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A COMPENDIUM OF *P*- AND *S*-WAVE VELOCITIES FROM SURFACE-TO-BOREHOLE LOGGING: SUMMARY AND REANALYSIS OF PREVIOUSLY PUBLISHED DATA AND ANALYSIS OF UNPUBLISHED DATA

by

David M. Boore
with assistance in some data analysis by James F. Gibbs and Magda Rodriguez

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INTRODUCTION

For over 28 years, the U.S. Geological Survey (USGS) has been acquiring seismic velocity and geologic data at a number of locations in California, many of which were chosen because strong-ground motions from earthquakes were recorded at the sites. The method for all measurements involves picking first arrivals of P- and S-waves from a surface source recorded at various depths in a borehole (as opposed to noninvasive methods, such as the SASW method [e.g., Brown *et al.*, 2002]). The results from most of the sites are contained in a series of U.S. Geological Survey Open-File Reports (see References). Until now, none of the results have been available as computer files, and before 1992 the intepretation of the arrival times was in terms of piecemeal interval velocities, with no attempt to derive a layered model that would fit the travel times in an overall sense (the one exception is Porcella, 1984). In this report I reanalyze all of the arrival times in terms of layered models for P- and for S-wave velocities at each site, and I provide the results as computer files. In addition to the measurements reported in the open-file reports, I also include some borehole results from other reports, as well as some results never before published. I include data for 277 boreholes (at the time of this writing; more will be added to the web site as they are obtained), all in California (I have data from boreholes in Washington and Utah, but these will be published separately). I am also in the process of interpreting travel time data obtained using a seismic cone penetrometer at hundreds of sites; these data can be interpreted in the same way of those obtained from surface-to-borehole logging. When available, the data will be added to the web site (see below for information on obtaining data from the World Wide Web (*WWW*)). In addition to the basic borehole data and results, I provide information concerning strong-motion stations that I judge to be close enough to the boreholes that the borehole velocity models can be used as the velocity models beneath the stations.

FIELD PROCEDURES

Although few new field measurements were made for this report, a knowledge of the field procedures will help in understanding the analysis required to obtain the velocity models described in this report. The field procedures are explained in detail in the individual open-file reports, but in general they involve surface sources of P- and S-waves, offset some few meters from the borehole. The waves are recorded on a fixed surface geophone and a three-component geophone package clamped to the borehole casing. The downhole geophone package is raised (or lowered), with measurements made at approximately every 2.5 m in depth. The P-wave source is usually a vertically directed blow of a sledge hammer on a metal plate; the S-wave source was orginally a horizontal blow from a sledge hammer or a slide hammer on the end of a plank held to the ground by the front wheels of a truck. In the last 15 years the shear waves were generated by an air-powered horizontal ram (Liu *et al.*, 1988) striking an anvil at either end of an aluminum channel 2.3 m long. The ram is driven first in one direction and then in the other to generate pulses of opposite polarity.

In almost all cases a geologist attended the drilling of each borehole and made note of the rate of penetration and cuttings coming from the hole, and constructed a geologic log of the materials penetrated by the hole. In addition, various downhole logs were often made (details are in the open-file reports). These logs are useful in fitting layered models to the travel time data.

DETERMINATION OF VELOCITY PROFILES

The USGS started the borehole logging program in 1975. Until 1992 layered models were not fit to the travel times; only interval velocities were determined. While interval velocities are useful in making correlations of velocity and geologic materials, a layered model starting from the surface is needed for site response computations. Starting in 1992 a piecewise continuous set of straight line segments are fit to the arrival times using least-squares regression. The inverse of the slopes of the line segments yields a velocity model made up of a stack of constant-velocity layers. Before 1999 the times were corrected for the horizontal offset h from source to borehole (also referred to as *hoffset*) using the following equation:

$$tt_{vrt} = tt_{slant} \frac{z}{\sqrt{h^2 + z^2}}, \qquad (1)$$

where tt_{slant} is the measured travel time to depth z and tt_{vrt} is an approximation of the time that it would have taken the waves to go from the top of the borehole to depth z. Starting in 1999, the computer program that fits the travel times accounts for refraction of the waves at layer interfaces, and the measured slant time tt_{slant} is the parameter being fit by the layered model.

In the results reported on here, all pre-1999 borehole measurements were reinterpreted using the modern analysis program. The first step in doing this was to enter, by hand, the travel times from the tables in the open- file reports. Where only tt_{vrt} was available, they were converted to tt_{slant} using equation (1) if *hoffset* was known. If *hoffset* was not known, it was set to 0.0 in the analysis (the differences between models obtained using tt_{vrt} and tt_{slant} are generally small).

As input, the analysis program uses depths to layer boundaries. The procedures to determine the initial set of depths to the layer boundaries differed somewhat for the newer data and older data, as discussed below.

Newer Data: In the open-file reports published starting in 1992, these depths were chosen iteratively by a team made up of the seismologists and geologist who logged the hole, as well as other seismologists. A trial set of layer boundaries was chosen for the S-wave model, based on the lithologic descriptions and geophysical logs. The travel-time data were fit in a least-squares sense by a model made up of constant-velocity layers, taking into account refraction across the interfaces between layers. The travel times were weighted by the inverse of an assigned normalized variance. A normalized standard deviation of 1 was assigned to the clear arrivals and values up to 5 were assigned to the others. The residuals were examined, and layer boundaries were added or deleted, if necessary, to reduce large residuals or to remove systematic trends in the residuals. The iterative process continued until the team was satisfied that the interfaces were consistent with the borehole seismic data as well as available geological and geophysical logs. The P-wave travel time data were analyzed initially with the set of layer boundaries finally determined for the S-wave data. Layer boundaries were then added if needed to fit the data and deleted if not needed. Commonly, an additional layer boundary corresponding to the top of the zone of water saturation was needed to fit the P-wave data.

After the P-wave and S-wave velocities were determined independently, Poisson's ratios (σ) were calculated. Some of the Poisson's ratios, calculated with initial velocity models, resulted in Poisson's ratios that were out of the accepted range of 0.0–0.5. This will occur if $\frac{V_p}{V_s} < 1$ or if $1 < \frac{V_p}{V_s} < \sqrt{2}$, in which case $\sigma \geq 1.0$ or $\sigma < 0$, respectively. Although $\sigma < 0$ is theoretically possible (e.g., Fung, 1968), the authors of the newer reports decided that the P-wave and S-wave velocities should yield σ between 0.0 and 0.5. To obtain a value in the acceptable range minor adjustments were made to the velocities using one or more of the following procedures: repicking shallow arrivals (usually P-wave arrivals because small changes in P-wave travel-times have a greater effect on σ), adding a shallow layer, and/or adjusting layer thickness to ensure that Poisson's ratio was in the range 0.0–0.5. In most cases the small changes were made in the P-wave velocities at shallow depths (for more details see, Gibbs *et al.*, 1999). Overall, the changes in velocity required to produce acceptable values of σ were small and were only in a few, usually shallow, layers.

Older Data: Independent analyses were made by myself, J. Gibbs, and M. Rodriguez for much of the older data. The results presented here are those from my analyses. After consulting the analyses of the other authors, I sometimes altered my set of layer depths if my subjective judgement was that the other models had some features that better fit the data. For the analysis of the older data, I generally tried to use the depth ranges of the interval velocities in the older open-file reports.

In some cases (particularly for P-waves), it appears that a cycle was skipped in the picking of the first arrival times. Examples include `SMWP.VEL` (hole_code 064, where the meaning of "hole_code" is given later) and `MHJP.VEL` (hole_code 069). The proper thing to do in such cases is a subjective decision based on how the models will be used, but because the analysis program requires a layered model, some decision must be made. The subjectivity required in such cases is a drawback to deriving a complete layered model rather than just interval velocities over a possibly noncontiguous set of depth ranges. But the overall usefulness of a layered model and the relatively small number of cases where problems occur in the S-wave models argues in favor of the analysis method that I have chosen. By specifying a thin layer spanning the range of depths over which the travel times seem to jump from one trend to another (usually this range equals the distance between consecutive measurements), a model could be constructed that "connects" the portions where the velocities seem to be well defined, based on arrival times over a range of depths on either side of the connecting layer. This also gives a model that matches the overall travel time to the bottom of the hole. If a connecting layer is used, the P-wave velocity and the Poisson's ratio in the connecting layer are obviously useless; the Poisson's ratios in layers on either side, however, are usually well determined. Including a connecting layer seems preferable to fitting an average through the region, for then the interval velocities and Poisson's ratios do not represent true velocities for a wide range of depths. Apparent missed cycles in the S-wave travel times are less common than for P-waves, and because I consider that the S-wave models will be primarily used for site amplification calculations, I usually smooth through the offending depth range rather than introduce a thin, artificial layer (which will result in sharp impedance contrasts on either side of the layer).

Unlike the more recent data, the older data were not stored in digital format, and therefore it is difficult to apply postprocessing (filtering, plotting using different scales) to check the picks of the first arrival times. For this reason, even if a cycle did not seem to be skipped, the Poisson's ratios for the older data are rarely in the 0.0 to 0.5 range for all depths. The problem is usually that for some depth ranges the P-wave velocities are too low. In spite of the problems for some depth ranges, the models in this report provide reasonable overall travel times. The reliability of the P-wave velocity models can be assessed by looking at the Poisson's ratio files. Invalid Poisson's ratios at shallow depths are not unexpected because small errors in travel time can lead to relatively large errors in velocities, and because the sources for the P-waves and the S-waves are in different locations, and the travel paths to the borehole receiver are different. If lateral heterogeneiities exist in the velocities, this can lead to apparent problems in the Poisson's ratios, particularly for shallow depths. Unrealistic Poisson's ratios at deeper depths, however, might indicate problems in the travel time picks.

DATA AND DERIVED VELOCITY MODELS

The data and models have been put into several zip files, which can be obtained from the online_data link on the following *WWW* site: `http://quake.usgs.gov/~boore`. The Fortran programs used to fit models to the travel times, produce the csv files, and calculate the Poisson's ratios are available upon request (email: `boore@usgs.gov`); the programs will eventually be placed on the online_software page of my web site (the url is given above).

The data and models have been placed in the following files, compressed using the

PKZip compression scheme:

BH_CSV_XLS.ZIP: Contains files with the basic borehole information, the velocity models, and the travel times used to derive the velocity models in both comma separated text files (*.csv files) for convenience in importing into spreadsheet or database programs and in Excel spreadsheet format (*.xls files). The files in spreadsheet format are particularly useful because they can be sorted in various ways. Separate sets of files are given for the P-waves and the S-waves, and the filenames indicate whether the file contains borehole and measurement information, travel times, or models. The files and their contents are as follows:

> **all_ip.*, all_is.***: Information files for P-waves and S-waves, giving for each borehole the following fields: hole_code; site name; latitude; longitude; *hoffset*(m); depth to deepest measurement, in m; travel time to 30 meters, in sec, calculated from the model; average velocity to 30 meters, in m/sec, computed by dividing 30 meters by the computed travel time to 30 meters; distance of extrapolation, in m, needed to reach 30 meters (necessary for many of the older boreholes; the recent boreholes are usually close to 100 meters in depth); short reference to the publication containing more information about the site (see Table 1 for a mapping between the short reference and the standard citation; the complete reference is in the reference list); the name of the file for the model, in the format produced by the analysis program (files in this format were the standard way of presenting the results in the open-file reports starting in 1992). The hole_code is a unique number assigned in my database to each borehole; the latitudes and longitudes generally use the 1927 datum (to convert to the 1983 datum, use the calculator available from http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.html; and *hoffset* is the horizontal offset between the source and the borehole (0.0 if the slant times from source to receiver were not available, in which case the times in the travel time files have been corrected to vertical).

> **all_tp.*, all_ts.***: Travel-time files for P-waves and S-waves, giving for each borehole: hole_code; *hoffset*, in m; depth, in m; time from source to receiver, in sec, not corrected to vertical unless *hoffset* = 0.0.

> **all_mp.*, all_ms.***: Model files for P-waves and S-waves, giving for each borehole: hole_code; depth to bottom of layer, in m; thickness of layer, in m; and velocity in layer, in m/sec.

BH_VEL_OUT.ZIP: Contains text files of the velocity models (*.vel files) and the Poisson's ratios (*.out files) in the format used in recent open-file reports. The files for each open-file report have been put into separate folders rather than being collected together; the relative folder information is carried along in the zip files. This was originally done because in some cases the 3- or 4-letter code used to name a station is the same for stations in different open-file reports. For the convenience of the user, however, duplicated station codes names were renamed and all velocity files were collected into one directory (velfiles). The zip file therefore contains two copies of each velocity file.

BH_PS.ZIP: Contains Postscript plot files showing the fit of the model to the travel times, the residuals to the fit, and the velocity model. In the plots of travel time versus depth the times are the slant times, uncorrected for distance, and the arrival times, calculated only at depths for which measurements were made, are joined by straight lines. The actual travel times would be curved for shallow depths, and therefore the display can seem odd at shallow depths (e.g., 84-562\EC6.PS).

BH_GEOLOGS.ZIP: Contains scanned versions of the summary geologic logs, from the open-file reports. The files have names such as GEOLOGS_XX-XXX.PDF, where XX-XXX is the open-file year and number. The geologic logs are in the process of being scanned and will be added as time goes on; I did not want to hold up putting the models on the web until all the logs had been scanned. As there will be in excess of 13Mb of scanned files, I will probably break BH_GEOLOGS.ZIP into several parts. The summary logs often have plots of the velocity models on the same page, but the user is warned that these models might differ somewhat from the models contained in the files available from the web site, because the analysis methods have changed through the years (as discussed earlier). This can result in small differences in the velocities from 1992 to 1999, and larger differences for the earlier models, compared to the reinterpreted models contained here.

If data are missing from a large interval of depth (e.g., EC9P [hole_code 107, OFR 84-562] and RD7S,P [hole_code 285, OFR 00-476]), the model derived from surface-to-borehole logging still gives the proper overall travel time of the waves; the range of depths for which data are missing is replaced by a layer with a velocity such that the travel time to depths below the missing data is preserved. This is an advantage of surface-to-borehole logging over suspension logging, in which both the source and the receiver are within the borehole. Care must be taken, however, in cases of data missing over a large range of depths when doing layered-model calculations. Impedance contrasts that exist in the zone of missing data will not be detected and artificial impedance contrasts will be introduced; these artificial impedance changes might lead to erroneous site response. On the other hand, these models can be used in square-root-impedance amplification calculations to derive site response smoothed over frequency (e.g., Boore, 2003).

BOREHOLE AND STRONG-MOTION STATION CORRESPONDENCE

For the convenience of the user, I include files containing the correspondence between a borehole and those strong-motion recording stations that I judge to be close enough to the borehole to share similar subsurface velocity properties. The more recent boreholes were usually specifically sited at strong-motion stations, but this may not be the case for the older boreholes (or if it was, that information is no longer available because the people involved are no longer available). I investigated the possible correspondence by first searching for all strong-motion stations within a radius of 1 km of each borehole (by "stations", I mean entries in my database that had or have strong-motion instruments installed at the station, even if the instruments recorded no events; a number of these stations no longer exist). I used the program `Topo!` to plot the locations of boreholes and stations (using the 1927 datum in most cases), checking the coordinates of the stations against my database, U.S. Geological Survey (USGS) and California Geological Survey (CGS, formerly the California Division of Mines and Geology [CDMG]) publications, the CGS California Strong-Motion Instrumentation Program (CSMIP) (from their web site, `http://docinet3.consrv.ca.gov/csmip/`), the USGS National Strong Motion Program (NSMP) NOD database, and the station table on the NSMP web site (`http://nsmp.wr.usgs.gov/`); I also used `Yahoo! Maps` in some cases when a street address was available. I found that the borehole locations corresponded with the hard copy maps in the open-file reports, which is very reassuring. Unfortunately, the same cannot be said for the station locations. Many of the older stations (often no longer in existence, and therefore not in the NSMP databases) had coordinates given only to 2 decimal places (a 1 km uncertainty!), so it is not surprising that the plots often indicated that the station and borehole were farther apart than I knew them to be (based on similarity of names or my knowledge of the geography). I accepted a correspondence in some cases even if the station and borehole were not "co-located", when it seemed that there would be small lateral changes in velocity, as judged by flat topography and in a few cases, similarity of boreholes in the region. If I had cast my net farther (say, a radius of 2 or 3 km around each borehole), I might have associated more stations with boreholes.

`STA_BH.ZIP`: Contains the correspondence between strong-motion recording stations and boreholes. The fields of information include: hole_code; borehole site name; borehole latitude; borehole longitude; borehole reference; depth to bottom of borehole; distance needed to extrapolate to 30m; average velocity to 30m, including any needed extrapolation; sta_code; agency code 1; agency code 2; station name; station location; station latitude; station longitude. hole_code and sta_code are unique numbers assigned in my database to each borehole and station. The station database was started by importing the contents of a USGS open-file report containing station info (Switzer, 1981); this database was then built up using the various data reports for the bigger California earthquakes (Loma Prieta, Cape Mendocino, Landers, and Northridge). Because of the evolutionary nature of the database, the two "agency code" fields may not be accurate in all cases (stations were sometimes transferred between the USGS and CGS, but they can be useful in identifying stations, because the agencies providing data for the stations know nothing about my database code numbers. Note that more than one station can sometimes be associated with a borehole (usually it does not work the other way around), and therefore a borehole may occur in a number of rows in the file, each with a different strong-motion station.

DISCUSSION

The results here include some sites for which velocity models have not been published. These are in folder `03-191` (see the files in `BH_VEL_OUT.ZIP`). Travel times used in the analysis, mostly obtained a number of years ago, were obtained from the files of T. Fumal, J. Gibbs, and R. Warrick. The hole_codes of the new sites are 260, 263, 284, 315–317, 319, 322–327, and 330. The data for sites 284, 315–317 were obtained recently, using modern digital recording equipment; the results from these sites had not been previously published because the primary investigator (J. Gibbs) retired before he had a chance to publish the results; I have used material from his files in this report.

In addition to the boreholes for which models had never before been published, results based on a reanalysis of travel times are included here for sites that have not appeared in the series of open-file reports. These are primarily in folder `others`. The hole_codes of the reanalyzed sites are 207, 208, 262, 318, 320, 321, and 328.

Travel times for two holes appearing in open-file reports have been augmented and reanalyzed. These are Beach Park Boulevard (hole_code 135, OFR 94-222), for which times from a seismic cone penetrometer made by T. Noce of the USGS have been added, allowing more detail in the velocity model at shallow depths, and Gilroy 2 (USGS)(hole_code 121, OFR 92-287), for which a few times at deeper depths have been added from a survey made by R. Warrick of the USGS.

I also would like to draw attention to the deep hole in the Parkfield, California region. Measurements in this hole, known as the "Varian" hole (hole_code 262), were made to a depth of 1350 m (Daley and McEvilly [1990]; T.V. McEvilly, written commun., March 1, 1996). This is by far the deepest borehole in this report.

WHAT IS MISSING?

Besides the geologic logs (mentioned above), there are several other things contained in the individual open-file reports that are not included in this report. The most important missing items are location maps and record sections of waveforms used in picking the travel times. These were not included because they would result in much larger files for downloading and would have greatly delayed publication of this report. The latitudes and longitudes of the stations are given here, however, as are the arrival times.

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Note that some of these references appear only in the information files (`all_ip.*`, `all_is.*`) and not in the text or in Table 1.

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Table 1. Mapping of brief reference given in all_ip.* and all_is.* files and the reference as a standard citation; see the reference list for the full reference.

Short Reference	Citation
OFR 75-564	Gibbs *et al.*(1975)
OFR 76-731	Gibbs *et al.*(1976)
OFR 77-850	Gibbs *et al.*(1977)
OFR 80-378	Gibbs *et al.*(1980)
OFR 81-399	Fumal *et al.*(1881)
OFR 82-407	Fumal *et al.*(1982a)
OFR 82-833	Fumal *et al.*(1982b)
OFR 84-562	Porcella (1984)
OFR 84-681	Fumal *et al.*(1984)
OFR 89-630	Gibbs (1989)
OFR 90-248	Gibbs *et al.*(1990)
OFR 92-287	Gibbs *et al.*(1992)
OFR 93-376	Gibbs *et al.*(1993)
OFR 94-222	Gibbs *et al.*(1994a)
OFR 94-552	Gibbs and Fumal (1994)
OFR 94-706	Gibbs *et al.*(1994b)
OFR 99-446	Gibbs *et al.*(1999)
OFR 00-470	Gibbs *et al.*(2000)
OFR 01-506	Gibbs *et al.*(2001)
OFR 02-203	Gibbs *et al.*(2002)
OFR 03-191	This open-file report