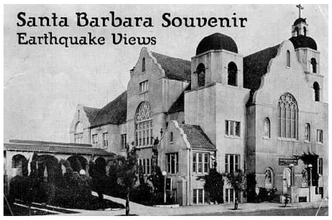

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TREASURE ISLAND GEOTECHNICAL ARRAY – CASE STUDY FOR SITE RESPONSE ANALYSIS

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ABSTRACT

Methods of site response analysis require theoretical and empirical testing and validation before they can be used in seismic hazard assessment. Comparison of site amplification function (SAF) calculated using earthquake data recorded by seismic arrays with SAF obtained using analytical approaches represent the most important tests of reliability of those methods. The Treasure Island (TI) downhole array was installed in 1992 by the California Geological Survey (CGS) to study the response of soft-soil over rock geologic structure to earthquake motion. The TI array has sensors located in the Franciscan bedrock (104 and 122 m depths), bay sediments (16, 31 and 44 m depths), artificial fill (7 m depth) and at the surface. High-quality low-amplitude earthquake data not exceeding 0.03 g recorded by the array between 1993 and 2010 were used for comparisons with the two versions of the equivalent linear (EQL) site response methods implemented in the computer program STRATA (Kottke and Rathje, 2008, 2010):

- Time Series (TS) approach
- Random Vibration Theory (RVT) approach.

Use of the TS approach in STRATA produces the same results as SHAKE, and matches well empirically determined SAF between bedrock and surface. The STRATA version of the RVT approach can produce significantly different site amplification function from the empirically determined and the TS approach when input motion is located in the downhole (within the media with up- and down-going waves). The differences in the calculations of site amplification using TS and RVT approach were also observed when both input and output motions are outcrops. Further testing of different realizations of RVT method is desirable to assess method's reliability and limitations.

Key words: *Site response analysis, Equivalent-linear (EQL) approach, Treasure Island downhole array, Random Vibration Theory (RVT)*

INTRODUCTION

Treasure Island is an artificial island in the San Francisco Bay between San Francisco and Oakland, California (Fig. 1). The island was created in 1936 and 1937, from fill dredged from the bay, for the Golden Gate International Exposition (1939 and 1940). The island is named after the novel "Treasure Island", by Robert Louis Stevenson, who lived in San Francisco from 1879 to 1880. Many places on Treasure Island (TI) near San Francisco experienced liquefaction during the M_W 6.9 Loma Prieta earthquake of 1989 (Ferrito, 1992). The Treasure Island array was installed in 1992 by the California Geological Survey (CGS) with support of the National Science Foundation (NSF) to study the response of soft-soil over rock geologic structure to earthquake motion (Darragh et al., 1993; de Alba et al., 1994). The TI downhole array has acceleration sensors located in the Franciscan bedrock (104 and 122 m depths), alluvium (16, 31 and 44 m depths), artificial fill (7 m depths) and at the surface (Graizer et al., 2000; Graizer and Shakal, 2004). In September 2003 the original digital 12- and 16-bit instrumentation was replaced with modern 19-bit instruments.

High-quality low-amplitude earthquake data not exceeding 0.03 g were recorded by the TI array between 1993 and 2010. They present an excellent opportunity for comparisons with the analytical methods of site response analysis and studies of wave field structure in complex medium (Mehta et al., 2007a, 2007b). This paper present results of testing of the Time Series (TS) and the Random Vibration Theory (RVT) approaches implemented in the computer program STRATA (Kottke and Rathje, 2008, 2010). Both TS and RVT approaches are based on the equivalent linear (EQL) method assuming vertical propagation of shear-waves. Earthquake data recorded by TI downhole array were used for site response analysis in a number of publications (e.g., Darragh et al., 1993; Darragh and Idriss, 1997; Graizer et al., 2000; Baise et al., 2003; Graizer and Shakal, 2004; Mehta et al., 2007a, 2007b).

Fig. 1. View of the Treasure and Yerba Buena Islands. Picture downloaded from http://inhabitat.com/

VELOCITY AND GEOLOGY PROFILE

Velocity and geology profiles are shown in Fig. 2. Weathered Franciscan shale and sandstone are encountered at 88 m beneath the site with more competent sandstone found at a depth of about 98 m (Darragh and Idriss, 1997). Original downhole S-wave velocity measurements were performed in the 104 m downhole by the U.S. Geological Survey (Gibbs et al., 1992). I performed new S-wave velocity averaging compared to that of Gibbs et al. (1992) based on the P-S suspension logging performed in the more recently drilled 122 m deep downhole (Graizer and Shakal, 2004). As can be seen from the Fig. 2, the main differences in the new and previous S-wave velocity averaging are in the depths of 88 m and more. P-S suspension logging demonstrates significantly higher bedrock velocity of ~ 2200 m/sec than previously assigned velocity of 645 m/sec (Gibbs et al., 1992).

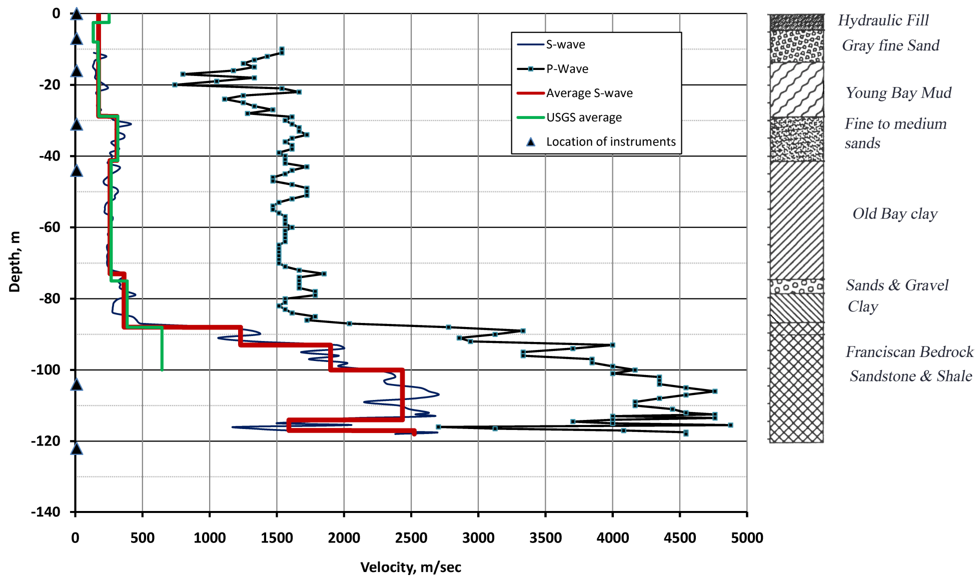

Fig. 2. P- and S-wave velocities and soil profile at Treasure Island array. Triangles show locations of the instruments.

EARTHQUAKE DATA

Since 1993, more than a dozen low amplitude earthquakes were recorded by the TI array (Center for Engineering Strong Motion Data at http://www.strongmotioncenter.org/). In this paper records of eight earthquakes with 3.6<M<5.4 are used for site amplification studies (Table 1). The strongest shaking of 0.03 g at the surface was recorded at the epicentral distance of 13.2 km from the M_W 4.0 Berkeley earthquake of September 5, 2003. The earthquake parameters were obtained from the ANSS catalog (http://www.ncedc.org/ncedc/catalog-search.html).

Table 1. Earthquakes Recorded by Treasure Island Array

Date	Time (UTC)	M	M-type	N.Lat.	W.Long.	Depth	Epi Dist	Surface PGA
1993/01/16	06:29:35.01	4.8	Md	37.018	121.463	7.7	120.2	.014
1994/06/26	08:42:50.31	4.0	Mw	37.915	122.285	6.3	12.6	.021
1998/08/12	14:10:25.14	5.1	Mw	36.753	121.462	9.1	143.8	.006
1998/12/04	12:16:07.77	3.9	Mw	37.920	122.289	6.5	13.0	.014
1999/08/18	01:06:18.94	4.6	Mw	37.907	122.686	7.9	29.0	.017
2003/09/05	01:39:53.68	4.0	Mw	37.843	122.222	11.1	13.2	.027
2006/12/21	03:12:28.76	3.6	Mw	37.857	122.245	8.8	12.6	.020
2007/10/31	03:04:54.81	5.4	Mw	37.434	121.774	10.0	68.4	.013

Figure 3 demonstrates an example of the N-S component of the recordings (acceleration, velocity and displacement) obtained during the 1999 M_W 4.6 Bolinas earthquake. Acceleration velocity and displacement at both bedrock locations (104 and 122 m depths) are almost identical, and relatively simple. The motion becomes much more complex with longer duration and few times higher amplitudes in soft material (alluvium, bay mud and artificial fill) and at the ground surface.

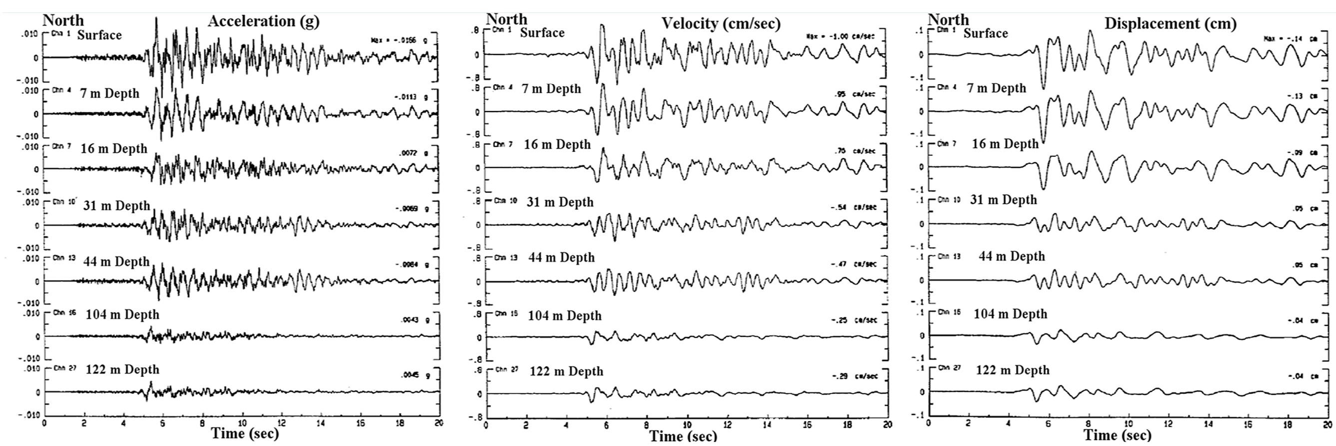

Fig. 3. Acceleration, velocity and displacement recorded at Treasure Island at the surface and depths of 7, 16, 31, 44, 104 and 122m during the M_W 4.6 Bolinas earthquake of August 18, 1999.

Fourier transfer functions from the surface to rock (104 and 122 m instruments) are shown in Fig. 4. Both horizontal components demonstrate amplification at the following six frequencies: 0.8, 1.9, 3.4, 4.4, 5.8 and 6.8 Hz. Amplifications at these frequencies are very stable. The lowest frequency (first mode) is associated with the depth of alluvium to rock interface at the depth of 88 m. Using average S-wave velocity of V_S ~ 267 m/s in the upper layer of thickness h = 88 mm, results in the resonance peak with fundamental frequency $f = Vs/4h$ (e.g., Dobry et al., 2000) of 0.76 Hz, which is fairly close to the empirical value of 0.8 Hz.

Figure 5 demonstrates an average (yellow line) and median (red line) ± one standard error response spectral ratios of surface to downhole bedrock motions. 5% damped response spectral ratios demonstrate significant variations in amplitudes (Fig. 5) between different earthquakes with the first (0.8 Hz) and the second (1.9 Hz) amplification frequencies same as at the Fourier amplification functions (Fig. 4), and the three other peaks also at close frequencies of 3.3, 4.5 and 6.25 Hz. Large variations in amplitudes of SAF are most likely due to the differences in wave propagation paths through anisotropic crust of Northern California with waves coming from different azimuths and angles. Similar type of large SAF variations during different earthquakes were also observed at the pair of Coyote Lake stations (Boore et al., 2004) and at Tarzana surface-downhole pairs of instruments (Graizer, 2009).

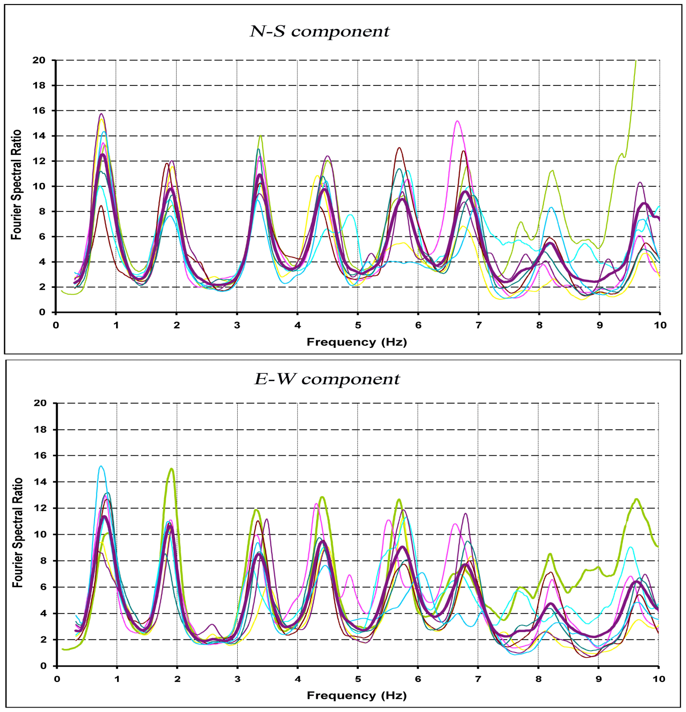

Fig. 4. Average and individual earthquake Fourier spectral ratios of surface/rock ground motion at Treasure Island

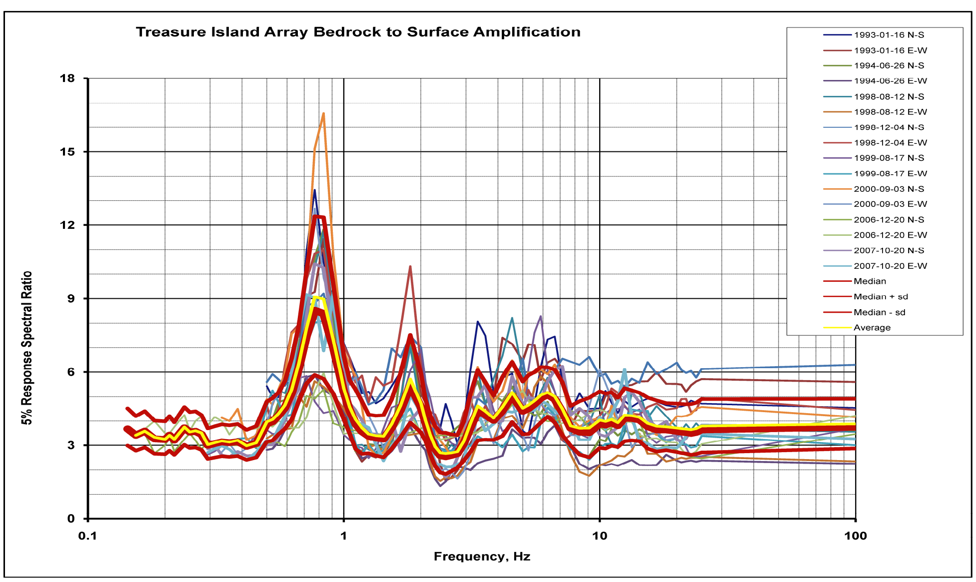

Fig. 5. Average and median response spectral ratios of surface/rock ground motion at Treasure Island

SITE RESPONSE ANALYSIS

As a first step in the site response analysis, I performed a number of comparisons between the TS version of STRATA (Kottke and Rathje, 2008, 2010) and SHAKE2000 programs (G. Ordonez, 2002). Both programs reproduce the original EQL method introduced by Idriss and Seed (1968) and implemented by Schnabel et al. (1972) in SHAKE and by Idriss and Sun (1992) in SHAKE91. Those tests demonstrated that as expected both STRATA and SHAKE2000 produce same results. EQL site response analysis uses one-dimensional, linear-elastic vertical wave propagation through layered media to model the dynamic response of the soil deposit. The method incorporates soil nonlinearity through the use of strain compatible soil properties for each soil layer.

Time Series Approach

I used acceleration data recorded at the bedrock (104 and 122 m depth) from the eight earthquakes shown in Table 1 (16 horizontal components) as an input to the STRATA TS version to calculate the surface-to-bedrock site amplification function. Other inputs used are the shear-wave velocity profile shown in Fig. 2 and the EPRI (1993) shear-modulus reduction and damping ratio curves. Figure 6 demonstrates the comparison of the empirically determined SAF (red line) and the SAF calculated using the recorded data (yellow and blue lines). The SAF calculated using the STRATA TS method matches well the empirically determined SAF. As a test of stability the yellow line was calculated using 10 out of 16 available time series as input which is not all the data used in the empirical SAF determination. The main differences between the calculated yellow and blue SAFs are at the frequencies below 0.5 Hz, and are not significant. Therefore, the STRATA TS method demonstrates stable results given use of 16 horizontal components as inputs, and SAF well matches the empirically determined SAF.

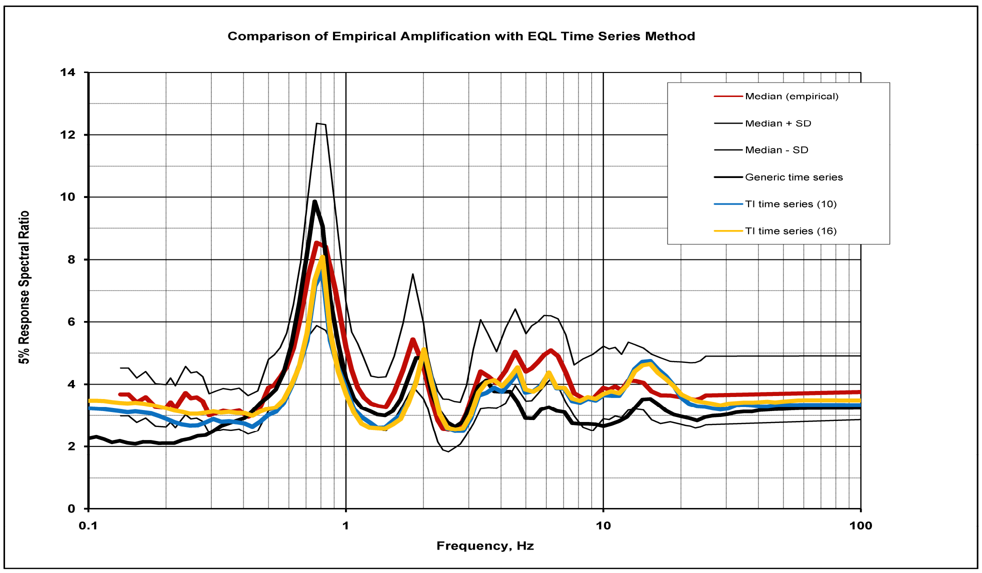

Fig. 6. Effect of number of input time series using STRATA time series approach.

To further test the STRATA TS approach, I calculated the SAF using 10 generic (not recorded at the TI array) time series scaled to the same level of PGA as input. The SAF calculated using the generic set of time series data (thick black line) is also close to the empirically calculated with peaks at the same frequencies. There is under prediction of site amplification (exceeding ± one standard error range) in the frequency range of 0.1 - 0.3 Hz and 4.5- 12 Hz.

STRATA allows profile randomization of both shear-wave velocities and layer thicknesses. Random variation of S-wave velocities in the range of their actual variations within the layers results in smoothing the SAF. In contrast, generic profile randomization of layer thicknesses developed by Toro (1995) results in a significant frequency shift of peaks (Fig. 7), and also a decrease in amplitude of the SAF. Toro (1995) proposed generic depth dependent rate model using the method of maximum likelihood applied to the layering measured at 557 sites, mostly from California. In the Toro (1995) model, the layering thickness is modeled as a non-homogeneous Poisson process where the rate changes with depth. The layering is modeled as a Poisson process, which is a stochastic process with events occurring at a given rate. Possibly, this type of randomization of layer thicknesses is useful in the situations where the site characterization is generic. For example, in cases when detailed characterization from neighboring sites is applied to nearby location. However, based on Fig. 7, randomization of layer thickness and shear-wave velocity (Toro, 1995) in cases where these parameters are well determined (typical for many recent critical facilities requiring good P- and S-wave site characterization) could result in unnecessary inaccuracies. Instead, variations of velocity and layer thickness should be based on the observed geologic and geotechnical measurements and randomization of these parameters should be based on the observed variability at a site.

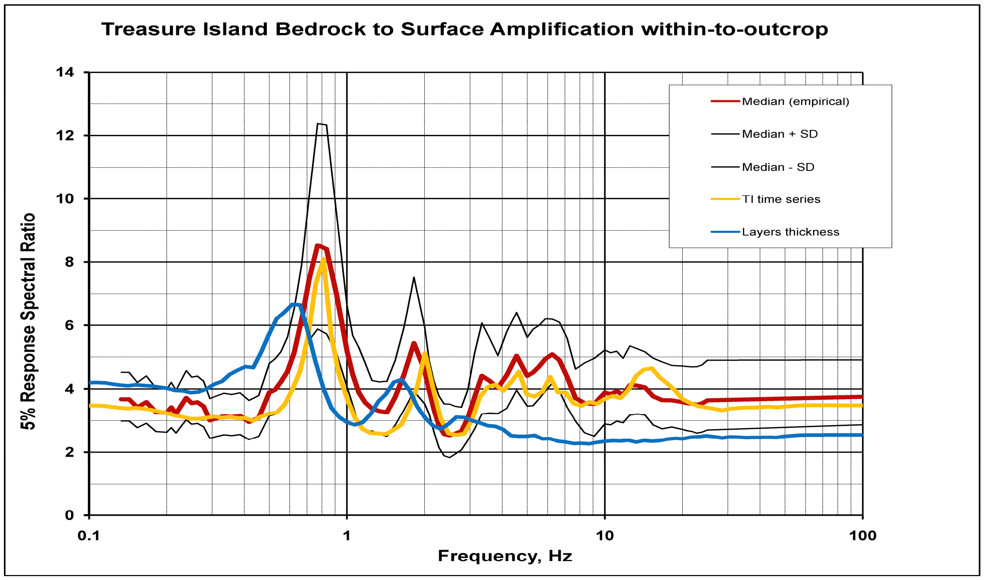

Fig. 7. Effect of varying layer thickness using STRATA time series approach.

Random Vibration Theory Approach

The EQL analysis using the RVT approach was introduced in modeling strong ground motion by Hanks and McGuire (1981), Boore (1983 and 2003), Boore and Joyner (1984), Herrmann (1985). It became even more popular in recent years because it is much less labor intensive than the classical TS approach since the RVT approach does not require choosing and matching strong motion records (Silva and Lee, 1987; Silva et al., 1997; Deng and Ostadan, 2008; Kottke and Rathje, 2008; Kottke, 2010). RVT can be applied to EQL analysis, such that only the Fourier amplitude spectrum (FAS) and the duration of ground motion are required and the selection of input motion is avoided.

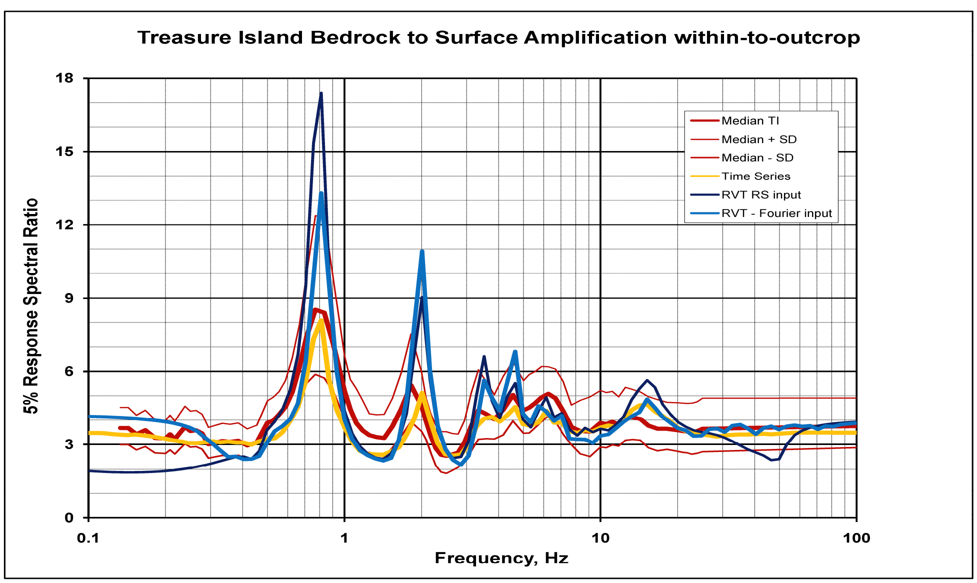

Fig. 8. Comparison of empirical site amplification function with that of STRATA time series and RVT using response or Fourier spectra as input.

It is important to remember that strong earthquake ground motions violate many of the assumption on which RVT is based including stationary and randomness of the process. Despite these problems, studies conducted by Hanks and McGuire (1981), Boore (1983, 2003), Silva and Lee (1987), Silva et al. (1997) and Deng and Ostadan (2008) indicated that RVT can be used to provide reasonable estimates of mean response of earthquake ground motions.

Figure 8 shows the SAF calculation using STRATA RVT based on TI bedrock 5% damped response spectrum as an input. The results show significant over prediction of the amplitude of the 1-st mode of the site amplification (Fig. 8, black line). Use of Fourier spectrum as an input to the RVT analysis improves the result, but still demonstrates significant over prediction (Fig. 8, blue line).

Figure 9 shows comparison of peak ground velocity (PGV) recorded at different depths during the 12/21/2006 M_W 3.6 Piedmont, California earthquake with PGVs calculated using STRATA TS and RVT approaches. Calculations performed using TS approach demonstrates good agreement with the recorded data, with RVT significantly over predicting PGV amplitudes. RVT calculations were performed twice with the Fourier and 5% damped response spectrum as inputs. RVT (with Fourier spectrum input) and time series calculations produce same results for the deep part of the profile up to the interface between the bedrock and alluvium at the depth of 88 m. In the upper part of the profile RVT calculations differ significantly from that of the TS. Using Fourier as opposed to response spectrum improves results, but still produces significant over prediction.

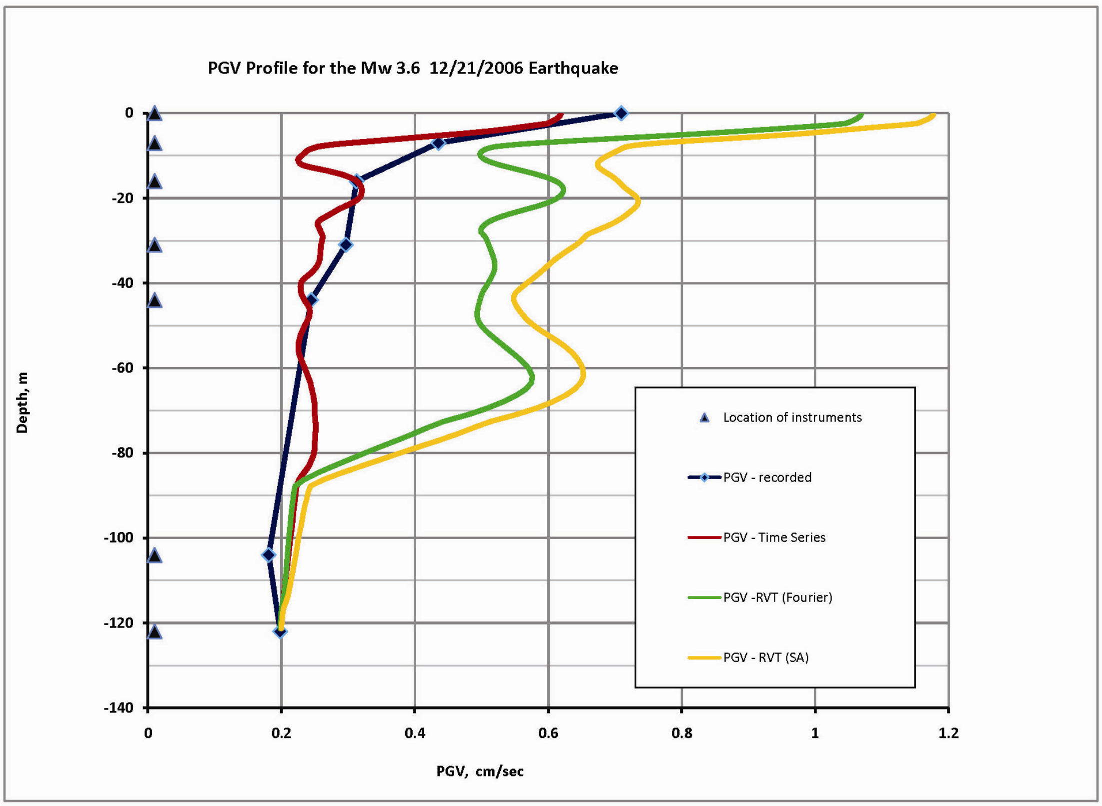

Fig. 9. Comparison of peak ground velocity recorded during the Mw 3.6 12/21/2006 Piedmont, California earthquake with that of STRATA time series and RVT approaches.

I also performed a number of comparisons between SAF calculation using STRATA TS and RVT methods for different types of profiles. Those comparisons demonstrated that the largest differences between TS and RVT results occurred when the S-wave velocity profile had large impedances between layers (Fig. 10, Profile 1). In those cases the differences between SAF amplitudes calculated using STRATA TS and RVT can exceed 30% (Fig. 10). In cases of gradient increases of velocity with depth (Fig. 10, Profile 2) the differences are smaller (less than 15%). Those results are in agreement with the results of Kottke (2010) who has shown that the surface response spectrum and associated spectral ratios computed using the STRATA RVT approach may be noticeably different (with difference as large as 30% at the first mode) than the median response computed from a suite of input motions. A number of similar comparisons performed recently as a part of the PEGASOS project (a major international seismic hazard study to assess seismic hazard at nuclear power plant sites in Switzerland) using other RVT computer codes also demonstrated significant differences between TS and RVT site amplification calculations (Renault, 2010; Renault and Hunfeld, 2011; Thomson and Boore, 2011). It is important to further investigate the source of differences between TS and RVT results, and to formulate the limitations of RVT approach.

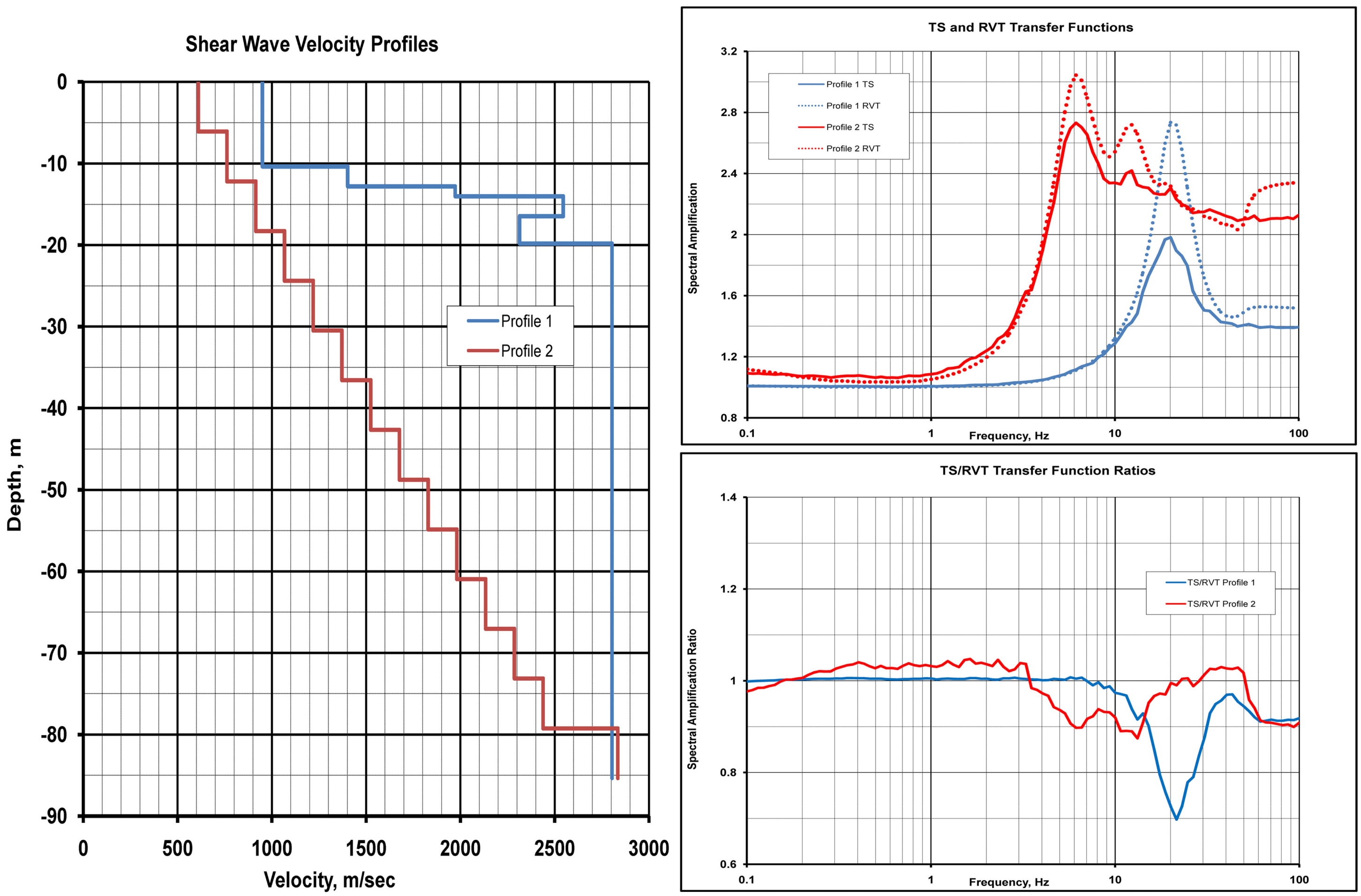

Fig. 10. Comparison of site amplification functions (5% damped SA) calculated using STRATA TS and RVT methods for two different profile types.

Yerba Buena and Treasure Island

It is important to test the applicability of the same shear-wave velocity and modulus profile to the comparison of the pair of records from the 1989 M_W 6.9 Loma Prieta earthquake recorded at the Yerba Buena (Franciscan bedrock site) and Treasure (soft soil) Island sites at the epicentral distance of 95-98 km. TI is connected by a small isthmus to Yerba Buena Island (YBI) with the distance between those sites of ~2 km. Liquefaction occurred at TI during this earthquake (Ferrito, 1992). Figure 11 demonstrates comparison of the 5% damped spectral accelerations from the Loma Prieta earthquake with that off the TI downhole array. Amplitudes of the Loma Prieta records are about an order higher than that recorded by the TI downhole array.

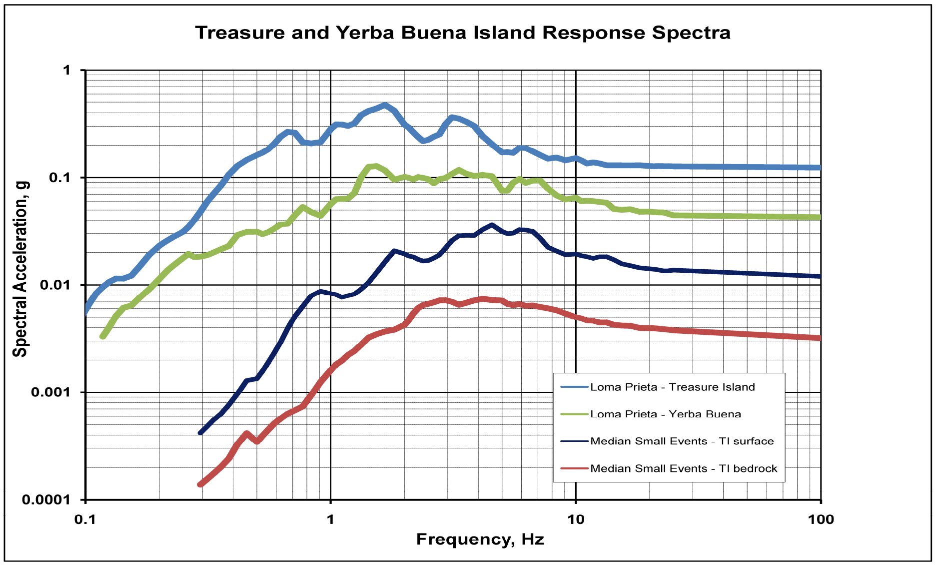

Fig. 11. Comparison of SA recorded at Yerba Buena and Treasure Island during M_W6.9 Loma Prieta earthquake (median of two horizontal components) and median response from small earthquakes recorded by the TI array.

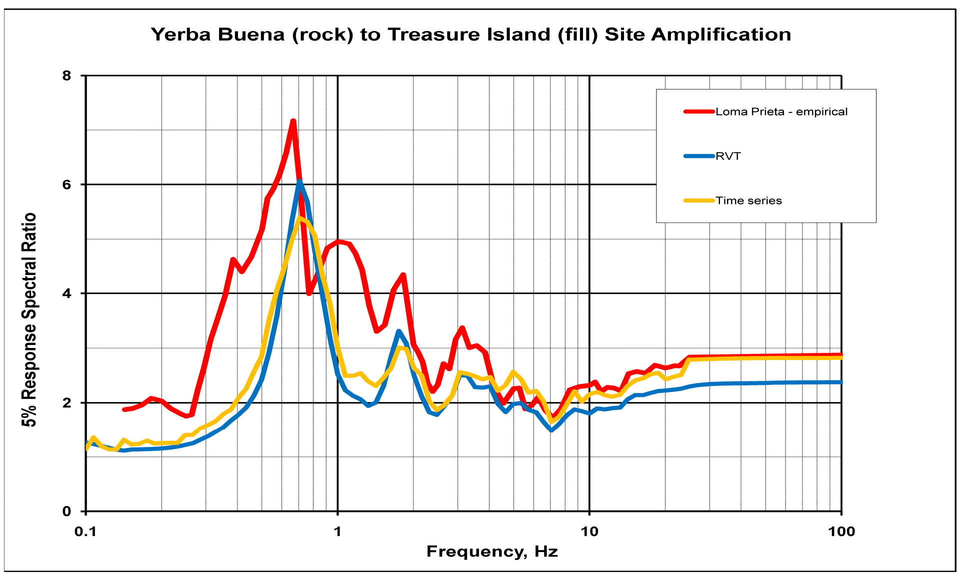

Fig. 12. Comparison of empirical site amplification function with that of STRATA time series and RVT for the YBI –TI pair.

Figure 12 demonstrates comparison of the empirical SAF for the TI-YBI pair with that calculated using the STRATA TS and RVT approaches. There are significant differences between the calculated and empirical SAF. Interestingly, in this case the difference between TS and RVT methods is not as significant as in case of TI downhole array (Fig. 8). In the case of TI downhole array the bedrock motion is located within the media with both incoming and reflected from the surface (up- and down-going) waves used as an input to STRATA. In contrast to TI downhole bedrock, YBI location represents an outcrop motion. It seems that STRATA RVT produces significantly better agreement with the TS approach when both motions are outcrops.

Figure 12 demonstrates that the YBI surface reference site used as an input for calculating TI site response (with the same soil column as at TI downhole array shown in Fig. 2) is not in complete agreement with empirical data. This is similar to the results of Baise et al. (2003), which showed that the one-dimensional approach in combination with vertical wave propagation is incapable of capturing the site response at TI beyond the initial four seconds of motion.

CONCLUSIONS

Earthquake data recorded by downhole arrays at different depths and geologic settings present an excellent opportunity to test and calibrate analytical methods of site response analysis. High-quality low-amplitude earthquake data recorded at the Treasure Island downhole array between 1993 and 2010 allow testing of those methods at low strain level.

Use of the equivalent-linear method with the Time Series approach in STRATA produces the same results as SHAKE2000 and results match well the empirically obtained surface to bedrock site amplification function. The STRATA version of SHAKE is very user friendly compared to SHAKE2000.

Random variation of S-wave velocities in the range of their actual variations within the layers results in smoothing SAF. In contrast to that, generic randomization of layer thicknesses (Toro, 1995) results in a significant frequency shifts of peaks, and a decrease in amplitude of the SAF. This type of randomization of layer thicknesses is possibly useful in the situations when site characterization is generic, for example in cases when detailed characterization from neighboring sites is applied to nearby location. Based on my tests, I do not recommend applying generic (Toro, 1995) type of layer thicknesses and S-wave velocity randomization in cases when layer and velocity profile are well determined (typical for many recent critical facilities requiring detailed P- and S-wave site characterization). I recommend applying randomization of velocity and layer thickness based on actual geologic and geotechnical measurements providing actual limits of variability.

Realization of the equivalent-linear method in combination with RVT approach in STRATA may produce results that differ significantly from the empirically determined site amplification function and Time Series approach. Those differences are larger when input motion is located within the media (with up- and down-going waves), and also when the S-wave velocity profile has large impedances between the layers. In case of gradient increase of S-wave velocity with depth both TS and RVT produce similar amplification curves with smaller differences usually not exceeding 15%. The differences in calculations of site amplification using TS and RVT approach were recently observed in other studies.

RVT approach to site response analysis became very popular in recent years because it is much less labor intensive since it does not require choosing and scaling time series. In mean time there are a number of different codes developed independently and based on different approximation formulas, and apparently producing different results (Boore, 1983; Silva and Lee, 1987; Deng and Ostadan, 2008; Kottke and Rathje, 2008). It is desirable to assess strengths and weaknesses of different implementations of the RVT method including potential limitations of the method by comparing results with recorded earthquake data.

DATA AND RESOURCES

Earthquake data used in this study were collected by the California Strong Motion Instrumentation Program (CSMIP) of the California Geological Survey. Other data used in the paper came from published sources listed in the text or in references.

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DISCLAIMER

Any opinions, findings and conclusions expressed in this paper are those of the author and do not necessarily reflect the views of the United States Nuclear Regulatory Commission.

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