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Assessing earthquake site amplification for deep soil sites with uncertain bedrock conditions

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ABSTRACT: Site-response analysis is commonly performed using shallow (<50m) shear-wave velocity profiles. The depth at which the bedrock motion is input into the analysis is one of the main parameters that influences the site response. Deciding on the appropriate depth can be difficult because of a lack of information (the “dark zone”) below a few tens of meters of depth due to the high cost of investigating greater depths. However, the deep part of the profile can have a large impact on the site response.

Here we use a database of over 1,000 shear-wave velocity profiles from strong-motion stations in the USA, Europe and Japan to develop a procedure to generate deep profiles that are consistent with observations and imposed constraints (e.g. presence of velocity inversions). By comparing the site response from the generated profile with the response of a known profile we demonstrate the importance of this “dark zone”.

1 INTRODUCTION

Ground motion site amplification is one the main topics of interest in geotechnical earthquake-engineering. The procedure usually adopted is to identify a shear-wave velocity profile (V_s), describing the site, the depth of the seismic bedrock and the mechanical characteristics of the soil deposit. Then, after choosing the most appropriate approach from a mechanic point of view (i.e linear, equivalent-linear or fully non-linear) and from a geometric point of view (i.e. one-dimensional, two-dimensional or three-dimensional), a site-response analysis is performed.

It is common to restrict the geotechnical investigations, which are expensive, to the shallowest part of the soil deposit (depths<50m), unless the site presents particular characteristics or the planned construction is particularly important.

The site characteristics that may mean deeper geotechnical investigations are undertaken include:

- Deep soil deposits, which brings uncertainties in the determination of the true bedrock;
- Presence of a second, deeper bedrock, with a higher V_s than the shallow bedrock;
- Uncertainty in the soil profile of the deeper zone, which we call the “dark zone”;

Whenever these types of site condition are encountered, it is important to move the investigation forward in order to understand the implication of these characteristics in site response analysis.

This study aims to provide some advice on this kind of issue. Starting from a well-known profile, for Memphis, Tennessee (USA) (Gomberg et al., 2003; Cramer et al., 2004), we undertake an investigation on the impact of the previous cited parameters on the results of a site response analysis.

We have chosen this site because: it appears to be a peculiar situation where the seismic bedrock can be found at an unusual high depth, it presents an inversion of velocity in the so-called “dark zone” and, in general, there are many uncertainties in the definition of the whole profile. Figure 1 displays the considered shear-wave profile (taken from Campbell, 2009).

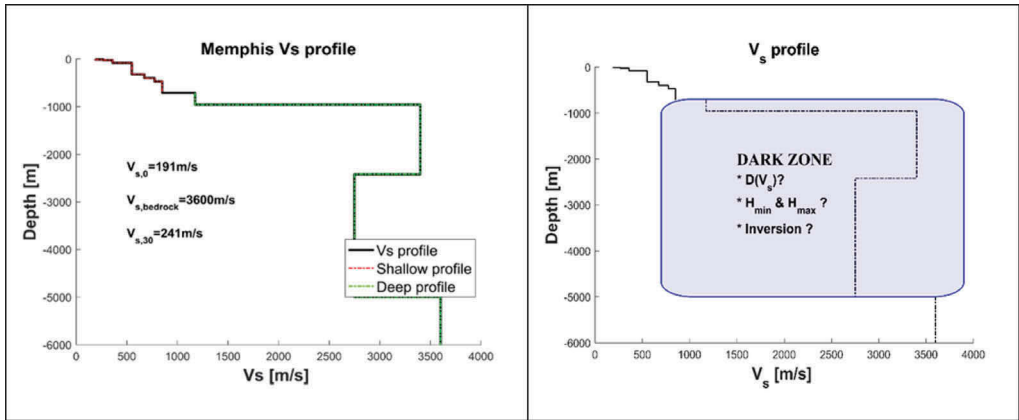


Figure 1. Left: Memphis Vs profile, as shown in Campbell (2009). Right: Range of “Dark zone” where uncertainties are high

According to Douglas et al. (2009), the list of important parameters, for site characterization, includes:

- Velocity of the seismic bedrock ($V_{s,bedrock}$), which can be defined as where $V_s > 800 \text{ m/s}$ (Pitilakis et al., 2018);
- Maximum depth, D , or thickness of the soil deposit, which is the depth corresponding to $V_{s,bedrock}$;
- V_0 , or the surface shear-wave velocity;
- $V_{s,30}$, the time-averaged shear-wave velocity of the top 30m;
- Minimum thickness of the layers (H_{min});
- Maximum thickness of the layers (H_{max});
- Deep bedrock shear-wave velocity and its depth (crustal depth).

Many of these factors are relatively easy to determine, such as surface shear velocity, V_0 or $V_{s,30}$, which is one of the main parameters (along with N_{SPT} blow count, plasticity index PI and undrained shear strength, S_u) used in Eurocode 8 to define the site classification. Others, such as maximum depth, D , and the velocity of the seismic bedrock are more difficult to determine and because of that, they can introduce great uncertainty in the resulting profile used for site response analysis.

Let us consider that we do not know the deep Memphis profile and we need to make a hypothesis on its shape and key characteristics. To do that, we need to impose some constraints on the generic shape a deep profile could have. In particular, we focus on the zone between D and the crustal depth, which we call the “dark zone” (Figure 1, right). Using the Douglas et al. (2009) shear-wave velocity database (857 profiles) plus the ones kindly provided by INGv from the ESM strong-motion database (Luzi et al., 2016) (245 profiles), we aim to model deep profiles more accurately.

2 OBTAINING INFORMATION FROM THE DATABASE

As explained above, we have a total of 1102 shear wave velocity profiles at our disposition. We have developed a taxonomy based on these parameters:

- $V_{s,bedrock}$;
- Depth of $V_{s,bedrock}$, which we will indicate by D ;
- Presence of a velocity inversion within the profile;

- Maximum and minimum thickness of the layers between D and the crustal depth; and
- Length of the profile after D ;

First of all, we search for two of these parameters, simultaneously. They are $V_{s,bedrock}$ and the presence of a velocity inversion. One cannot exclude the other. As a matter of fact, despite the engineering concept of $V_{s,bedrock}$ as the velocity beyond which we no longer have an inversion, we could, for instance, have one before reaching D . Or, we could have an inversion that does not decrease below $V_{s,bedrock}$ (case A of Figure 2). This is the case for the Memphis profile. According to the concept of $V_{s,bedrock}$ the one we should eliminate from our analyses is only case B of Figure 2, i.e. an inversion that occurs after reaching $V_{s,bedrock}$ and decreases the velocity below this value. The other two groups can be included into the macro-group of $V_s > 800$ m/s.

Once we have the final set of profiles, we proceed with the definition of some parameters.

Figure 3 displays the cumulate relative frequency of profiles total length after D and thickness of layers. As mentioned above, the majority of the profiles in this database have a shallow D . The peak of total length is always located in a range smaller than 50m. This can be because the measurements have been stopped, once a certain value of V_s was reached (seismic bedrock), even though sometimes it leads to misrepresentation of the whole deposit. In fact, encountering a stiff material does not mean we always have an increasing V_s , from that point until the crustal depth. Instead, we could face an inversion of velocity.

According to the cumulative relative frequency thickness plots, the peak is always located between 0m and 50m. Actually, there are lot of values between 0-1 and this is why all the three cumulative relative frequencies start in a range between 0.1-0.4.

Figure 3 misses the profiles with velocity inversions completely. For this group of profiles, we are going to characterize:

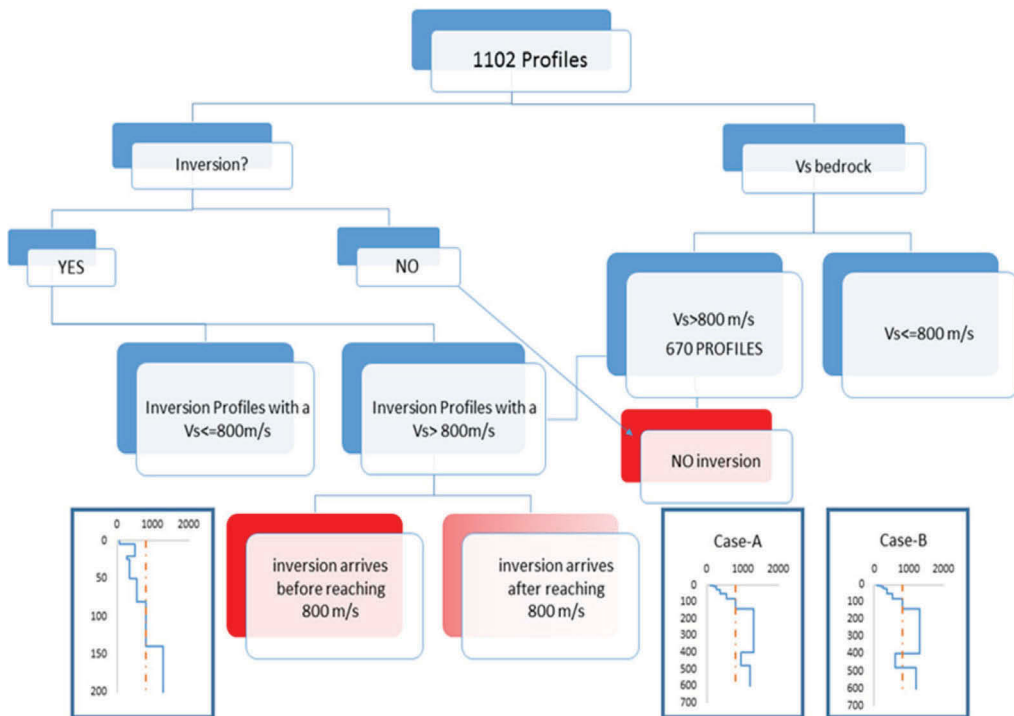


Figure 2. Taxonomy of the shear-wave velocity profile database

- Thickness of the layer with an inversion;
- Thickness of the top layer; and the
- Velocity step.

The chosen procedure aims to account for the effect of these three factors on site response. In particular, the thickness should shift the transfer function peaks, whereas the velocity step should modify the maximum amplification.

3 BUILDING A PROFILE FROM THE GIVEN INFORMATION

Based on the given information (Figures 3 and 4), our aim is to generate realistic shear wave velocity profiles for the deep portion of the Memphis site, as we are assuming that would not know it. Let us say that the only information we have is the shallow portion of it (Figure 1) and the crustal velocity. We will use the data from $D > 100\text{m}$, as for the Memphis profile $D = 400\text{m}$.

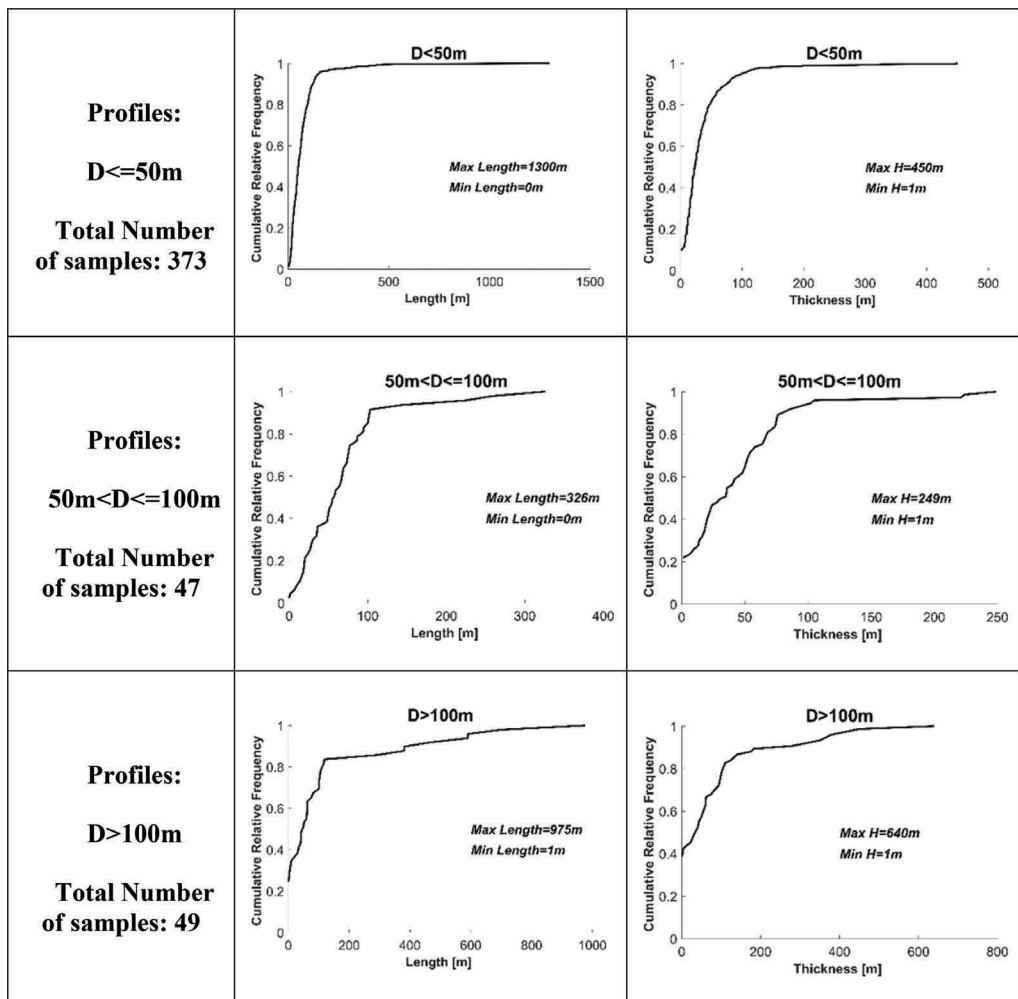


Figure 3. Cumulative relative frequency plots of length after D and thickness of the layers. Top: $D \leq 50\text{m}$ profiles, center: $50\text{m} < D \leq 100\text{m}$, bottom: $D > 100\text{m}$

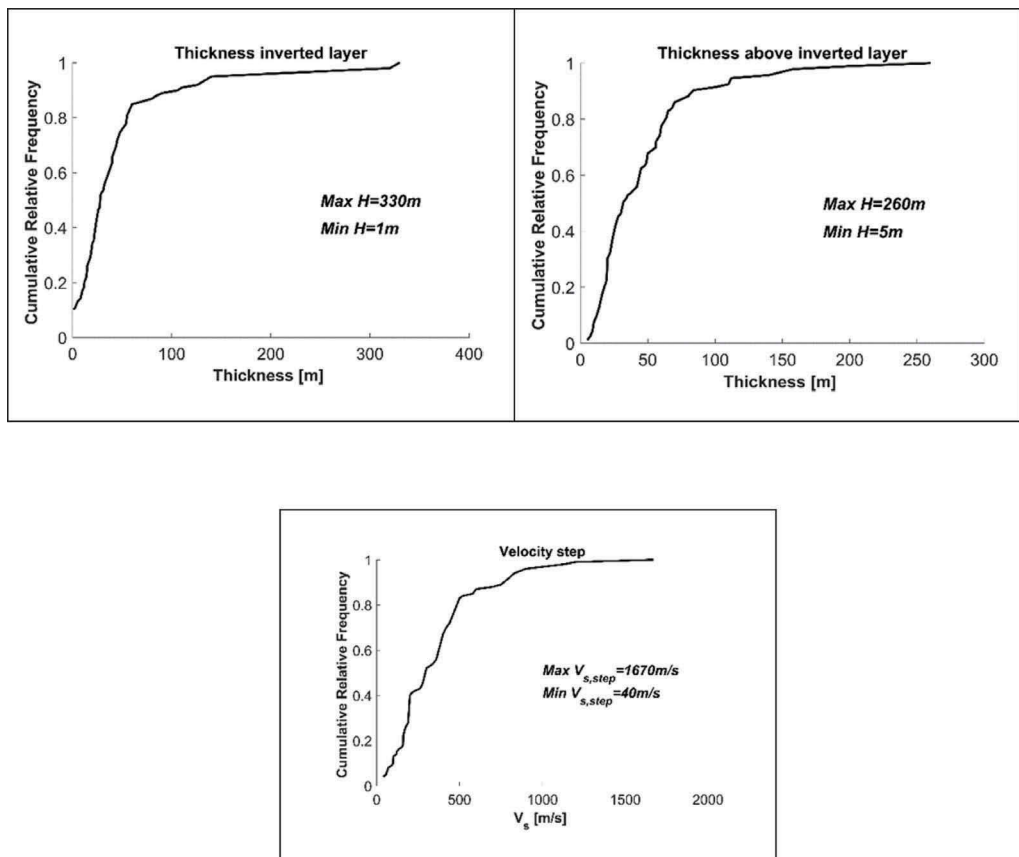


Figure 4. Top left: Thickness of velocity inversion; top right: Thickness of the top layer; bottom: velocity step in the inversion.

The procedure is explained in Figure 5, where two set of profiles are generated. The first kind does not present an inverted velocity. Indeed, it follows an increasing trend of V_s between $V_{s,bedrock}$ and the crustal velocity. Conversely, in the other one, which allows an inversion, the velocity actually decreases until a value that remains above $V_{s,bedrock}$. The basis of this procedure is to choose values in a random manner that is consistent with the frequency distribution plots given above.

Once these profiles have been generated, a full site response analysis is performed. As Figure 5 shows, the most uncertain response is the one with the inversion.

4 CONCLUSIONS

How much does the “dark zone” affect the final response? To answer this, we can compare the response from the:

- generated profile;
- the full original profile;
- quarter wavelength method profile, created using the procedure of Cotton et al. (2006) and the $V_{s,30}$ for this site; and
- the shallow profile;

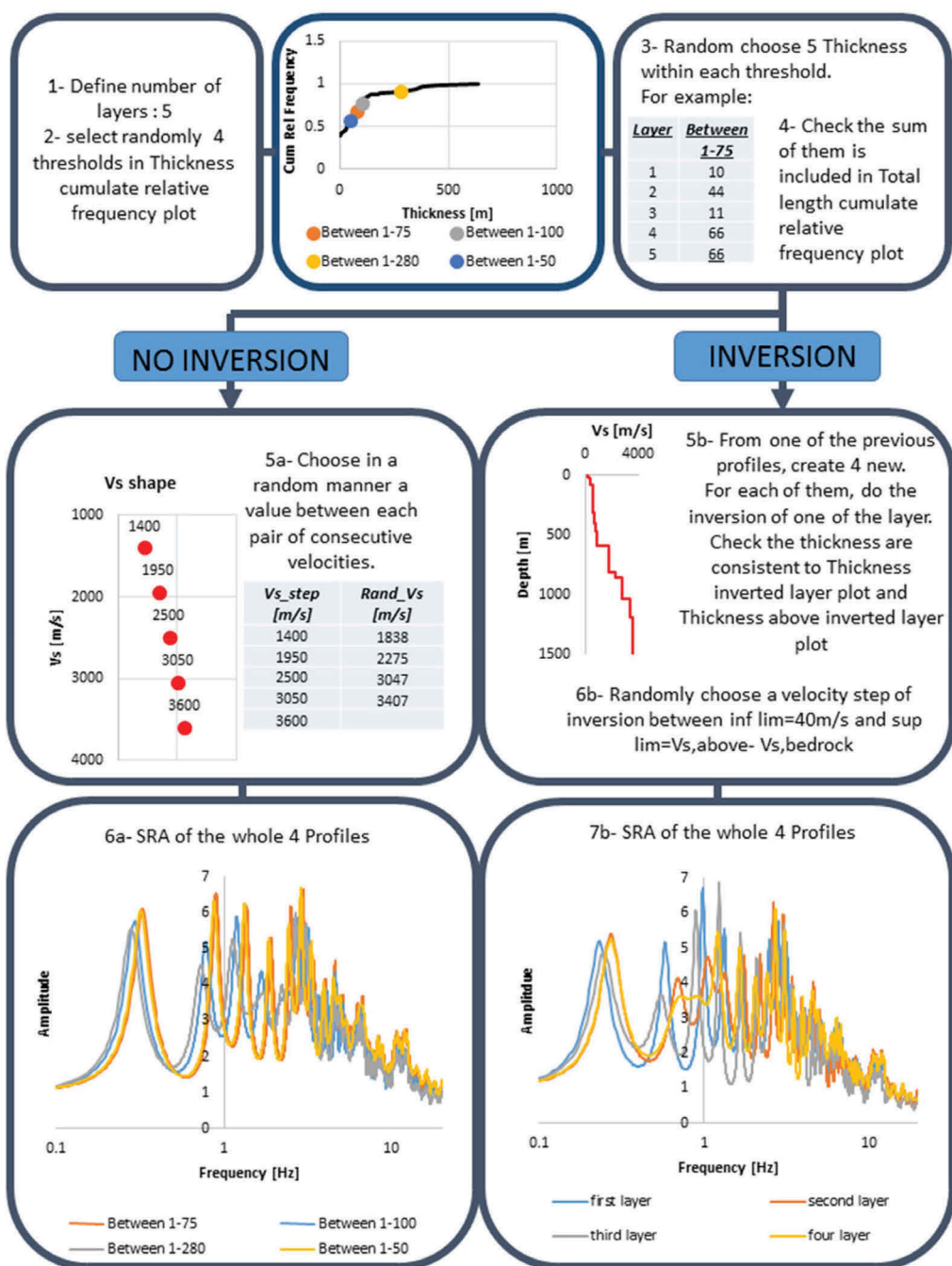


Figure 5. Procedure to create invented deep portion of Memphis shear wave profile.

Figure 6 shows this comparison. Considering just the shallow portion of the Memphis profile, we are actually ignoring the impedance ratio. That is why we do not have large peaks. We can say the same for the Cotton et al. (2006) profile because, although it reaches stiffer materials, it does so gradually. Conversely, comparing the original full profile and the generated one, we are comparing two similar results, at least for the first two peaks, although we observe a difference starting from 1Hz.

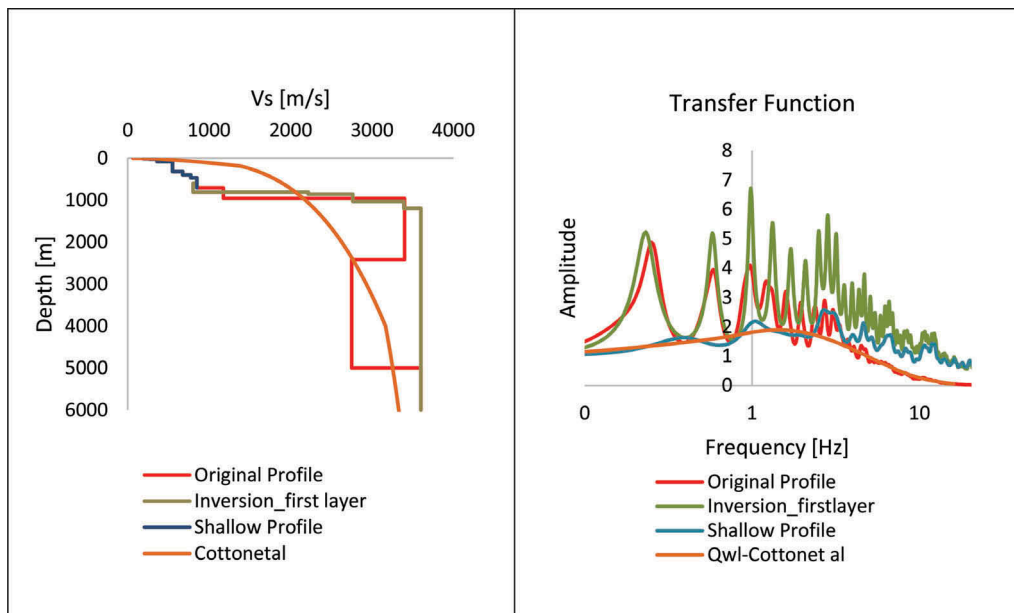


Figure 6. Comparison among original and shallow Memphis profiles, Cotton et al profile and the generated one with an inversion (left) and their transfer functions (right).

It appears to be important to study the deep portion of a shear-wave velocity profile, despite the fact that most of the time we do not have sufficient information about it. Therefore, a taxonomy, like the one in this work, can help to bridge this gap and give satisfactory results.

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