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The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 - 20 June 2019.

Comparing depth-to-bedrock and fundamental-frequencies as supplement proxies to V_{S30} in site response evaluation

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ABSTRACT: Alternative proxies as supplemental to V_{S30} for site-response predictions in Israel are examined. We use a large database of local velocity profiles to compute the expected amplifications, due to the lack of empirical ground-motion measurements. Amplification is computed with respect to a new generic rock profile, defined as part of this study. We test the correlation of eight different site proxies with the computed amplification factors and show that the average shear-wave velocity (V_{S30}) best describes amplification at short spectral periods, while some measure of depth is needed to also capture amplification at long spectral periods. We discuss optional depth proxies, including depth to a certain velocity (e.g. Z_{1100}), as well as peak frequencies in the acceleration transfer function which are highly correlated with depth. The selected proxy must be a combination of high statistical correlation as well as applicability for the local engineering community.

1 INTRODUCTION

Israel is located along the Dead-Sea transform, a left-lateral fault separating the Arabian plate to the east from the African plate to the west, which constitutes the main seismic source for this region. The recurrence interval of substantial ground motions which can cause a massive destruction in this region are in the order of 10^2 to 10^3 years (Hamiel et al. 2009). Due to lack in recorded earthquakes and a sparse seismic network, the Israel building code uses foreign site factors to incorporate site effects into seismic hazard practice.

Generally, ground motions on soils will be amplified with respect to stiffer rock sites. The transition of the seismic wave through the most upper layers of the crust may result in amplification of ground motion by as much as a factor of 10 (Boore 2004). This behavior is strongly related to the mechanical properties of the geological materials within the wave's path. Therefore, if knowledge of the full velocity profile and corresponding mechanical properties can be obtained, a site-specific site-response analysis is always preferred, for an accurate evaluation of the expected seismic amplifications.

In general cases of engineering interest, in which the available subsurface information is insufficient for a full site-specific analysis, site-response is often evaluated by a proxy – a single parameter which characterizes the average expected response. One of the most commonly used parameters, which is also used in the Israel building standard (SI-413), is the time-averaged shear wave velocity in the upper 30 meters (V_{S30}). V_{S30} is considered as a good index characteristic of site stiffness for the shallow geology and was suggested as a site categorization proxy for ground motion prediction equations (GMPEs) by Boore et al. (1993). It was later adopted by most worldwide GMPEs and is still the most common proxy for site response in GMPEs (Douglas & Edwards 2016). However, recent studies have questioned its capability to evaluate site effects as a single proxy (Cadet et al. 2008, Hassani & Atkinson 2017, Kamai et al. 2016) and suggested the use of complementary parameters. Among the proposed

complementary parameters are: the depth to bedrock value, suggested by Rathje & Navidi (2013), who combined the ratio of 2 V_S values and the depth to $V_S = 1000$ m/s. Cadet et al. (2012), Di Alessandro et al. (2012) and Luzi et al. (2011) examined the fundamental frequency of a site (f_0), generally defined as $f_0 = V_S/4h$, where V_S is the shear wave velocity of a layer with thickness of h (Boore & Joyner 1997). Finally, Hassani & Atkinson (2017), offered the use of the peak amplification frequency (f_{peak}) as complementary parameter to V_{S30} , indicating its physical representation of the investigated site.

In this paper, we explore a unique velocity database for Israel and suggest alternative proxies for site-response evaluation in Israel, with an emphasis on the depth-related proxies to complement V_{S30} .

2 DATA AND METHODS

The available dataset used for this work includes 1779 velocity profiles, mostly collected by the Geophysical Institute of Israel (GII) (Hofstetter & Aksinenko 2012). The profiles were divided into two principal groups, namely: profiles containing rock surface lithologies and soil surface lithology. All velocity profiles were extracted using 4 different methods: boreholes, surface waves, refraction and Horizontal to Vertical spectral ratio (HVSr). Out of the 1779 profiles, 206 profiles were used for the definition of the reference rock sites in an earlier stage of this study (blue line in Figure 1a). The remaining soil profiles were used for Spectral accelerations (Sa) and Fourier Amplitude Spectra (FAS) calculations, which were then divided by the evaluated acceleration spectra at the surface of the generic reference rock profile. The site response analysis was calculate using the computer program STRATA under 1D and linear elastic assumptions (Kottke & Rathje 2008). We used the random vibration theory (RVT) with a moderate magnitude value of 6.5 at a distance of 20 km. Such approach required all profiles to reach the same velocity at depth. Therefore, all profiles were extended to meet the reference rock velocity profile at 4 km depth. The near-surface profiles were then divided into four categories by their V_{S30} , according to the NEHRP classification (Table 1), and the average velocity profile was calculated for each group. All of the average soil profiles happened to reach a common shear-wave velocity of approximately 1100 m/s at a depth of 550 m. Therefore, all four ‘generic soil’ profiles were extrapolated to reach the generic rock profile, using 8 steps of increasing velocity, up to a velocity of 3200 m/s at depth of 1500 m, following the crustal velocity model of Kennett (1991) and Wetzler & Kurzon (2016). The remaining of the

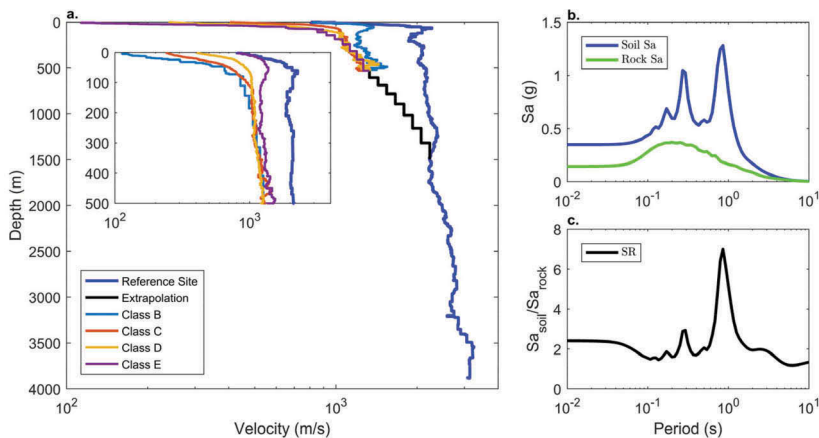


Figure 1. a. Velocity profiles used in this study: The Generic reference rock profile (in blue), alongside the average soil profiles, classified into 4 NEHRP classes and the artificial interpolation between the rock and soil profiles (in black). b. An example of the surface Sa for a single soil site compared to the reference rock spectra. c. The spectral ratio – SR associated with the respective soil profile.

Table 1. NEHRP Classification by V_{S30} as used in the Israeli building codes, and their corresponding amplification factors that are computed relative to a reference rock site with $V_{S30} = 760$ m/s, suitable for relatively low acceleration values and short periods (Martin & Dobry 1994).

NEHRP classification	Description	V_{S30} (m/s)	Amplification factors for $SS \leq 0.17$
A	Hard rock	$1500 <$	0.8
B	Rock	760-1500	1
C	Very dense soil and soft rock	360-760	1.2
D	Stiff soil	180-360	1.6
E	Soil	$180 >$	2.5

profile then followed the generic reference rock down to depth of 4 km. The four generic soil profiles, including their extrapolation to depth are presented in Figure 1a. Site response is presented here in manners of Spectral Ratios (SR) in favor of future engineering applications. The procedure is displayed in Figure 1b and was repeated for all soil profiles.

3 RESULTS AND DISCUSSION

Six different proxies were compared to the amplification factors and a linear fit from the general form of $\log(y) = a \cdot \log(x) + b$, shown by the solid line in Figure 2a, was applied. Figure 2a shows a good correlation between the amplification and V_{S30} proxy at short spectral periods, which weakens at longer spectral periods (e.g. $T > 0.1$ s). Figure 2b shows the correlation factor R^2 for five different V_S proxies, which differ from each other by the depth of which the average velocity was calculated for. In addition, a depth related proxy was correlated to the amplification, defined by the depth to the estimated reference conditions of $V_S = 1100$ m/s (Z_{1100}). Figure 2b shows a strong correlation of all V_S proxies at short periods, with a sharp drop at around $T = 0.1$ s. The correlation improves again at approximately $T > 0.5$ s, showing a stronger correlation as the weighted depth of the V_S proxy increases, suggesting the contribution of deeper portions of the profile to the amplification. In addition, the correlation to Z_{1100} is significantly favorable at long spectral periods ($T > 2$ s). Therefore, we suggest combining V_{S30}

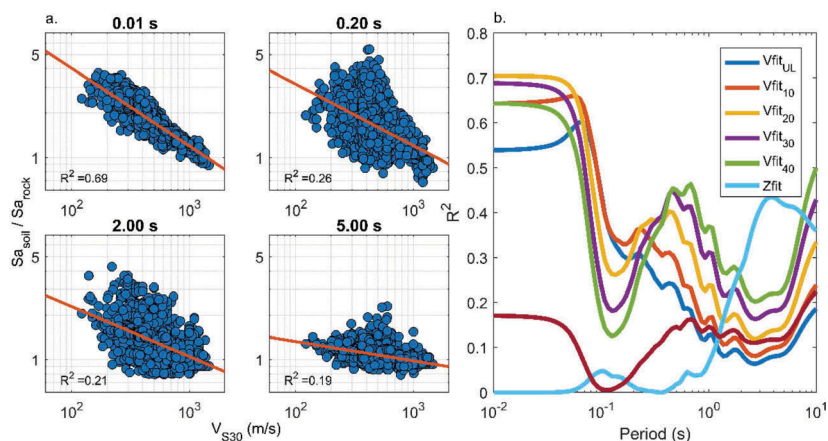


Figure 2. Correlations between calculated amplification and six optional site proxies. a. The correlation with V_{S30} for four spectral periods. In red, the linear fit and its corresponding coefficient of determination. b. Coefficient of determination for six alternative proxies, across the full period range: $V_{fit_{UL}}$: the shear wave velocity of the most upper layer; $V_{fit_{10}}$, $V_{fit_{20}}$, $V_{fit_{30}}$ and $V_{fit_{40}}$: the weighted average of the upper 10, 20, 30 and 40 m, respectively; Z_{fit} : the depth at which the velocity reaches the evaluated reflector velocity of 1100 m/s.

proxy, together with a depth related proxy to improve the amplification prediction at long spectral periods.

In this paper, we compare four different depth related proxies, including: depth to evaluated reference conditions of 1100 m/s, as suggested by our definition of the local reference rock, depth to 1900 m/s, as shown by Gvirtzman (2004), the fundamental frequency (f_0) and the peak site frequency (f_{peak}).

While the depth to reference velocities showed relatively good correlations for the long periods, there are two deficits regarding its use. First, the depth at which the profiles reach the bedrock velocity may in some cases be an outcome of the extrapolation of the shallow profiles (see Figure 1a) such that it does not necessarily reflect the actual measured profile. Also, in some regions in Israel, such as the Coastal Plain, the main reflector is typically associated with a lower-velocity geological unit ($V_S \approx 700$ m/s). This means that the depth to 1100 m/s does not really represent the main subsurface reflecting unit and thence the correlation with the amplification is expected to be weak. Second, and for practical reasons, it is advisable that the complementary proxy will be easily evaluated. However - the depth to 1100 m/s or 1900 m/s will not always be practical to evaluate, especially at very low-velocity, deep sedimentary sites. Therefore, we examine the amplified frequencies, obtained from the ATF calculations, as a complementary proxy for V_{S30} , designed to evaluate site responses while lowering the uncertainties.

Similar to previous studies which have suggested the use of f_0 as a complementary or replacement proxy for V_{S30} (e.g. Castellaro & Mulargia, 2013, Luzi et al. 2011, Cadet et al. 2008), our calculated amplification factors were correlated to the corresponding f_0 (Figure 3). We defined f_0 as the first peak of the acceleration transfer function above amplification factor of 1.4. Figure 3 shows a relatively good correlation between the SR and f_0 for the long spectral periods, in which the maximum amplification is obtained at the respective period of interest (e.g. $T=5$ s peaks at $f_0=0.2$ Hz). The short spectral periods, however, are less correlated and amplification seems to be dominated by V_{S30} (represented by the symbol color in Figure 3) rather than by f_0 .

Comparing f_0 to Z_{1100} and Z_{1900} (Fig. 4) demonstrates a weak correlation, suggesting that f_0 values are determined by higher velocities, originating at deeper parts of the profiles and hence may be hard to account for in practice. As mentioned in the introduction, all velocity profiles were extended to a great depth of 4 km and therefore, the observed f_0 might not represent the true profile properties. Additionally, the parameter f_0 was chosen in an arbitrary way

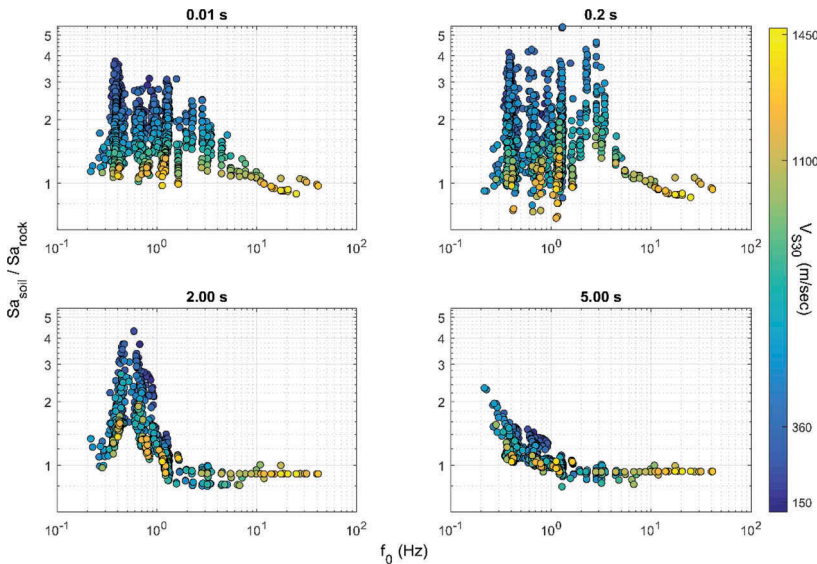


Figure 3. SR f_0 correlation. The colors representing V_{S30} values which were added as an additional argument for future correlation purposes.

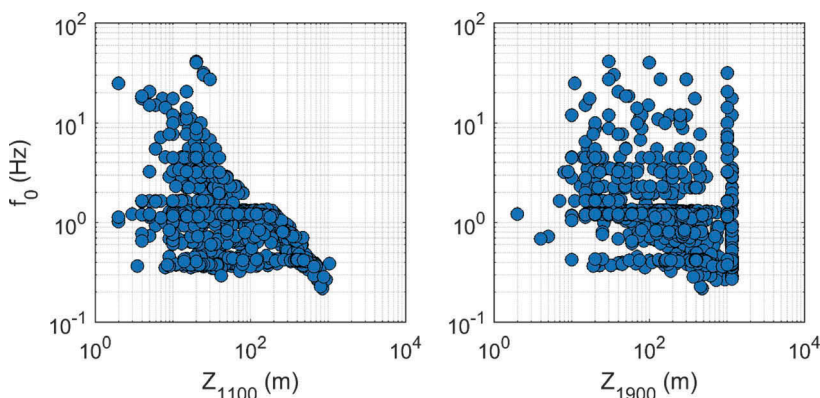


Figure 4. Correlations between f_0 and depths to a certain velocity parameter, refer to the dominated reflectors in Israel.

by picking the first significant peak ($ATF > 1.4$) for each of the calculated site responses, whereas most of the profiles experienced a more significant amplification at higher frequencies.

The parameter f_{peak} , defined as the frequency at which the amplification spectra peaks, is typically associated with the strongest impedance ratio within the velocity profile. This impedance contrast could potentially occur at the deepest bedrock contact but could also occur much shallower in the profile. Figure 5, presenting the correlation between f_{peak} and f_0 , demonstrates the variability in the peak frequency for the fundamental frequency (f_0), suggesting that f_{peak} in most of our profiles is associated with shallower depths, thus highlighting the significant effects of the shallow subsurface layers on site response.

The correlation of the amplification factors to f_{peak} is presented in Figure 6. In this figure, all profiles are presented as symbols, colored according to their respective V_{S30} value. In

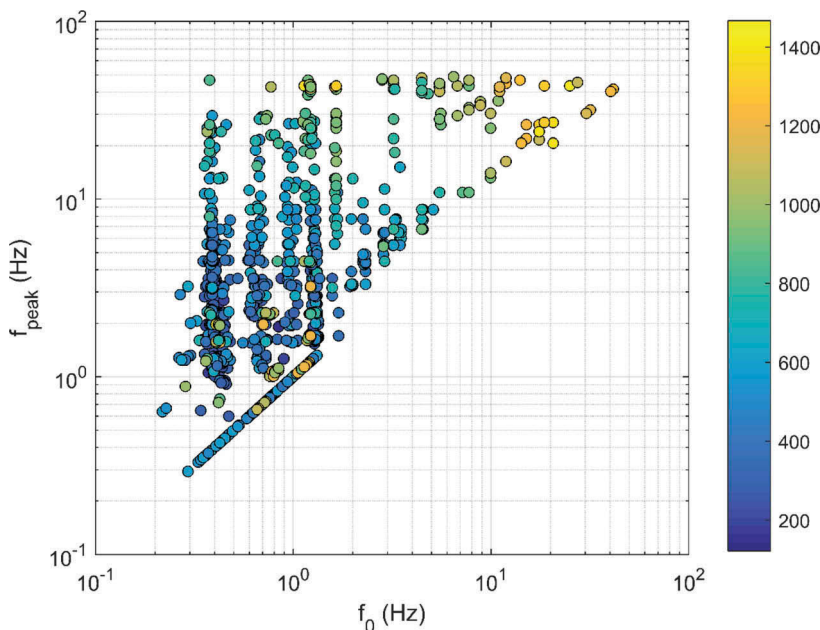


Figure 5. Correlation between f_{peak} and f_0 , showing weak fit between the two parameters, the colors represent the profile V_{S30} values.

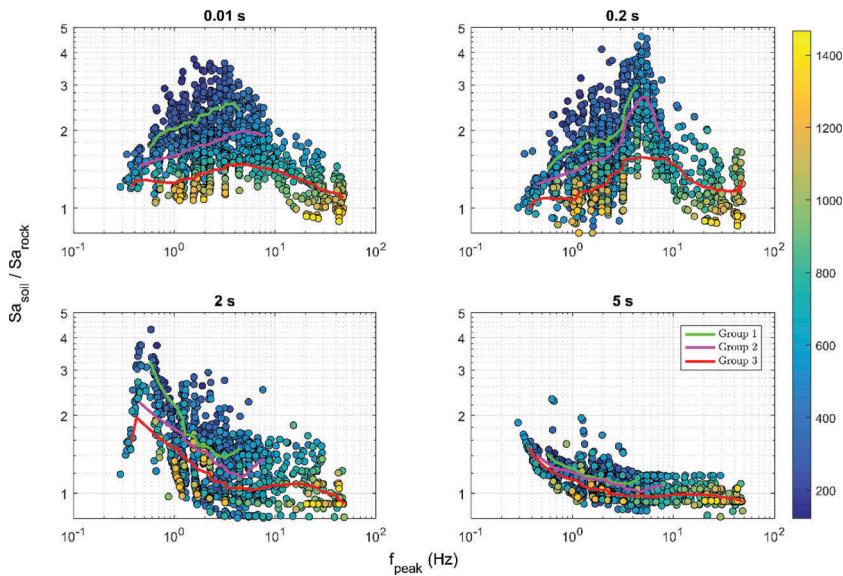


Figure 6. correlation between the SR and f_{peak} , the three groups represent the median values of V_{S30} , green curve for $V_{S30} < 450$ (m/s), magenta curve for $450 \leq V_{S30} < 600$ (m/s) and red curve for $600 \leq V_{S30} < 1500$ (m/s).

addition, the dataset was divided into three subgroups: group one includes all profiles with $V_{S30} < 450$, group two includes profiles with $450 < V_{S30} < 600$, and group three includes profiles with $600 < V_{S30} < 1500$ m/s. The solid lines in Figure 6 represent the average, smoothed, amplification ratio, calculated separately for each group. At the shortest spectral periods ($T = 0.1$ s)– there is a clear difference between the average amplification of the three subgroups, with very little dependence on f_{peak} . On the other hand – at the longest spectral period ($T = 5$ s) there is almost no difference between the V_{S30} groups, but they all show the same shape with respect to f_{peak} . In the two intermediate periods, the behavior is transitional, showing a dependence of both V_{S30} and f_{peak} : The site amplification of the three subgroups are approximately parallel, showing a steep increase towards a maximum value at the spectral period of interest, after which a non-linear reduction is observed. It is clear from this figure that the amplification is highly dependent on V_{S30} at short periods but more sensitive to f_{peak} at long spectral periods. Hence, we suggest that a combination of both proxies would yield an optimal site-characterization model for the velocity profile database presented in this study. Hassani et al. (2017) made use of this comparable behavior and suggests using f_{peak} as the primary parameter, along with V_{S30} , for site response estimation in Central and Eastern North America.

4 CONCLUSIONS

In this paper, we analyze a large velocity-profile database for Israel and compute the expected surface-to-surface amplifications, with respect to a new generic reference rock profile. We then test the correlation to six different site proxies and conclude the following:

- The use of a double proxy that includes both V_{S30} and an additional depth related proxy would be more effective in predicting site-response and hence is favorable for the use in local codes.
- Depth related proxies show poor results to our datasets, partly due to the way we calculate the amplifications (outcrop to outcrop) and due to the large depths represented by f_0 in our dataset.

- Both the f_0 and f_{peak} parameters can be evaluated relatively easily using non-intrusive measurements. On the other hand, depth proxies are more limited, because (a) the depth to rock velocity can sometimes exceed investigation depth such that the proxy becomes a rough estimation, and (b) the reference velocity is an arbitrary choice, which may sometimes be very different than the actual layer causing the main amplification at a site.
- Out of four depth related proxies, f_{peak} was found to be the most correlative proxy and most objectively defined.
- Additional work is required in order to create a continuous function that includes both proxies.

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