SYSTEM IDENTIFICATION OF BRIDGE-GROUND SYSTEMS FROM RECORDED SEISMIC RESPONSE

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Abstract

A unique opportunity for gaining knowledge and insights is facilitated by the CSMIP Eureka Bridge and Samoa Bridge seismic records, along with those of the nearby Geotechnical ground downhole array. Of special interest is the response of a bridge pier in each bridge with records at the deck level, pile cap and within the underlying pile foundation. This valuable data set is employed to evaluate the ground, pile foundation, and overall bridge seismic response. Spatial variation of the recorded motions is examined. Linear and nonlinear response of the ground and the bridge are assessed using system identification techniques. During the strong shaking phase of the 2010 Ferndale Earthquake, a clear and significant stiffness reduction was observed in the response of the columns and foundations. After the strong shaking phase, flexural rigidity was seen to increase back to its original value (i.e., no perceptible permanent reduction).

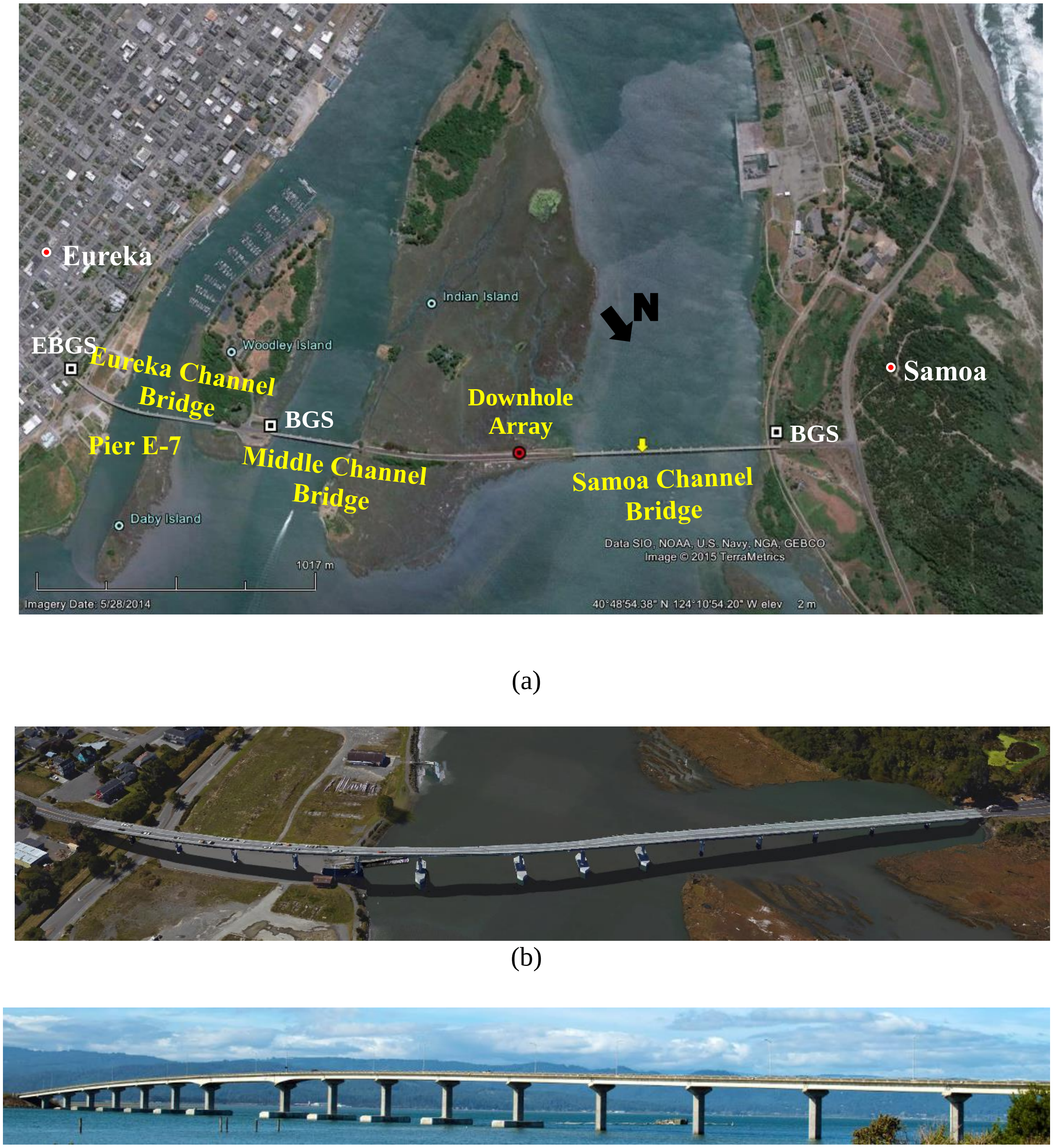
Introduction

A large set of earthquake records from the highly instrumented Samoa and Eureka Channel bridge-ground systems (Figure 1) has been compiled and made available by the California Geological Survey (http://www.strongmotioncenter.org). During a large number of seismic events, more than 20 data channels for each bridge have been documenting the seismic response of the deck, foundation, abutments, and adjacent ground surface. Of special interest is the response of a pier in each bridge, instrumented at the deck, pile cap, and below ground in the foundation. Response within the pile foundations may be compared to that of the ground as documented by the nearby Eureka geotechnical downhole array.

Bridge Configurations and Instrumentation

The Samoa Channel and Eureka Channel bridge configurations are shown in Figures 2 and 3 respectively. In these figures, dense instrumentation is seen along the deck, at the abutments, and the nearby ground surface. In addition, a Pier in each bridge (S8 in Samoa and E7 in Eureka) is instrumented at the pile cap and within the underlying pile foundation.

Significant variability in the ground stratification and soil properties may be observed in the soil profiles of both bridges (Figures 2 and 3). In addition, the Eureka Channel bridge includes a substantial horizontal curve, which results in significant coupling in its longitudinal and transverse response.



(c)

Figure 1. Bridge Configuration: (a) Samoa Channel Bridge, Eureka Geotechnical Array, Middle Channel Bridge and Eureka Channel Bridge (Map Data @ 2015 Google), (b) Close-up of the Eureka Channel Bridge (http://www.strongmotioncenter.org), and (c) photo of the Samoa Channel Bridge (http://www.strongmotioncenter.org)

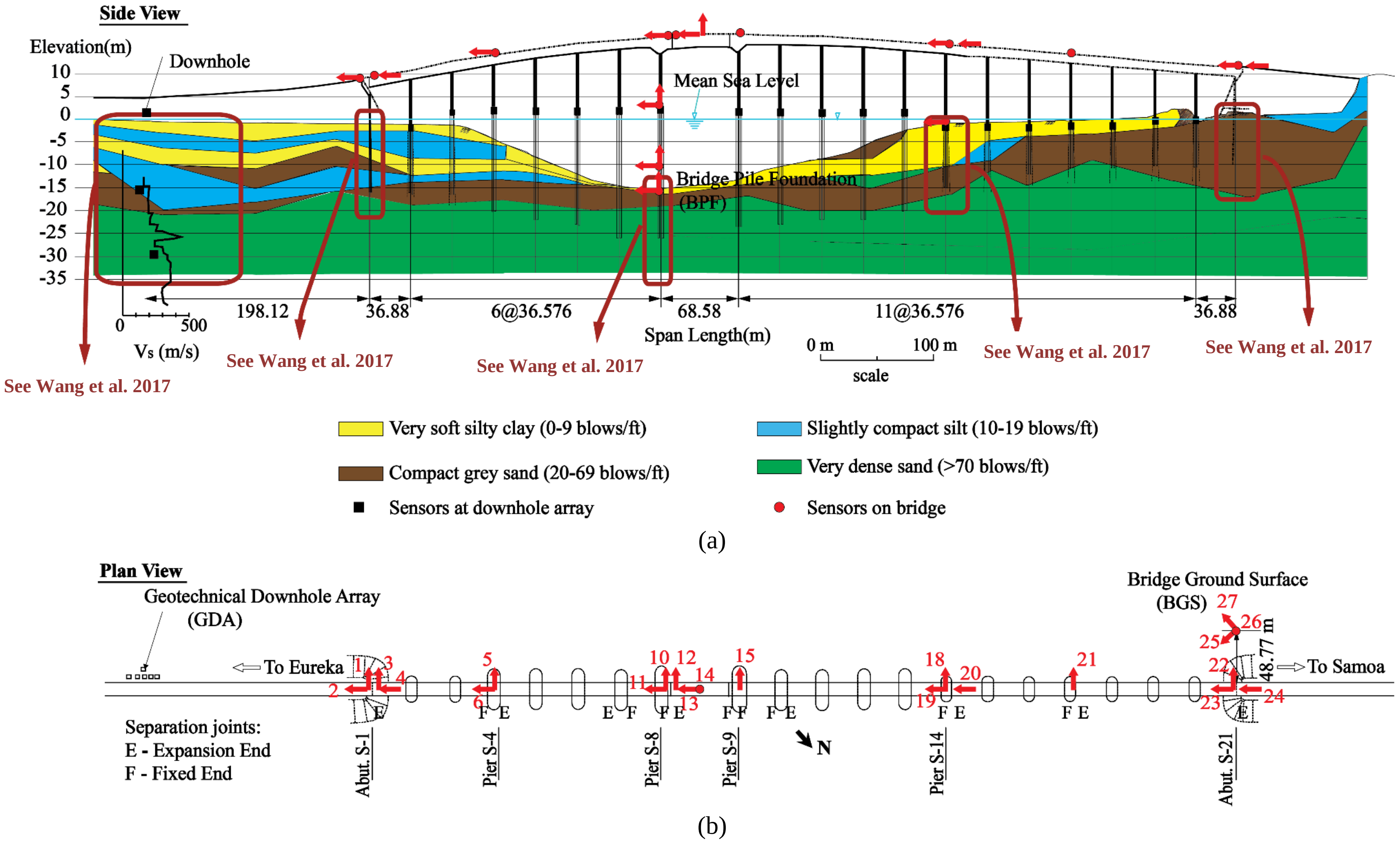
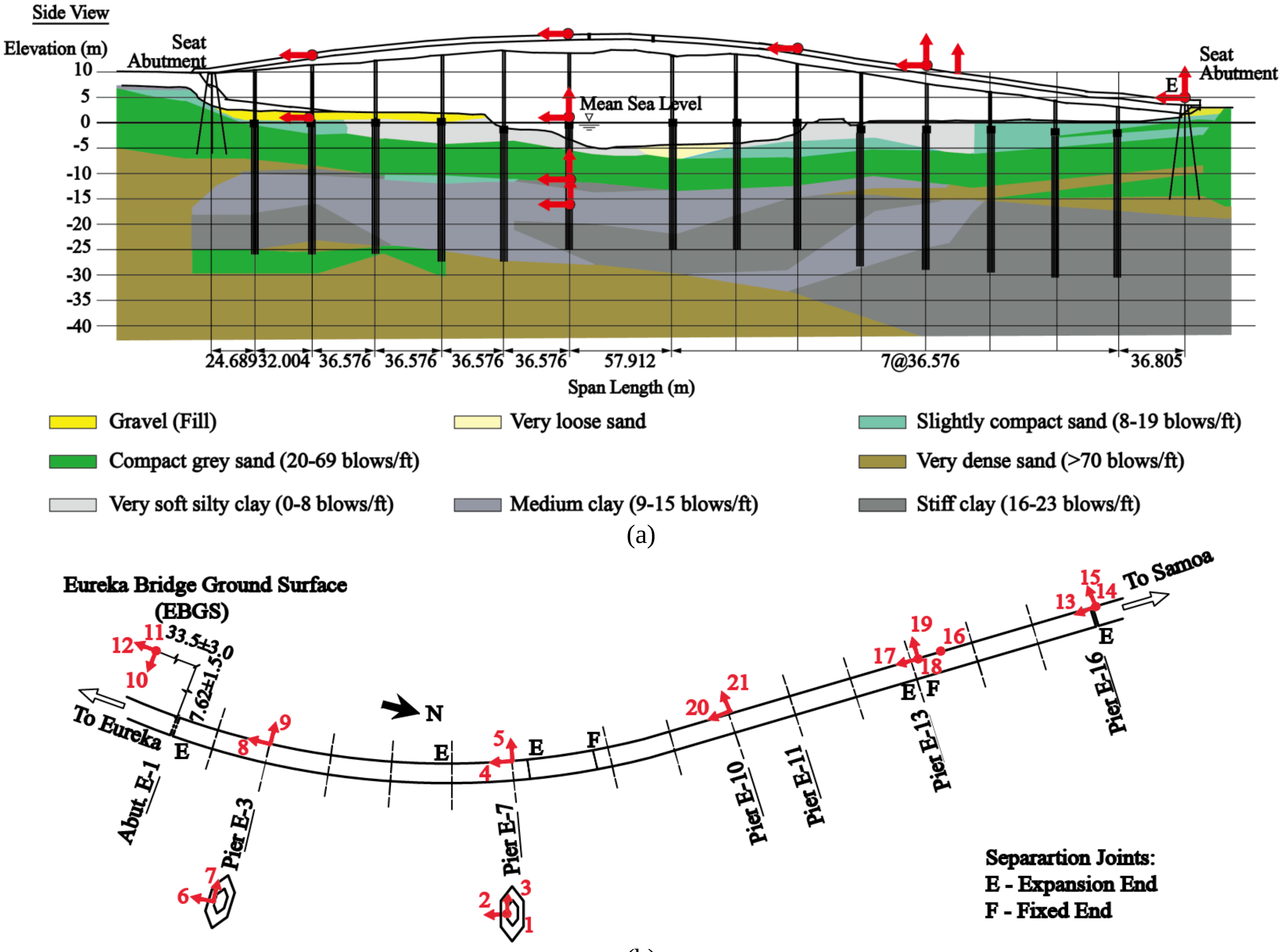


Figure 2. Layout of instrumentation at the Samoa Channel Bridge: a) bridge-ground side view (Caltrans 2002), and b) Plan view (http://www.strongmotioncenter.org)



(a)

(b)

Figure 3. Layout of Instrumentation at the Eureka Channel Bridge: (a) Bridge-ground side view (Caltrans 2002), and (b) Plan view (http://www.strongmotioncenter.org)

Earthquake Motions

Records from a large number of earthquakes (e.g., Table 1) during the period of June 2007 through March 2014 are currently available with Magnitudes in the range of 4.5 M_L (local magnitude) to 6.9 M_w (moment magnitude). To date, the highest levels of recorded acceleration are due to the 2010 $M_w = 6.5$ Ferndale Earthquake approximately 35 km away from Ferndale, CA in a deformation zone of the southernmost Gorda Plate (http://earthquake.usgs.gov, Storesund et al. 2010).

Table 1 Recorded earthquakes at the Eureka bridge site (arranged by order of peak acceleration)

Earthquake	Epicentral Distance (km)	Horizontal Peak Acceleration (g)		
		Ground	**Bridge**	
			TRAN	LONG
Ferndale 2010 (M_w=6.5)	54.5	0.253	0.510	0.955* 0.540**
Ferndale 2014 (M_w=6.9)	82.7	0.026	0.072	0.048
Trinidad 2008 (M_w=4.6)	41.7	0.022	0.060	0.047
Humboldt Hill 2013 (M_L=4.5)	20.8	0.022	0.019	0.014
Trinidad 2007 (M_L=5.1)	65.6	0.020	0.081	0.031
Ferndale 2010 Feb (M_w=5.9)	77.8	0.018	0.046	0.022
Willow Creek 2008 (M_w=5.4)	55.4	0.012	0.026	0.017
Ferndale 2007 (M_L=5.4)	63.3	0.011	0.021	0.014

*Large peak acceleration due to spikes emanating from interaction at the separation joints (Huang and Shakal 1995, Malhotra et al. 1995)

**Estimated after removing spikes using a band-pass filter

Samoa Bridge and downhole array

Response of the soil profile at the downhole array, along the ground surface and the bridge deck was studied (Wang et al. 2017). In addition, a pattern recognition and system identification effort was undertaken to define the bridge and foundation stiffness characteristics (Wang et al. 2018). A number of main findings based on this work are included below.

The downhole array motions revealed (Wang et al. 2017):

i) a shear wave velocity profile that is consistent with that documented earlier through in-situ investigations,

ii) with peak ground acceleration of about 0.16g, G/G_{max} in the upper 17 m zone reached as low as 36%, in agreement with the widely used such relationships, and

iii) below the depth of about 16 m, lower shaking amplitudes and higher soil stiffness precluded the appearance of detectable nonlinear response.

Motions along the Samoa Bridge and Instrumented Pier S8 (deck, pile cap, and pile near mudline) revealed (Wang et al. 2017):

i) significant variability in the bridge deck motion mainly in the transverse direction along with noticeable elongation of the bridge natural period (Figure 4),
ii) in the transverse direction, with high column Moment of Inertia, deformation was mainly occurring below the pile cap within the pile group 16 m long free span (Figure 2),
iii) conversely, in the longitudinal direction (with a lower column Moment of Inertia), deformation was more evenly distributed between the column and the pile group below the pile cap, and
iv) by studying the earthquake events chronologically, no clear evidence of permanent change in stiffness was identified.

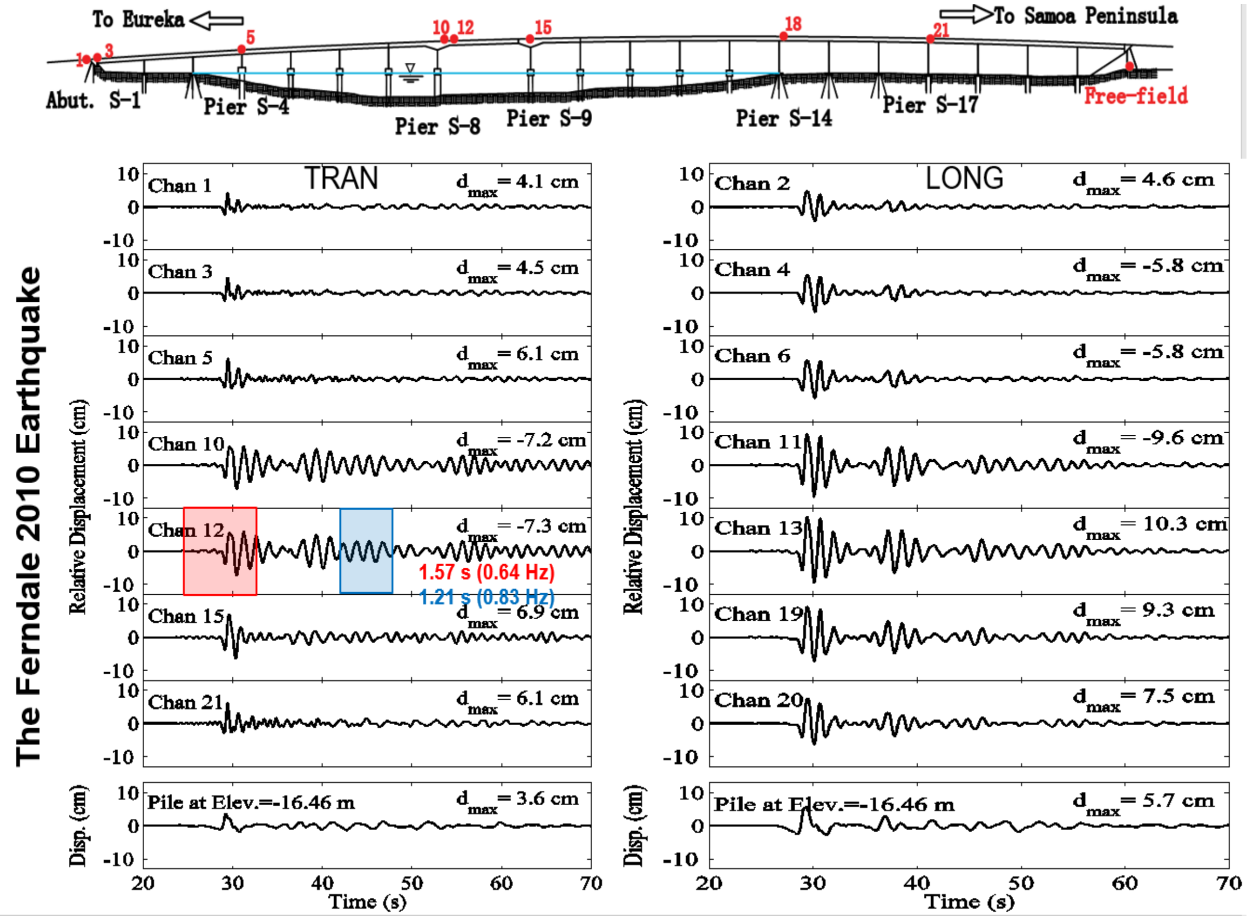


Figure 4. Motion along the Samoa Channel Bridge Deck showing variability (Wang et al. 2017) particularly as relates to the abutment (mainly in the transverse direction), and change compared to the motion at depth (reflecting resonant period of the bridge and elongation due to nonlinear response).

System Identification of the Samoa Channel Bridge Transverse motion response (Figure 5) revealed that (Wang et al. 2018):

i) Available practical guidelines concerning flexural rigidity estimates appear to be substantiated by the identified counterparts.
ii) While nonlinear response has been clearly displayed, no signs of permanent reduction in stiffness were identified to date, neither for the columns, nor for the supporting foundations.

iii) For the fully embedded pile groups, appreciable reduction in lateral stiffness was observed during the strong shaking phase of the 0.16 g PGA earthquake. The reduced stiffness was about 25 % of that during the low PGA events (Figure 5).

iv) Overall, this case history highlighted the value of strong motion instrumentation, with emphasis on the integrated monitoring of ground, foundation, and supported super-structure.

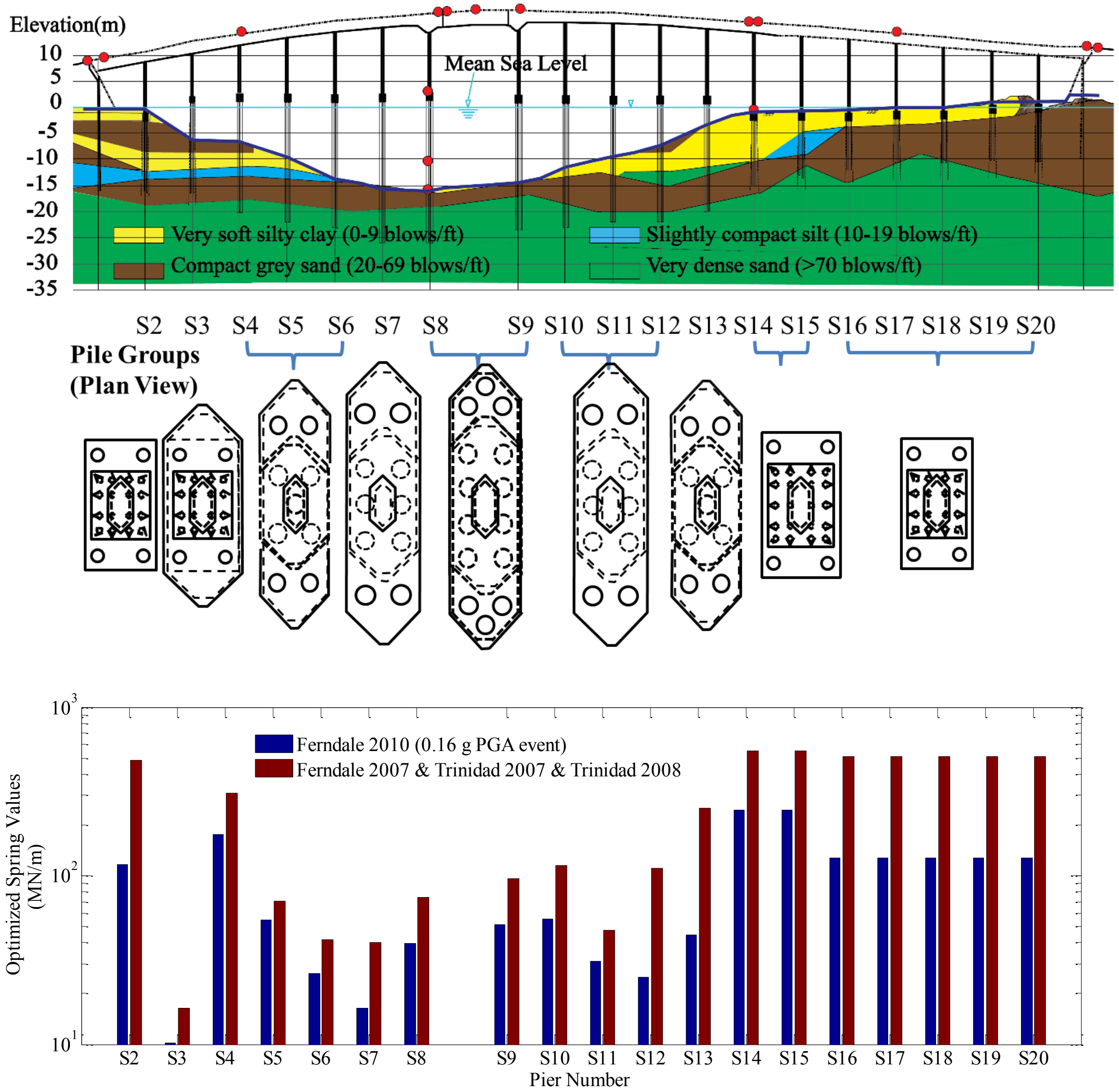


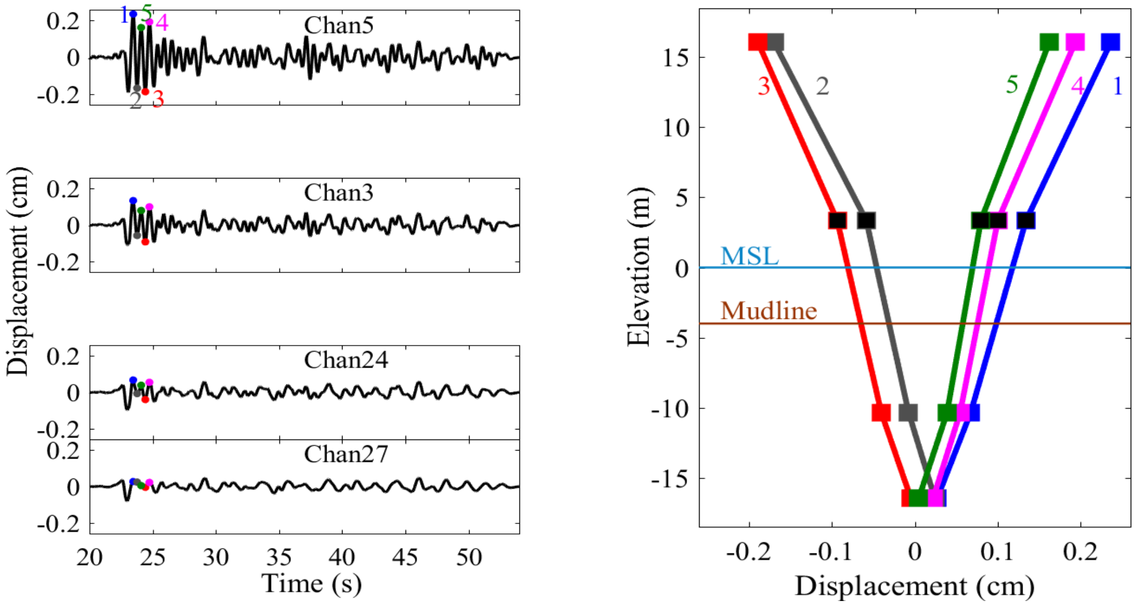
Figure 5. Samoa Channel Bridge, soil profile, pile group configurations, and identified transverse foundation stiffness (Wang et al. 2018).

Eureka Channel Bridge and Pier E7

Transverse displacement along Pier E-7 at the four instrumented elevations (Figure 3) is shown in Figure 6. In-phase response with a dominant fundamental period is evident (about 0.65

seconds). It can be seen (Figure 6) that the pile cap as well as the bridge deck displacements display a significant level of amplification. In general, the pier deformation is evenly accounted for by the column and the pile group deformations in both the transverse and longitudinal directions. This might be indicative of a less pronounced stiffness contrast between the column and pile group compared to the Samoa Channel Bridge pier S8 situation (Wang et al 2018).

Transverse Direction



Longitudinal Direction

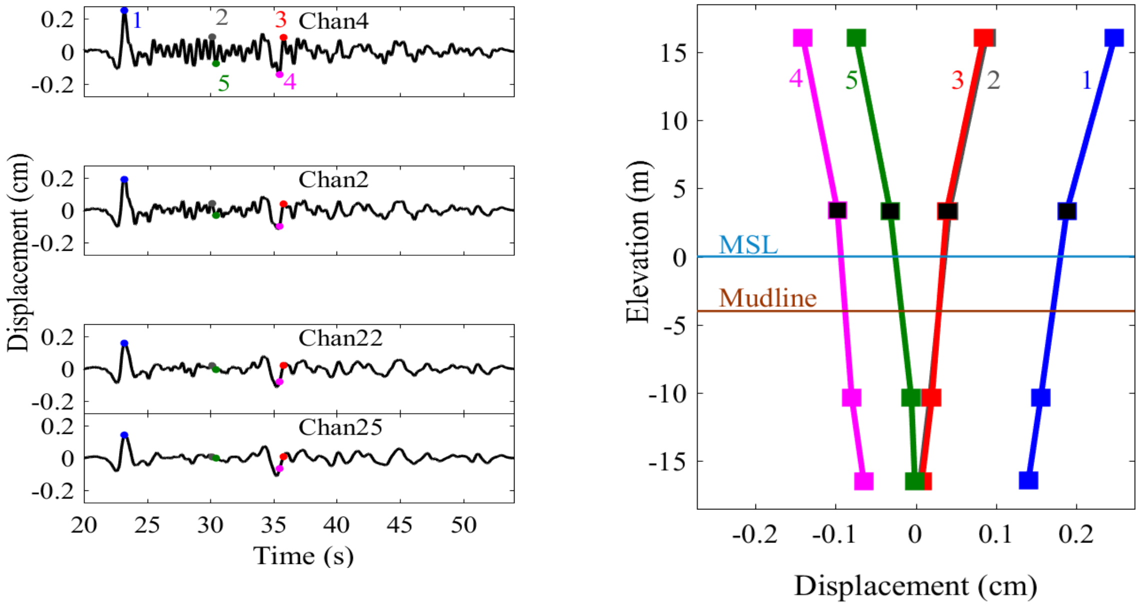


Figure 6. Time history of displacement and displaced configuration of Pier E7 at selected time instants during the 2007 Ferndale Earthquake

Eureka Channel Bridge Lateral Foundation Stiffness

A beam-column model (202 elements) representing the entire Eureka Channel Bridge with its different column heights was developed (Wang et al. 2019). The recently developed software MSBridge (Elgamal et al. 2014) was employed to generate the mesh for this curved bridge.

Focus was placed on the transverse response. Lateral springs were included at the base of the pier columns to account for stiffness of the underlying pile foundations and the associated soil-foundation-structure interaction (Lam and Martin 1986; Zafir 2002). These springs represent stiffness of the foundation down to an assumed uniform-excitation depth as defined by the recorded motion at -16.46 m. Stiffness of the lateral springs was optimized so that the computed response is compatible with the recorded motions along the bridge super-structure (Wang et al. 2019). The results shown in Figure 7 suggest (compared to the Samoa Channel bridge scenario):

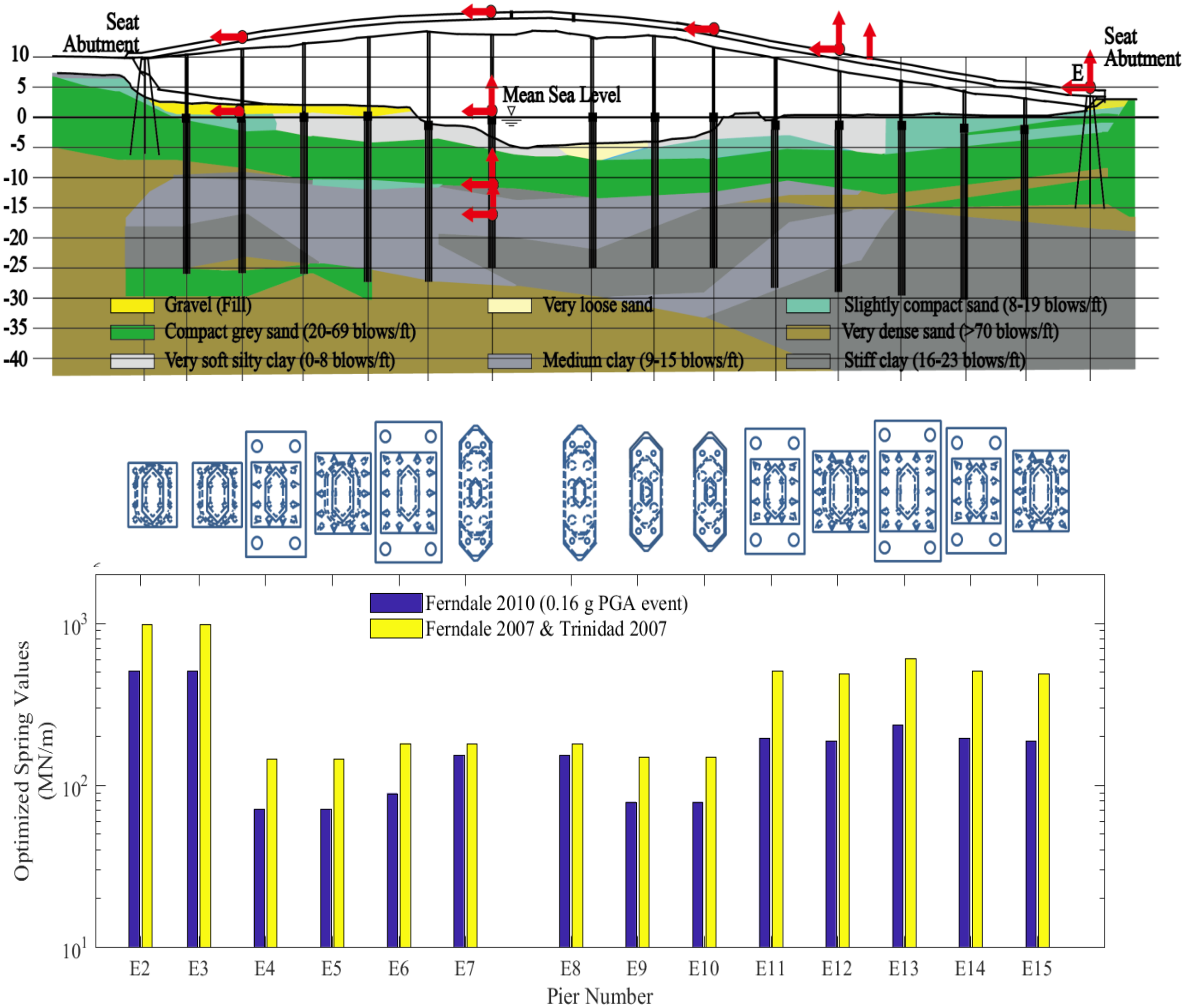


Figure 7. Identified Transverse direction base spring values along the Eureka Channel bridge

i) Foundation stiffness overall is higher,
ii) Reduction in stiffness during the strong shaking phase is pronounced, but to a lesser degree.
iii) Variability in stiffness along the bridge length is less pronounced.

Summary and Conclusions

The Eureka CSMIP seismic records (3 bridges and downhole array) constitute a unique invaluable resource for documentation of bridge and foundation response over a wide range of ground shaking scenarios. Inferred lateral stiffness of the involved pile-groups provides new insights about the actual foundation resistance at low and moderate levels of seismic excitation. These insights increase our confidence in current design/modeling assumptions, and allow for better understandings as relates to bridge response during strong earthquakes.

Acknowledgements

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