Paper:

Evaluation of Surface Soil Amplification for Wide Areas in Lima, Peru

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In order to create a soil amplification map for Lima, Peru, parameters that correlate best with amplification are examined. Shallow shear wave velocity profiles estimated from MASW measurements at 105 sites were used to provide amplification factor *AvTF*. *AVs10* seems to be the best value for estimating amplification in Lima from the data available. We have attempted to create *AVs10* map correlating three parameters – elevation, H/V peak period, and soil type. From this *AVs10* map, we have estimated an amplification map for Lima.

Keywords: microzonation, soil amplification, *AVs30*, shear wave velocity, H/V spectrum

1. Introduction

Lima, the capital of Peru, is located on the central western side of the South American continent, bordered by the Pacific Ocean in a zone of high seismic activity known as the Pacific Ring of Fire.

There are seismic microzonation maps for Lima proposed by CISMID in 2005 [1]. The dynamic analyses involved in their constructions were very general, however, and results did not consider a map of soil amplification.

Amplification factors were identified at specific places from the observation of transfer functions calculated either from arrays of microtremors or MASW measurements. An amplification map for Lima cannot be derived from these scarce transfer functions and, for this reason, a proposal for correlation among other available parameters in the city – such as soil type, elevation, and H/V peak period – and amplification is sought.

It is generally known that soil amplification can be estimated using the shear wave velocity of the surface layer [2]. Recent years, a number of studies on microzonation have taken into account the value of *AVs30* (the average of the shear wave velocity profile for the first 30 meters) as a way to estimate amplification or to perform site classification (e.g., [3, 4]).

The value of *AVs30* was first proposed by Joyner and Fumal in 1984 for the prediction of ground motion [5]. Since then, the value *AVs30* has been adopted by some building codes; for example the International Building Code [6].

Some authors, however, have criticized the use of *AVs30* and proposed to use the depth of 10 m instead of 30 m in some cases that the soft soil layer is thin in the area (e.g., [7, 8]).

In this study, the performance not only of *AVs30* but also those at other depths in Lima are examined in order to find the parameter that correlates best with amplification. From the data available, *AVs10* seems to be the best value for estimating amplification in Lima, and we have therefore attempted to create a *AVs10* map for the city correlating three parameters – elevation, H/V peak period, and soil type. From this *AVs10* map, we have estimated an amplification map for Lima.

2. Relationship Between Amplification and Shear Wave Velocity

2.1. Average Shear Wave Velocities in Lima

Measurement using the multichannel analysis of surface waves (MASW) method was conducted, and estimated shear wave velocity profiles are available at 105 locations in Lima (**Fig. 1**). In **Fig. 1**, the values of *AVs30* calculated from the profiles are shown on a soil classification map [1]. *AVs30* was divided into intervals according to IBC classification [6].

Comparing soil classifications of CISMID [1] and of IBC [6], it is easy to find that an important number of *AVs30*'s overestimate the soil characteristics in Lima. *AVs30* in what is considered to be a swampy soil deposit by CISMID, for example, is classified as a stiff soil deposit by IBC.

Figure 2 shows estimated shear wave velocity profiles derived from MASW measurement at 20 typical sites. In most cases, velocity reached about 400 m/s at a depth of about 10 m. For a depth of more than about 15 m, velocity did not vary that much.

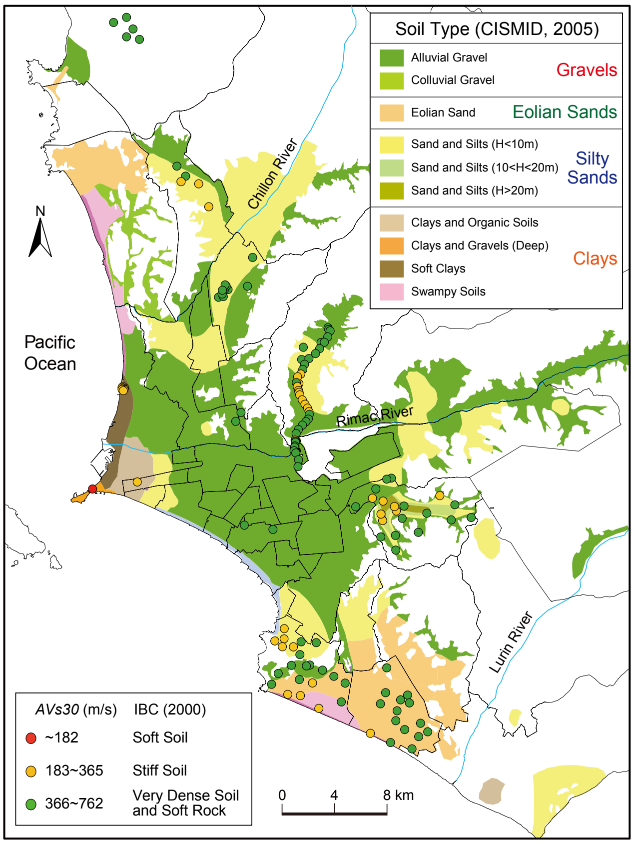

Fig. 1. Location of MASW measurements with *AVs30's* over soil distribution map by CISMID [1].

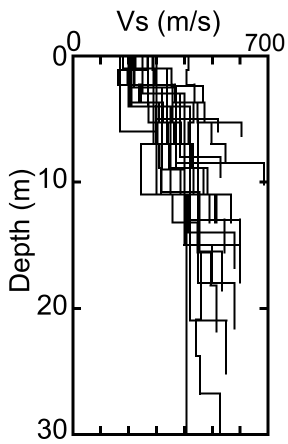

Fig. 2. Estimated shear-wave velocity profiles derived from MASW measurements.

As a result, the convenience of using *AVs30* for other purposes such as for the calculation of amplification becomes doubtful and in consequence, other depths for *AVs* calculation are examined. *AVs05*, *AVs10* and *AVs20* were thus calculated.

2.2. Amplification Factor

For an evaluation of amplification, peak values or peak periods of transfer functions between surface and bedrock are usually observed. These values can be very confusing, however. That is, despite the same peak period being found in transfer functions at different sites, the peak value was not necessarily the same. For this reason, another parameter that takes into account the peak period and peak value of transfer functions was introduced. This parameter is called the average transfer function (*AvTF*).

To calculate *AvTF,* transfer functions between the ground surface and engineering bedrock with shear wave velocity of about 500 m/s are calculated using 105 profiles from MASW measurement.

Figure 3 shows calculated transfer functions using 20 profiles from the 20 sites in **Fig. 2**. Because of high stiffness and low thickness of surface soils to engineering bedrock at these sites, peak periods are shorter than 0.3 s. For a period of more than 1 s, ground motion could not be amplified.

The formula for calculating *AvTF* is similar to seismic intensity calculation [9]. That is, it is the area of transfer function.

The formula adapted to calculate average transfer function (A_vTF) is

$$AvTF = \frac{1}{0.95}\int_{0.05}^{1.0} TF(T)dT \quad \ldots\ldots\ldots \quad (1)$$

where *TF* is the transfer function and *T* is period.

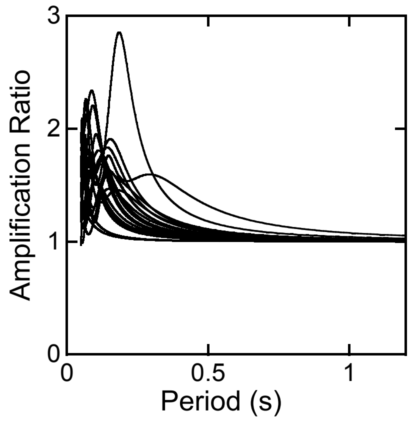

Fig. 3. Estimated transfer functions based on MASW measurements.

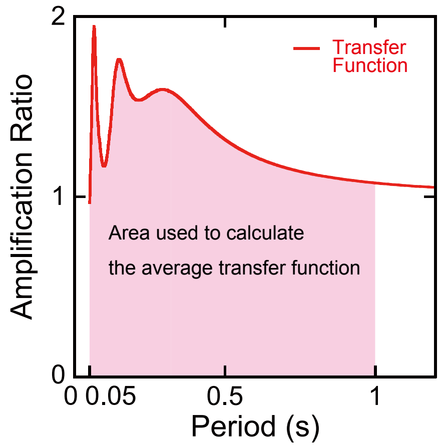

Fig. 4. Transfer function showing the area used to calculate the average transfer function (*AvTF*).

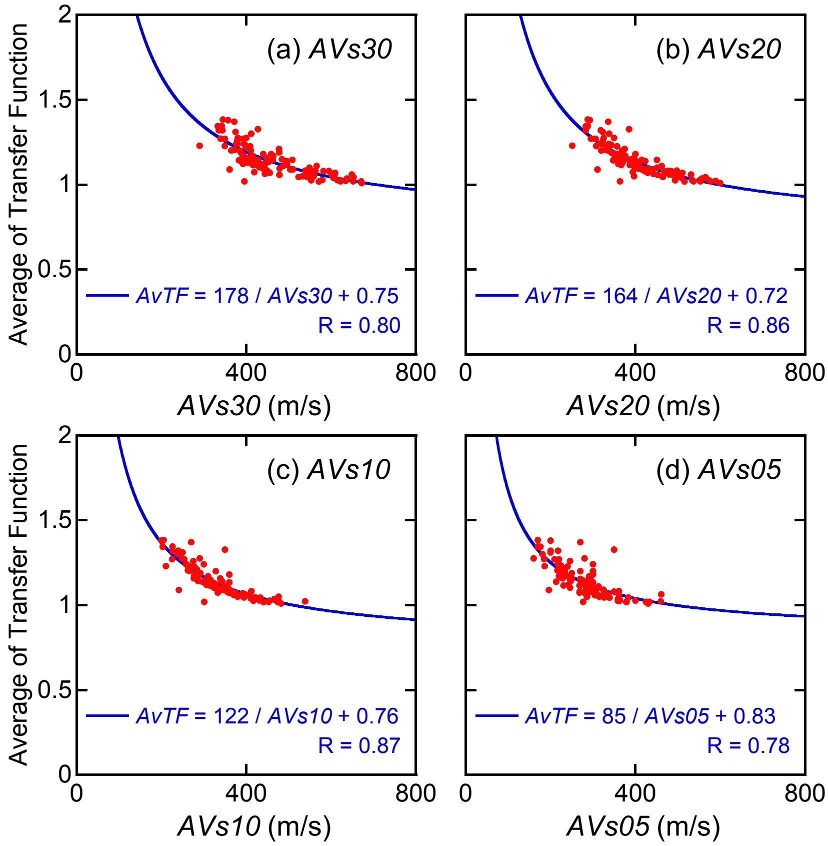

Fig. 5. Correlation between *AvTF* and *AVs30*, *AVs20*, *AVs10* and *AVs05*.

Figure 4 shows an example of the area used to calculate the average transfer function.

2.3. Correlations Between Average Velocity and Average Transfer Functions

Average shear wave velocities *AVs30*, *AVs20*, *AVs10* and *AVs05* and their corresponding *AvTF* for 105 profiles are correlated and shown by red dots in **Figs. 5(a)**, **(b)**, **(c)** and **(d)**, respectively. There seems to be an inverse proportion between *AVs* and *AvTF*. In the figure, fitted curves are also shown with correlation coefficients. *AVs10* vs. *AvTF* is the one that shows better correlation. **Fig. 5(c)** shows the approximation formula in the following equation:

$$AvTF = 122/AVs10 + 0.76 \quad \quad (2)$$

This formula will be used later to create the amplification map for the city.

3. Estimation of Average Shear Wave Velocity

Since the number of points for which *AVs10* was calculated is not enough to create *AVs10* map of the whole city and since there are other parameters available for Lima, such as elevation with a posting interval of 1 arc-second [10], soil types (**Fig. 1**) and H/V peak periods from microtremor measurement [1] (**Fig. 6**), the correlation be-

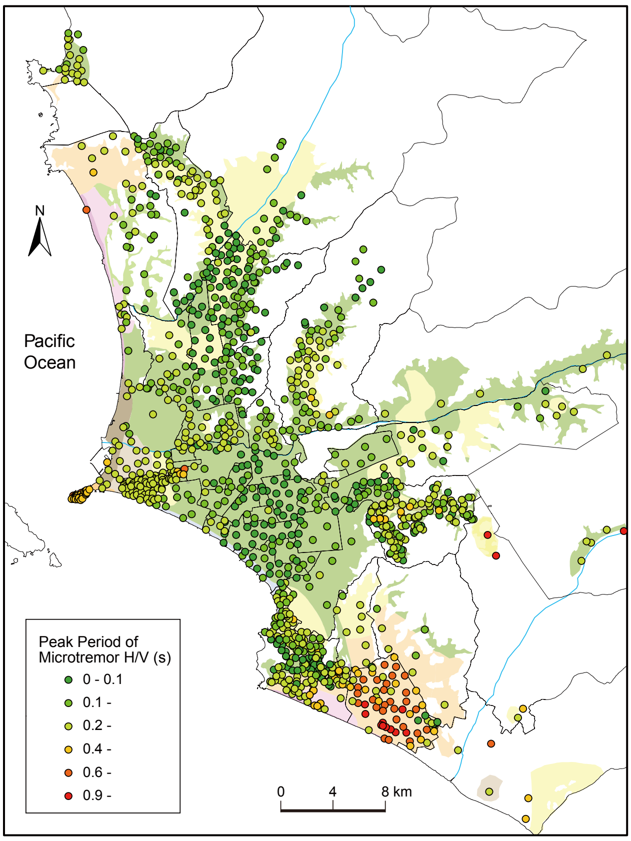

Fig. 6. Distribution map of microtremor H/V spectral peak periods [1].

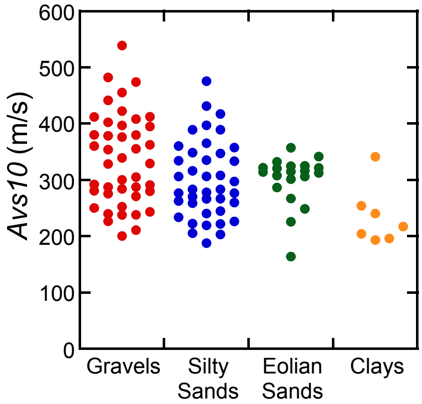

Fig. 7. Distribution of *AVs10* values with the soil type.

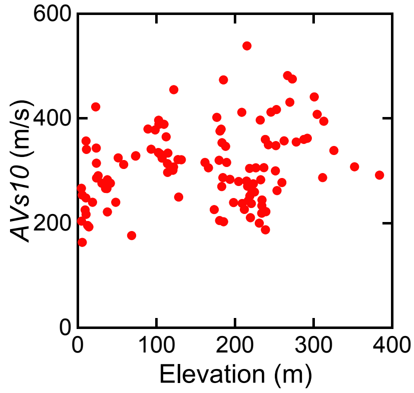

Fig. 8. Distribution of *AVs10* values with the elevation.

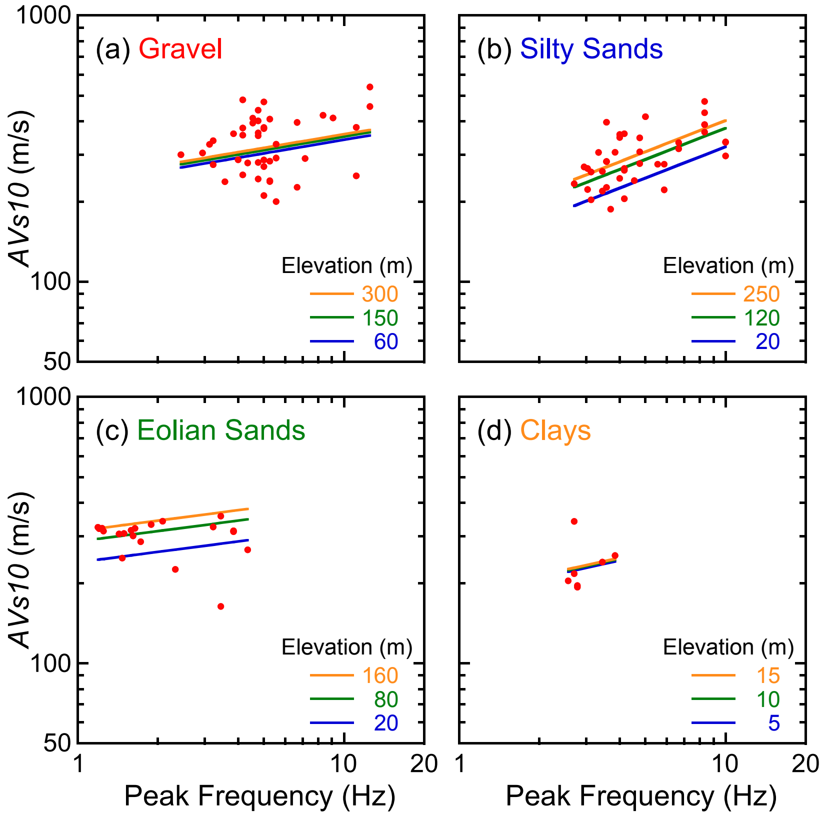

Fig. 9. Correlations of *AVs10* values with the peak frequency (inverse of the H/V spectrum peak period) for the soil types.

tween these parameters and *AVs10* are examined.

The 105 points where *AVs10* were available have also received values of elevation, H/V peak period and soil type. A correlation will be attempted using these data.

Soil class is a parameter considered for the estimation of *AVs10*. CISMID developed a soil classification map [1] (**Fig. 1**) containing more than 10 soil types. In order to simplify calculation, soil types were grouped into 4 – gravels, sandy silts, eolian sands and clays, as is shown in **Fig. 1**.

Figure 7 shows the correlation between soil types and *AVs10* values. Eolian sands are distributed mostly in the vicinity of 300 m/s. In the case of gravels and silty sands, in contrast, no single *AVs10* value can be identified. One reason for this may be that the value of *AVs10* for gravels and silty sands is governed by other parameters not yet considered here.

Figure 8 shows the correlation between elevation and *AVs10*. *AVs10* can be observed to increase with elevation. This trend is expected because soils found at high elevations in Lima are usually shallow and stiff.

Figure 9 shows the correlation of *AVs10* values with peak frequency (the inverse of the H/V spectrum peak period) for each of the four soil types. Trends are observed in which *AVs10* increases with an increment in peak frequency for the four soil types.

Analyses of multiple correlations between *AVs10*, frequency and elevation were carried out for the four soil

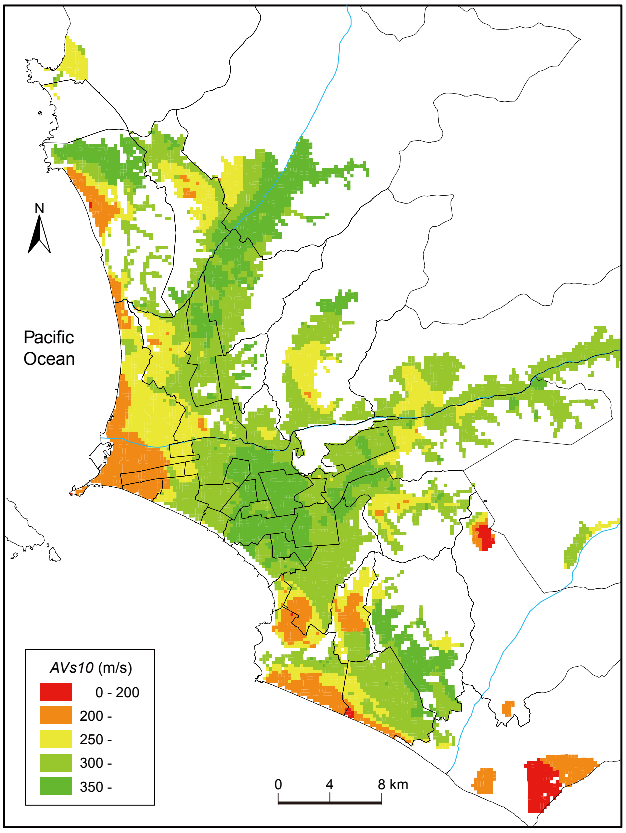

Fig. 10. *AVs10* map for Lima.

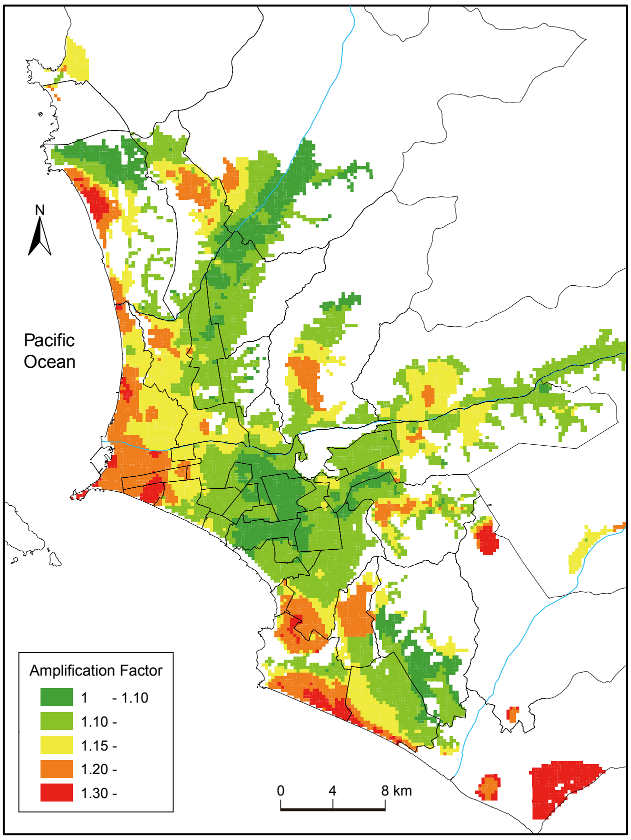

Fig. 11. Soil amplification map for Lima.

types, as shown in **Fig. 9**. Approximation formulas are listed in following equations:

Gravels:

$$\log(AVs10) = 0.16\log(f) + 0.03\log(z) + 2.31 \quad (3)$$

Silty Sands:

$$\log(AVs10) = 0.39\log(f) + 0.09\log(z) + 2.00 \quad (4)$$

Eolian Sands:

$$\log(AVs10) = 0.13\log(f) + 0.13\log(z) + 2.21 \quad (5)$$

Clays:

$$\log(AVs10) = 0.22\log(f) + 0.02\log(z) + 2.24 \quad (6)$$

where f is the peak frequency of the microtremor H/V spectrum and z is elevation.

As is seen from **Fig. 9**, in the case of gravels and clays correlations are not highly influenced by elevation. In the case of silty and eolian sands, in contrast, the elevation value has a high influence. In addition, because the number of data for the clay soil type examined is small, uncertainty may be introduced in the correlation equation.

It is also observed that the slope of the correlation equation in the case of eolian sands is very smooth, meaning that *AVs10* is not strongly influenced by soil frequency.

4. Creation of an Amplification Map

The city of Lima was divided into grids of 250 m size to create a soil amplification map. Values of H/V peak period, elevation and soil type are assigned to each grid. In areas where these parameters are not available, the value is found by interpolation of inverse distance weighting method using nearby values.

AVs10 is computed for all grids using Eqs. (3), (4), (5) and (6), resulting in the *AVs10* map shown in **Fig. 10**.

Equation (2) presents a formula that relates amplification or *AvTF* to the *AVs10* value. This formula is used with the *AVs10* map (**Fig. 10**) to create the map of amplification shown in **Fig. 11**.

A larger number of data will be necessary in order to develop a more detailed *AVs10* map. It is also recommended that the map be updated as new soil classification maps become available for Lima and for elevation maps with contours having smaller intervals.

5. Simplified Transfer Function for Building Design

For building design in Peru, the acceleration response spectrum is not necessarily a scalar value such as peak ground acceleration. The transfer function of shallow soil has to be multiplied by the design spectrum at engineering bedrock in the frequency domain.

A simplified transfer function is therefore created averaging amplification ratios for the 3 period ranges of 0.1 s (0.07 s–0.14 s), 0.2 s (0.14 s–0.32 s), and 0.5 s (0.32 s–0.70 s) as shown in **Fig. 12**. The simplified transfer func-

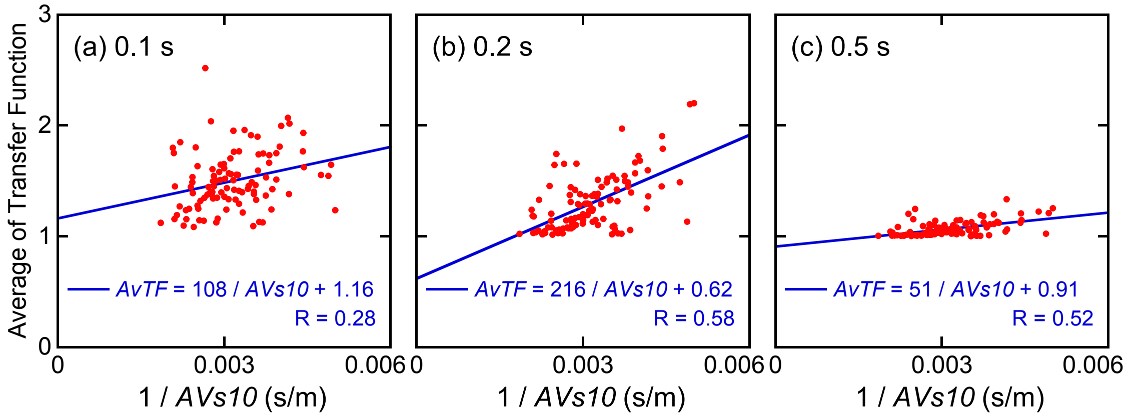

Fig. 13. Correlation between *AvTF* and *AVs10* for 3 period ranges with fitted line.

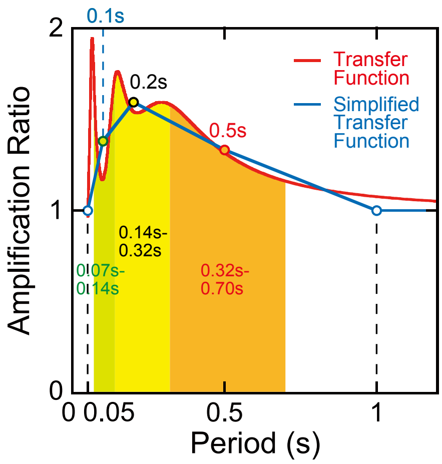

Fig. 12. Simplified transfer function.

tion is made of polygonal lines joining values at 0.05 s, the 3 periods and 1 s. Amplification ratios less than 0.05 s and more than 1 s are 1.0, which means there is no amplification.

Figure 13 shows approximation formulas in the same way as *AvTF* using *AVs10*. The following equations are based on profiles estimated from MASW measurement:

0.1 s (0.07 s–0.14 s):

$$AvTF01 = 108/(AVs10) + 1.16 \quad \ldots\ldots \quad (7)$$

0.2 s (0.14 s–0.32 s):

$$AvTF02 = 216/(AVs10) + 0.62 \quad \ldots\ldots \quad (8)$$

0.5 s (0.32 s–0.70 s):

$$AvTF05 = 51/(AVs10) + 0.91 \quad \ldots\ldots \quad (9)$$

6. Conclusions

In order to create a soil amplification map for Lima, Peru, parameters that correlate best with amplification are examined. The *AVs10* value has proved to be a good indicator of amplification factors in Lima.

Parameters, i.e., elevation, soil type and H/V spectrum peak period, that were available in large numbers were used in the construction of approximation formulas. Approximation formulas were developed for each soil type. Gravels show good correlation, but a low correlation is observed in the case of the eolian sands. Another limitation is the number of data, especially for the clay soil type.

Maps of *AVs10* and amplification ratios of shallow soil were created using the approximation formulas. It is recommended that microzonation maps and approximation formulas be updated as new data develops for the city. In addition, it is important to improve the quality of data – soil type, elevation intervals, etc – in order to create more accurate amplification maps.

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