One dimensional P wave velocity structure of the crust beneath West Java and accurate hypocentre locations from local earthquake inversion

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Abstract. A one-dimensional (1-D) velocity model and station corrections for the West Java zone were computed by inverting P-wave arrival times recorded on a local seismic network of 14 stations. A total of 61 local events with a minimum of 6 P-phases, rms 0.56 s and a maximum gap of 299° were selected. Comparison with previous earthquake locations shows an improvement for the relocated earthquakes. Tests were carried out to verify the robustness of inversion results in order to corroborate the conclusions drawn out from our reasearch. The obtained minimum 1-D velocity model can be used to improve routine earthquake locations and represents a further step toward more detailed seismotectonic studies in this area of West Java.

Key words: earthquake location, minimum 1-D model, West Java
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INTRODUCTION

Accurate earthquake locations are of primary importance when studying the seismicity of a given area because they provide important information on the ongoing seismotectonic processes. In standard location techniques, the velocity parameters are kept fixed to a-priori values, which are assumed to be correct, and the observed travel-time residuals are minimized by adjusting the hypocentral parameters. However, the use of an unsuitable velocity model can introduce systematic errors in the hypocentre locations [1,2]. Precise hypocentre locations and error estimates, therefore, require the simultaneous solution of both velocity and hypocentral parameters. In this paper, we define a reference P-wave velocity model for the west Java, using the approach by Kissling et al. [3]. This procedure also allows us to compute station corrections, which can be used in standard location methods to account for the heterogeneous velocity structures around individual stations. Special attention was paid to stability test of the inversion results. The concept of minimum 1-D model represents the first step towards more detailed seismic studies, is widely used around the world. One of the first applications of this method was in north-western Italy [4], but afterwards it was used in northern Chile [5], Costa Rica [6], New Zealand [7], and central and southern Italy [8–12]. The calculated minimum 1-D model must satisfy the following conditions, with regard to an a-priori model derived from independent geological and geophysical data observation e.g. [13, 14]: a) the P-wave velocity of each layer is the area weighted average of the velocity sampled at the depth interval by the data; b) the topmost layer and the station corrections reflect the basic features of near-surface structure; c) equally high precision locations should be found for all well-locatable earthquakes occurring anywhere within the seismic network.

LOCAL EARTHQUAKE DATA AND STATION

In the west Java, a local seismic network of 14 stations (Figure 1) has been installed by BMKG (IA) and GEOFON. The stasions are LEM, TNGI, CMJI, KPJI, CBJI, DBJI, CNJI, CLJI, JCJI, SKJI, SBJI, TGJI and CGJI from IA and CISI from GEOFON. The arrival times of the P- and S-waves are picked with an accuracy that is generally using software WINQUAKE [15]. Earthquakes are routinely located using the software VELEST [4] and the a-priori velocity model

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proposed by Koulakov et al. [13]. In the inversion process we use additional information to select the a-priori model, as suggested by Kissling [16] to ensure that we are minimizing arrival-time residuals, rather than minimizing residuals resulting from the kinematic hypocentre determination. In this case, the initial layering of the a-priori velocity model was chosen considering the local geological and geophysical data [13]. We used ten layers to approximate the crust, and a half-space for the mantle below the Moho.

The resulting velocity model (Figure 2) has reduced average station residuals when calculating earthquake locations compared to other models.

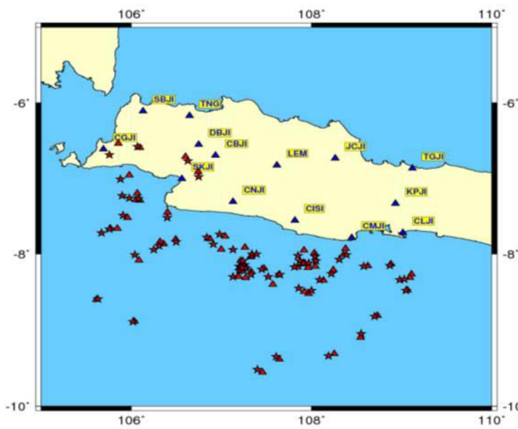

FIGURE 1. The earthquake initial hypocentres (stars) were selected for the inversion and final hypocentres (red triangles) and seismic stations (blue triangles).

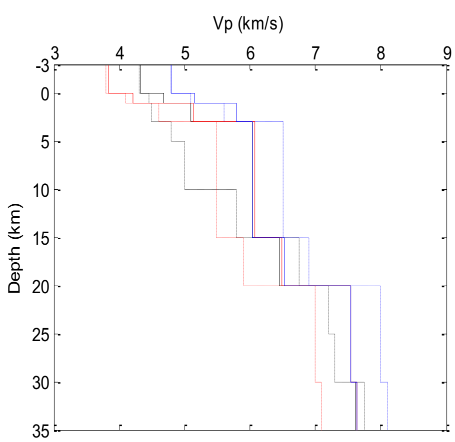

FIGURE 2. Test of the stability of the minimum 1-D velocity model. The solid black lines correspond to the resulting models after the inversion.

COMPUTATION OF A 1-D VELOCITY MODEL

As a reference 1-D velocity model must approximate a weighted average of the data, but must also reflect the local structure, the computation of a reference model starts with the definition of three elements: 1) the zone of study, 2) the geometry of the initial 1-D velocity model, 3) the selection of a high-quality set of local earthquake data.

For the identification of an optimum 1-D P-wave velocity model we used the widely known software VELEST [4]. The program, for local earthquakes, comes with two options: in 'simultaneous mode', it solves the coupled hypocentre-velocity model problem; in 'single-event-mode' it computes only the earthquake locations, keeping the velocity parameters fixed. In both approaches the forward problem is solved by ray-tracing from source to receiver, computing the direct, refracted, and the reflected rays passing through the 1-D model. The inverse problem is solved by inversion of the damped least square matrix. Because the problem is non-linear, the solution is obtained iteratively, where one iteration consists of solving both the complete forward problem and the complete inverse problem once.

Within the west Java about 204 earthquakes were recorded between 2008 and 2010. Since large uncertainties in the hypocentre location would introduce instabilities in the inversion process, we located the events by using the a-priori velocity model and the program VELEST in single event mode before including the earthquakes in the joint inversion of velocity and hypocentral parameters. The database was then filtered matching minimum requests with respect to location quality criteria. Earthquakes were selected using the criteria of at least 6 detectable P-phase arrivals, rms < 0.9 s and a maximum GAP of 299°. The maximum GAP is an important parameter that ensures that events can be well located within the local network. We chose to consider also a few epicenters with a gap larger than 180° which are outside the network, because their raypaths help to constrain the study volume. The resulting dataset includes 61 earthquakes, with a total of 484 P-wave observations. Figure 1 shows the location of the selected events.

These events were inverted using the program VELEST in simultaneous mode to calculate hypocentre locations as well as the parameters of the velocity structure and station corrections. The model damping parameters were chosen following the default values proposed by Kissling (see VELEST user's guide Kissling, [4]). As the layer depths are kept fixed according to the recommendations of Kissling et al. [3], we began with a large number of thin layers (3 km thick) and then combined layers for which velocities converged to similar values during the inversion process. The inversion process stopped when earthquake locations, station delays and layer velocities did not vary significantly in subsequent iterations.

Accurate Hypocentre Location

The seismic wave travel-time is a non-linear function of the hypocentral parameters and the seismic velocities sampled along the ray path between the hypocentre and the station. The dependence on hypocentral parameters and seismic velocity is called the coupled hypocentre- velocity model problem [1, 17, 18]. It can be linearized and written in matrix notation as [3]:

$$t = Hh + Mm + e = Ad + e \qquad (1)$$

where t is the vector of the travel-time residuals, H is the matrix of the travel-time partial derivatives with respect to hypocentral parameters, h is the vector of the hypocentral parameter adjustments, M is the matrix of the travel-time partial derivatives with respect to the model parameters, m is the vector of the velocity parameter adjustments, e is the vector of the travel-time errors, which includes contributions from errors in measuring the observed travel times, errors in tcalc due to errors in station coordinates, use of the wrong velocity model and hypocentral coordinates, and errors caused by the linear approximatiom, A is the matrix of all partial derivatives and d is the vector of hypocentral and model parameter adjustments.

In a standard location procedure, the velocity parameters are maintained fixed to a-priori values and the observed travel time residuals are minimized by perturbing the four hypocentral parameters (origin time, epicentre coordinates, and focal depth). Neglecting the coupling between hypocentral and velocity parameters during the location process, however, can introduce systematic errors. Precise hypocentre locations and error estimates, therefore, demand the simultaneous solution of both velocity and hypocentral parameters. Kissling et al. [3] concur with Thurber [1] that the correct hypocentral coordinates are most reliably achieved by solving the coupled hypocentre-velocity model problem, rather than alternating independent hypocentre and velocity adjustment steps. The obtained minimum 1-D model represents a velocity model that reflects the a-priori information and leads to a minimum average of rms values for the best-selected earthquakes used in the inversion. Each velocity value in a given layer of the Minimum 1-D model is the weighted average over all rays within that depth interval.

RESULTS

After 10 iterations we obtained a velocity model that is compared in Figure 2 with the initial model. This final model satisfies the following requirements: 1) earthquake locations, station delays and velocity values do not vary significantly in subsequent iterations; 2) the total rms value of all events is significantly reduced with respect to the first routine earthquake locations. We obtained a variance improvement of about 79 % and a final rms of 0.56 s. The average deviations, after the first iteration, in origin time, x, y and z were 0.33 s, 1.74 km, 1.23 km and 0.97 km, respectively.

Standard deviations of the velocity values of the proposed model are 0.07 km/s or less. The P-wave velocity in the starting model contained ten layers, while the final model to seven layers. P wave velocity below the third layer at a depth greater than 3 km show the stability, while the three upper layers are unstable (Figure 2).

Relocation Hipocentres

In order to estimate the improvement introduced by using the computed minimum 1-D velocity model and the station corrections, the 61 selected events were relocated using VELEST in ‘single event mode’ [4] and the errors have been compared those associated with the initial locations. In Figure 4, which shows the difference in between the two locations. To further explore the robustness of the results we performed tests which give a direct indication of the inversion stability and the model sensitivity with different initial models. A stability test was carried out, as suggested by Haslinger [18], keeping the final hypocentre coordinates of the 61 inverted events fixed, and repeating the inversion process with the same parameters but using different initial velocity models, i.e. with higher and lower velocities with respect to our minimum 1-D model (Figure 1). The convergence of the final inverted models to the minimum 1-D model indicates that this is an adequate 1-D approximation of the upper 35 km of depth.

Station Correction

Station corrections are an integral part of the minimum 1-D velocity model since they should partly account for the three-dimensionality of the velocity field that cannot be adequately represented by a 1-D model [16]. Thus, part of the travel-time residuals not explained by the 1-D structure are included in the station correction. Station corrections are strongly coupled with the velocity and structure directly below the station. A change in the velocity structure of the uppermost layers beneath the station is reflected in a more or less constant time-shift of the calculated travel times, which can be compensated for by adjusting the station correction. Typically, they are correlated to a ‘reference station’, which is preferably chosen close to the geometric centre of the network, and is among the stations with the highest number of readings. The reference station is assigned a correction value of 0. Negative corrections are encountered when the true velocities are higher than the calculated ones, positive corrections occur for lower velocities than predicted by the model. We may exclude biases on the station corrections due to topographic effects because VELEST uses station elevations for the joint inversion of hypocentral and velocity parameters. Consequently, rays are traced exactly to the true station position [5]. In the station corrections are given as relative values with respect to the reference station CLJI. They support the validity of the obtained Minimum 1-D model, as it can be related fairly well to the general near-surface conditions inferred from geological evidence. They show negative corrections at all stations deployed on compact calcareous or dolomite rocks.

CONCLUSIONS

We have derived a reference 1-D model and station corrections for the West Java, in Java Island, Indonesian by minimizing P-wave residuals for high quality hypocentre locations according to the procedure of Kissling et al. [3]. Sixty one events were inverted using VELEST [4] in order to calculate adjustments to the P-wave velocity model and to the station corrections. The whole set of local earthquakes was then relocated with VELEST in ‘single event mode’, using the model obtained from the inversion procedure. As indicated by the resulting lower mean rms values and data variance, our minimum 1-D model shows a better fit to the data, which in turn results in more precise and consistent hypocentre locations.

A test was performed to determine the robustness of the hypocentre locations and the minimum 1-D model. The inversion process was repeated keeping either the obtained velocity model or the final earthquake locations fixed. In the test a range of starting velocity models converge to the same minimum 1-D model, showing that it is an adequate approximation of the crust above 35 km of depth.

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