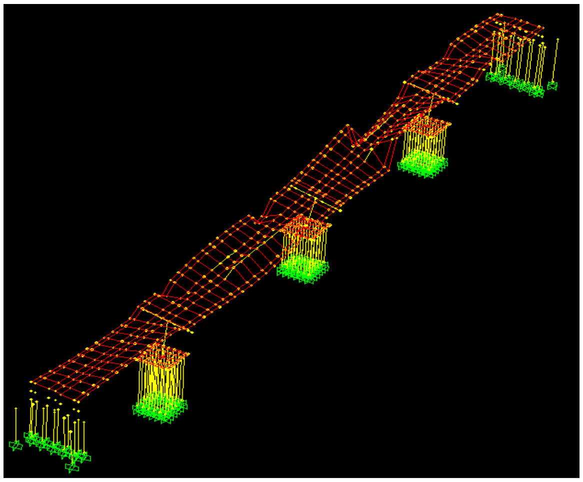

Figure 35: C-865 (Trans. Loma Excitation)

The maximum deflections for each excitation in each direction for the C-865 Bridge can be seen as Figures 32 through 33. From these figures we can get an idea of where accelerometers need to be placed. Although the response will be different for any given excitation, using these models, general guidelines can be formed. Using these models as guidelines, an instrumentation map can be constructed. These maps show locations of proposed instrumentation. Accelerometers can be retrofitted to the existing bridge to record the seismic response to future ground excitations that may occur in the area of the bridges. Proposed instrumentation locations for the C-865 bridge can be seen as Figure 36. The sensor types, locations, and box numbers can be seen as Table 4.

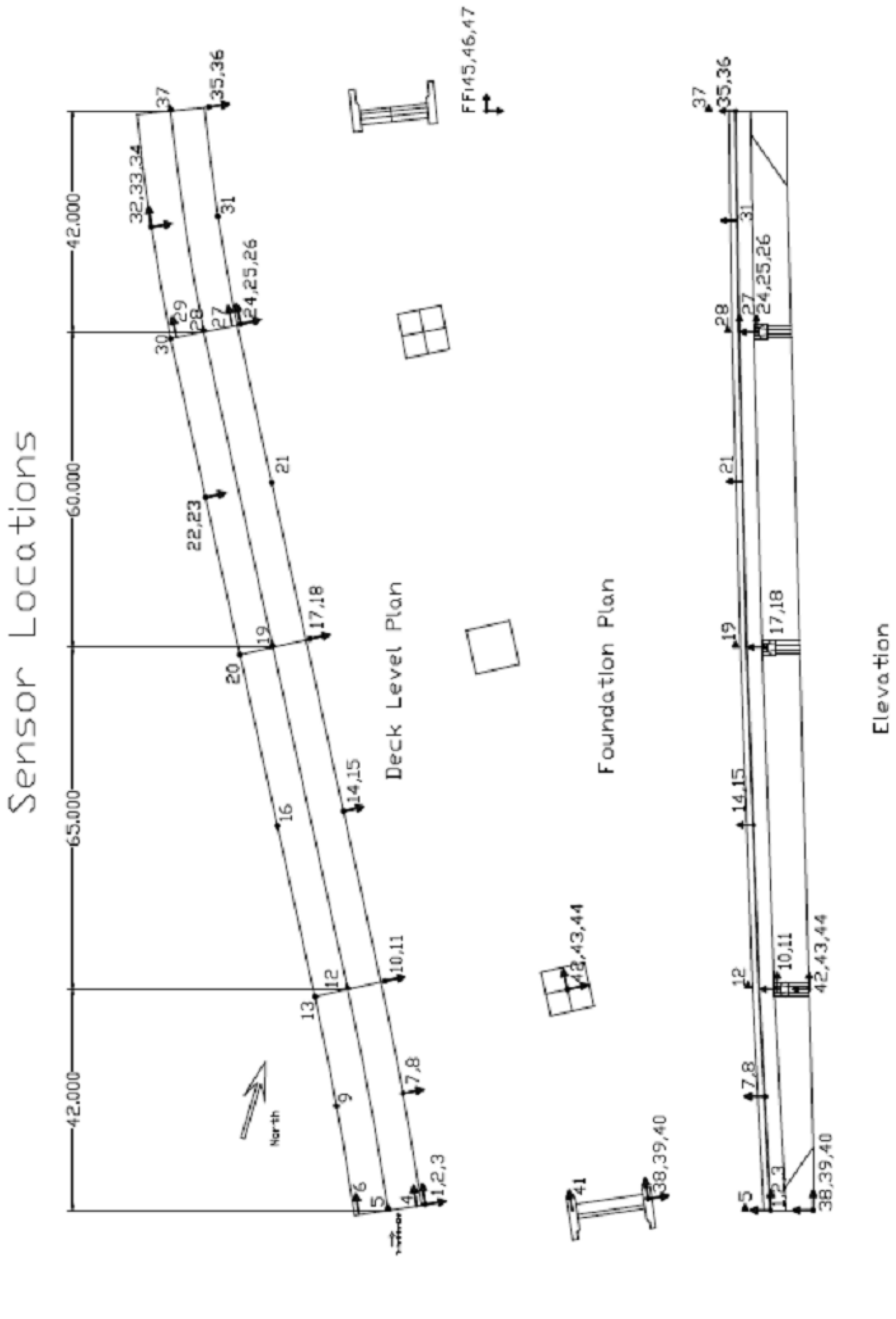

Figure 36: C-865 Bridge Instrumentation Plan

Table 4: C-865 Bridge Instrumentation

C-865 Bridge Instrumentation			
Box No.	Location	Type	Sensor Number
1	On Abutment 1	ES-T	1-3
2	On deck above Abutment 1	ES-U	4
3	On deck above Abutment 1	ES-U	5
4	On deck above Abutment 1	ES-U	6
5	On deck at 0.4L from Abutment 1 to Bent 2	ES-T	7-8
6	On deck at 0.4L from Abutment 1 to Bent 2	ES-U	9
7	On Bent 2	ES-T	10-11
8	On deck above Bent 2	ES-U	12
9	On Bent 2	ES-U	13
10	On deck at 0.4L from Bent 2 to Bent 3	ES-T	14-15
11	On deck at 0.4L from Bent 2 to Bent 3	ES-U	16
12	On Bent 3	ES-T	17-18
13	On deck above Bent 3	ES-U	19
14	On Bent 3	ES-U	20
15	On deck at 0.4L from Bent 3 to Bent 4	ES-U	21
16	On deck at 0.4L from Bent 3 to Bent 4	ES-T	22-23
17	On Bent 4	ES-T	24-26

18	On deck above Bent 4	ES-U	27
19	On deck above Bent 4	ES-U	28
20	On deck above Bent 4	ES-U	29
21	On Bent 4	ES-U	30
22	On deck at 0.4L from Bent 4 to Abutment 5	ES-U	31
23	On deck at 0.4L from Bent 4 to Abutment 5	ES-U	32-34
24	On Abutment 5	ES-T	35-36
25	On deck above Abutment 5	US-U	37
26	Base of Abutment 1	US-T	38-40
27	Base of Abutment 1	US-U	41
28	Pile Cap 2	US-T	42-44
29	Free-Field	US-T	45-47

Sensor locations are suggested here due to maximum displacements determined by the SAP model. The sensors placed along each span of each bridge should be placed at forty percent of the total span or 0.4*Length as stated in Tables 4 and 5. The reason for this is to collect the maximum response due to the contribution of each modal shape. Odd-numbered modal shapes will contribute a maximum displacement at the mid-span of the deck and girders, but the even-numbered modal shapes will contribute little or no displacement at the mid-span. For this reason it was determined to locate the accelerometers at 0.4L.

9.2.2 The F-669 Bridge

The same process was repeated for the F-669 bridge and maximum deflections can be checked according to excitation and direction of excitation. The maximum deflected shapes for the F-669 bridge can be seen as Figures 37 through 42.

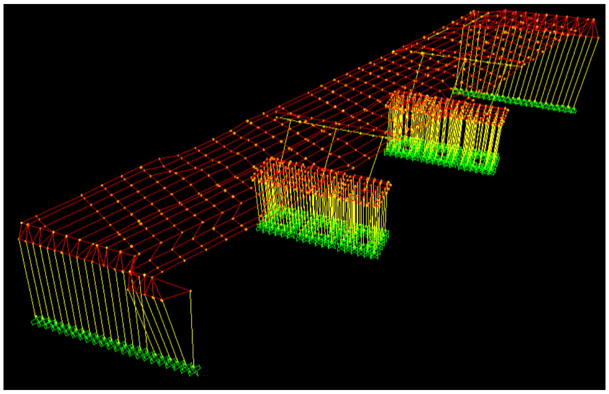
Figure 37: F-669 Bridge (Long. Gazli Excitation)

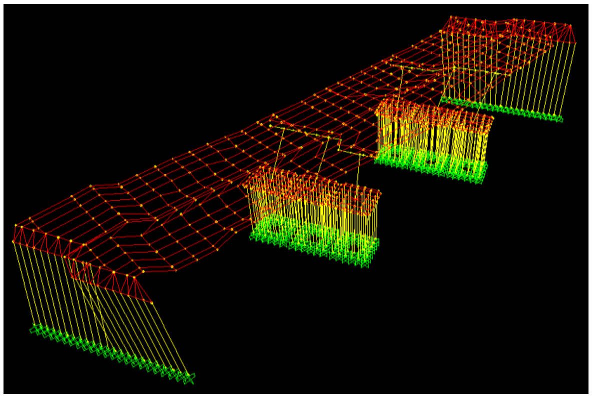
Figure 38: F-669 Bridge (Trans. Gazli Excitation)

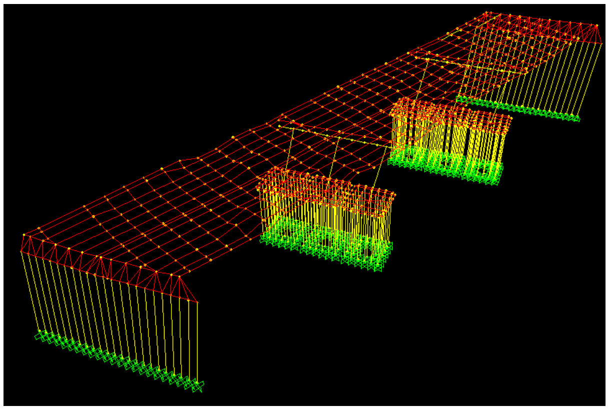
Figure 39: F-669 (Long. Irpinia Excitation)

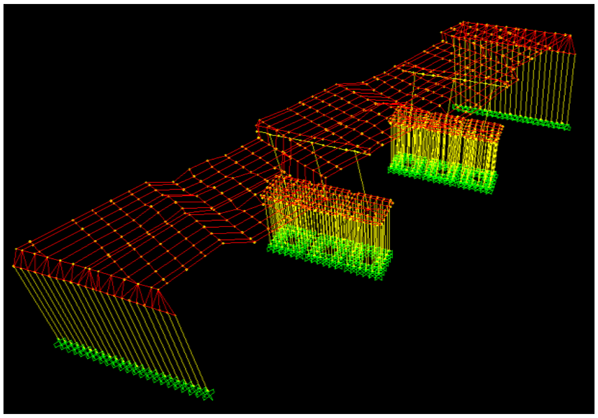
Figure 40: F-669 (Trans. Irpinia Excitation)

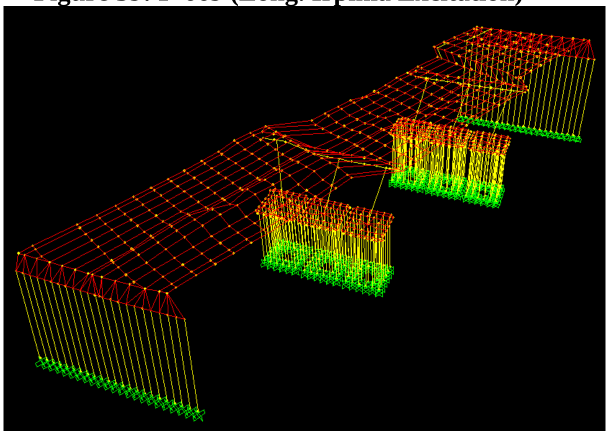
Figure 41: F-669 Bridge (Long. Loma Excitation)

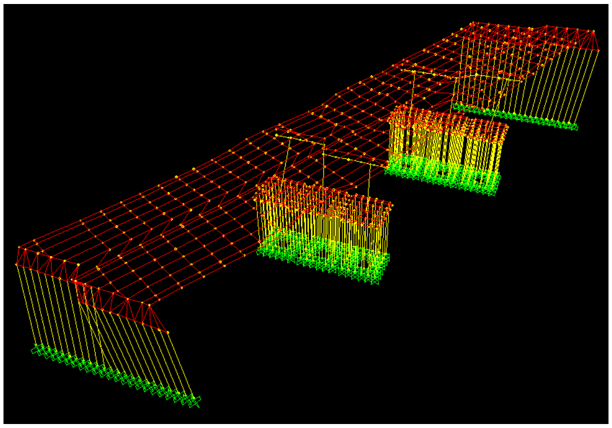
Figure 42: F-669 Bridge (Trans. Loma Excitation)

Vertical displacements are not as prevalent in the F-669 bridge. As can be seen from the previous figures, vertical displacement does not play as significant of a role in the F-669 bridge as it did in the C-865 bridge. This can also be seen in Figure 26. The mass contributions in the longitudinal and transverse directions have more of a contribution to the overall movement of the structure. For this reason, more longitudinal accelerometers were specified more on the F-669 bridge. The bridge instrumentation plan and bridge instrumentation guide can be seen as Figure 43 and Table 5 respectively.

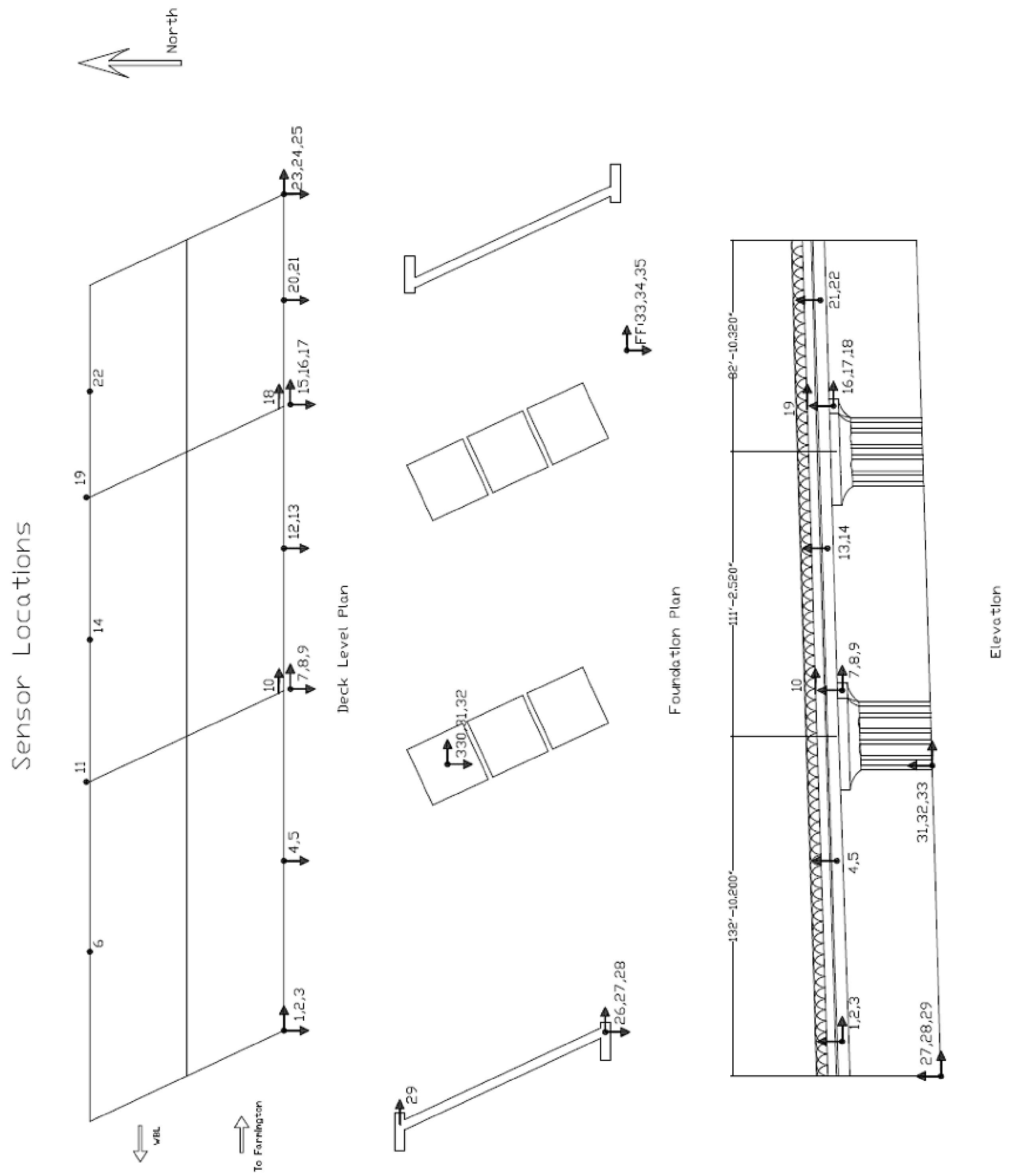

Figure 43: F-669 Bridge Instrumentation Plan

Table 5: F-669 Bridge Instrumentation

F-669 Bridge Instrumentation			
Box No.	Location	Type	Sensor Number
1	On Abutment 1	ES-T	1-3
2	On deck at 0.4L from Abutment 1 to Bent 2	ES-T	4-5
3	On deck at 0.4L from Abutment 1 to Bent 2	ES-U	6
4	On Bent 2	ES-T	7-9
5	On deck above Bent 2	ES-U	10
6	On Bent 2	ES-U	11
7	On deck at 0.4L from Bent 2 to Bent 3	ES-T	12-13
8	On deck at 0.4L from Bent 2 to Bent 3	ES-U	14
9	On Bent 3	ES-T	15-17
10	On deck above Bent 3	ES-U	18
11	On Bent 3	ES-U	19
12	On deck at 0.4L from Bent 3 to Abutment 4	ES-T	20-21
13	On deck at 0.4L from Bent 3 to Abutment 4	ES-U	22
14	On Abutment 4	ES-T	23-25
15	Base of Abutment 1	ES-T	26-28
16	Base of Abutment 1	ES-U	29
17	Pile Caps below Bent 2	ES-T	30-32
18	Free-Field	ES-T	33-35

10.0 CONCLUSION

The highway transportation system in Utah is essential for the continuing prosperity of the state. Additionally, the sizable public investment in infrastructure must be properly and appropriately managed. Therefore, a strong motion instrumentation plan for the state is necessary and justified.

This report contains the information required for UDOT planning and strong motion program development. The guidelines provided and accompanying decision tree will assist in the selection of appropriate structures for instrumentation that are consistent with the overall state framework.

These guidelines will assist UDOT in the evaluation of all proposed bridges. The evaluation will be used to select bridges to be a candidate bridge for an expanded strong motion instrumentation program.

This report also contains specific modeling and instrumentation design for two example bridges. The approach takes into account regional, importance, structural, site and age considerations.

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12.0 ACKNOWLEDGEMENT

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