Density prediction from ground-roll inversion

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Summary

Bulk densities are often predicted from seismic velocities using the Gardner's relation if density information is unavailable. P-wave velocity is used in the Gardner's relation. We used a modified Gardner's relation to predict bulk densities from S-wave velocities where we estimated S-wave velocities using the noninvasive ground-roll inversion method. Different types of seismic data sets have been used: i) numerical and physical modeling; ii) data from: Red Lodge, Montana, and the Barringer (Meteor) Crater, Arizona. The main objectives of the paper are: i) to test the modified Gardner's relation for different types of materials, ii) to estimate errors between known and predicted bulk densities, and iii) to compare different empirical exponent values to minimize the error. We estimate predicted densities with maximum error of 0.5 gm/cc for known values (the blank glass model and Montana site). A maximum change of ± 0.01 in the exponent values provide a better match for the known models. We find exponential values for the modified Gardner's relation varying from 0.21 to 0.23 for all the cases compared to the suggested value of 0.22. So, the prediction of bulk densities for varied materials maintains a confidence level of above 90%.

Introduction

We need a good approximation of seismic velocities and bulk densities to estimate reflectivity in synthetic seismogram generation. Sometimes both seismic velocities and bulk densities are known from the well log or any other available sources (drill cores, previous works etc.). But often this is not the case. Gardner et al. (1974) provided the popular empirical relationship to relate bulk density to seismic velocity. But, this was originally only for P-wave velocities (V_P). A few attempts have been made (Miller and Stewart, 1990; Dey and Stewart, 1997; and Potter and Stewart, 1998) to test that relationship for S-wave velocities (V_S). In this paper, we have used the modified Gardner's relationship (Potter and Stewart, 1998) to predict bulk densities from S-wave velocities. We have analyzed seismic data sets from significantly different settings to estimate S-wave velocities using the ground-roll inversion method. We used varied seismic data sets such as – a) synthetic data from finite-difference modeling for layered elastic media, b) physical modeling data for an uniform blank glass block using ultrasonic measurement facilities at the Allied Geophysical Laboratories, University of Houston; and data from- c) the Yellowstone-Bighorn Research Association (YBRA) field camp at Red Lodge, Montana, and d) the Barringer (Meteor) Crater, Arizona. Modeling data are useful to test the ground-roll inversion method and the existing density prediction formula. Field data are used to test the dependability of the predictions for varied geological settings and rock properties (especially for the near-surface).

Seismic data sets from various settings

a) **Numerical modeling:** Synthetic seismic data sets for a three-layered (two layers over a half-space) model are generated using a elastic finite-difference numerical modeling code for layered isotropic medium (Manning, 2007 and Al Dulaijan, 2008). We used the code written by Manning (2007). We used receiver interval of 2 m with a receiver spread of 300 stations, source-receiver offset of 10 m, and shot interval of 10 m. Physical properties of the model are given as – Layer 1: V_P = 1000 m/s, V_S = 500 m/s, density = 1.74 gm/cc, thickness = 30 m, Layer 2: V_P = 1300 m/s, V_S = 740 m/s, density = 1.86 gm/cc, thickness = 70 m, and Half-space: V_P = 1800 m/s, V_S = 1100 m/s, ρ = 2.02 gm/cc. Densities of each layer are set using the original Gardner's relation for P-wave.

b) Physical modeling: We acquired seismic data sets over a uniform velocity blank glass model (Figure 1) using the ultrasonic measurement systems at AGL, University of Houston. Vertical contact transducers of 1 MHz central frequency are used as source and receivers. We used receiver interval of 0.4 mm (i.e. 4 m when scaled by the seismic-ultrasonic factor) with 26-receiver spread, source-to-receiver offset of 1.6 mm (160 m) and shot interval of 0.4 mm (4 m). The blank glass model has V_P of ~5465 m/s, V_S of ~3400 m/s and density ~ 2.6 gm/cc.

c) YBRA, MO: The YBRA field camp site of the University of Houston is situated on a highly complex structural set up in the Beartooth Mountain range with overturned beds and a tear fault involving the Mississippian Madison limestone and younger strata (Mukherjee and Stewart, 2010). An East-West trending 2D seismic line was shot along the tear fault with a truck mounted accelerated weight drop as source and vertical planted geophones as receivers. We used both shot and receiver intervals as 3 m while shot location is in between receivers. Two shallow wells (YB1-30 m and YB2-60 m) were also drilled at the tear zone and different geophysical loggings (sonic, density, natural gamma, resistivity, full waveform sonic, acoustic televiewer and neutron porosity) and VSP surveys were performed.

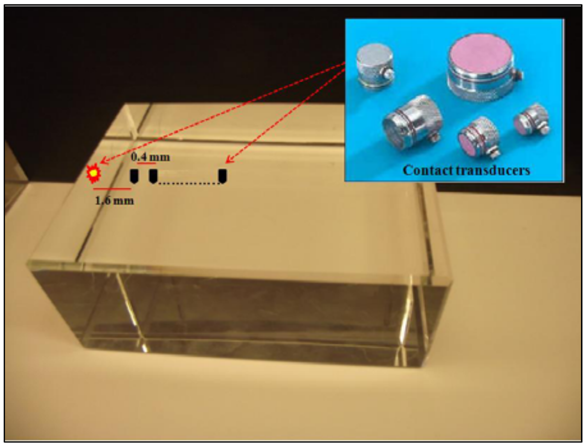


Figure 1. The figure shows a blank glass model at AGL, University of Houston with the ultrasonic measurement facilities (contact transducers) in inset. The shot-receiver offset is 1.6 mm (x10000 m) and receiver interval is 0.4 mm (x10000 m). Total 26 receivers were used per shot.

d) Barringer (Meteor) Crater, AZ: This 49000 year old meteorite impact crater was created by excavating the pre-existing Colorado Plateau. The present day stratigraphy from bottom to top consists of the following sequences – Coconino (sandstone)-Toroweap (sandstone and dolomite)-Kaibab (dolomite and dolomitic limestone)-Moenkopi (calcareous siltstone with iron-rich matrix and sandstone) overlain by the low-velocity ejecta blanket at the top (Kring, 2007). The ejecta blanket is a sheet of debris thrown out of the crater during the impact and composed of overturned sequences (the normal stratigraphy was overturned due to impact) and fragments of meteorites. Some old drill cores are available from which some idea of bulk densities can be obtained. We used data from a 645 m long seismic line with same acquisition parameters as the YBRA site.

S-wave velocities from the ground-roll inversion

We use a high resolution, near-surface S-wave velocity structure to predict bulk densities. We have applied the ground-roll inversion method to obtain this near-surface S-wave velocity. We used the Multichannel Analysis of Surface Waves (MASW) method from available ground-roll inversion methods (Park et al., 1998; ibid, 1999; Xia et al., 1999). MASW uses the dispersion properties of ground-roll (or Rayleigh wave) to create dispersion curves (phase velocity versus frequency plots). Then, these dispersion curves are inverted for the fundamental (and higher) modes to obtain the near-surface S-wave velocity structure. The practical advantages we can have from this method are: a) cost effective as this does not require any additional data acquisition and it is noninvasive in nature; and b) easy to use as no tiresome first-break-pick method is involved.

Bulk density prediction from S-wave velocities

As mentioned previously, Gardner et al. (1974) established an empirical relationship based on the broad range of P-wave velocities and relatively narrower range of bulk densities for the dominant sedimentary rocks throughout wide range of geological settings. The range of data samples contained depths less than 25000 ft and P-wave velocities more than 5000 ft/s. The Gardner's relationship can be represented as –

$$\rho = aV_P^b \qquad (1)$$

where, ρ is the bulk density in gm/cc, a and b are empirical parameters and V_P is the P-wave velocity in m/s or ft/s. The value of a is 0.23 when V_P is in ft/sand the exponent b is 0.25. Densities for most of the common sedimentary rocks fall in the neighborhood of the Gardner's line with exceptions such as coals and evaporate.

On the other hand, the use of multicomponent data and increasing availability of S-wave seismic data sets opens up the avenue to use S-wave velocities also for predicting bulk densities. It should add more value to the predicted densities from P-wave (as in general, the S-wave is a good indicator of lithologies). Also, S-wave velocities can be used when P-wave velocities are unavailable or of poor quality. A modified Gardner's relation for S-wave velocities was provided by Potter and Stewart (1998) where they used a = 0.37, b = 0.22, and V_S (instead of V_P) in ft/s.

We first applied the formula to the known blank glass model to test the modified Gardner's equation for S-wave. For the blank model, V_S is 11152 ft/s (3400 m/s). Using the modified Gardner's relation with a = 0.37 and b = 0.22, we estimate bulk density = 2.87 gm/cc. The estimate shows an error of 0.27 gm/cc as the known density is 2.6 gm/cc. But, the prediction is very close and in fact b = 0.21 gives the exact match. Then, we applied the formula for the YBRA field site data where we have a measured density log. The measured bulk densities obtained from a 30 m well vary from 1.63 - 2.46 gm/cc. S-wave velocities are obtained from S-wave refraction analysis of the VSP data of the same well (Mukherjee and Stewart, 2010). We considered those values as ground-truth. Applying the modified Gardner's relation for S-wave velocities, we estimated bulk densities in the range of 1.74 – 2.22 gm/cc. The predicted result is in the range of the measured values with an error range of 0.25 – 0.5 gm/cc. The use of b = 0.23 gives a better match with a maximum error of 0.4 gm/cc. The cross plot of the logarithm of V_S in ft/s versus the logarithm of the bulk density in gm/cc is shown in Figure 2 for the YBRA site and the blank glass model. The best-fit line shows a = 0.14 and b = 0.36. But, these estimated values should not be conclusive as – i) the number of suitable data points from YBRA site is very small and scattered, ii) they are from the near-surface with low-velocities (where original Gardner's relation is valid for velocities > 5000 ft/s), and iii) when we fitted a line with fixed intercept (as the original a = 0.37), we estimated b = 0.23 which is very close to the suggested value.

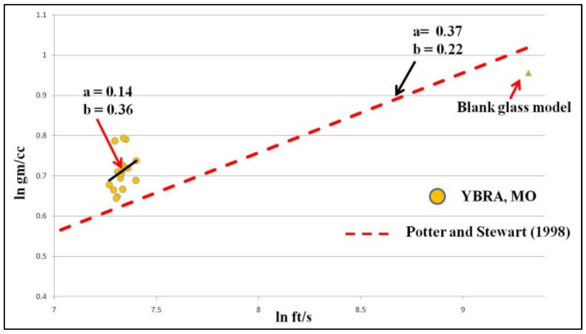
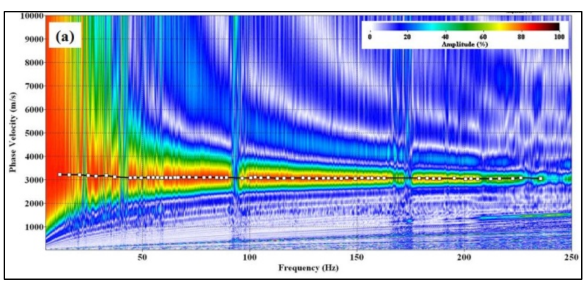


Figure 2. The cross-plot of logarithm of Vs in ft/s and bulk density in gm/cc for the YBRA field site along with the blank glass model.

Results

We then applied the ground-roll inversion method to above mentioned seismic data sets. First, the dispersion curve for one shot gather is generated and then it is inverted for the fundamental (and higher) mode to obtain the 1D S-wave velocity profile. Many 1D profiles are merged to obtain a 2D S-wave velocity structure. Examples of such dispersion curves are shown in Figure 3. The blank glass model consists of only a uniform layer over the half-space. Hence, the dispersion curve (Figure 3a) is relatively flat compared to the Barringer Crater data (Figure 3b) since it is the real data with unconsolidated, complex, multilayered, near-



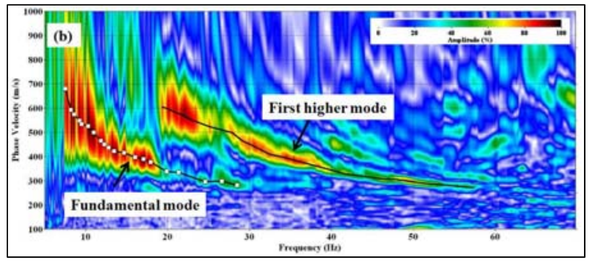


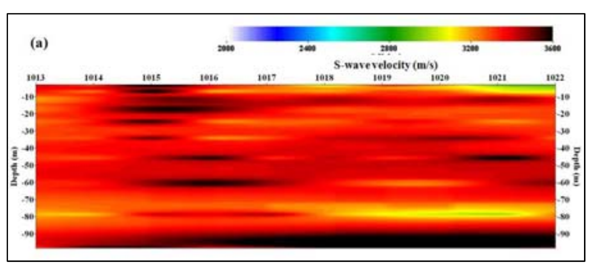
Figure 3. Dispersion curves from a) the blank glass model, and b) the Barringer Crater site. The curve in (a) is very flat compared to the well-developed multimodal dispersion curves in (b).

surface materials. S-wave velocities (~ 3400 m/s) of up to 90 m are obtained for the blank glass model (Figure 4a). S-wave velocities vary from 200-700 m/s for the top 16 m depth to 900-1000 m/s at 36 m depth (Figure 4b) for the Barringer site which is hugely different from the model case. We interpreted a prominent change in S-wave velocity (500-550 m/s) as the transition from the ejecta blanket to the bed-rock Moenkopi (Figure 4b). Estimated S-wave velocities from the ground-roll inversion method for all data sets are provided in Table 1.

Table 1. A summary of known and estimated Vs.

Vs (m/s)	Numerical Model	Physical model	YBRA, Montana	Barringer Crater
Known	500-740	3400	300-900	N/A
Ground-roll inversion	450-800	3200-3500	300-1000	400-1000

Then, we used the modified Gardner's relation (Potter and Stewart, 1998) to predict bulk densities from estimated S-wave velocities from the ground-roll inversion. Examples of the predicted bulk density results are shown in Figure 5. The 2D bulk density profile for the numerical modeling up to a depth of 44 m has been estimated. The range of predicted bulk densities for the numerical modeling is 1.65-2.05 gm/cc where the known densities vary from 1.75-1.86 gm/cc. Also, predicted densities up to 45 m for the Barringer Crater site is 1.6-2.5 gm/cc where known values



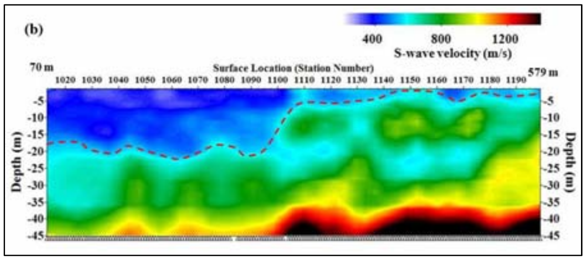


Figure 4. 2D S-wave velocity profiles for (a) the uniform blank model, and (b) the Barringer Crater site. The dashed red line in (b) shows our interpretation of the transition from the lower to higher velocity (ejecta blanket to Moenkopi) based on the estimated S-wave velocities from the ground-roll inversion method.

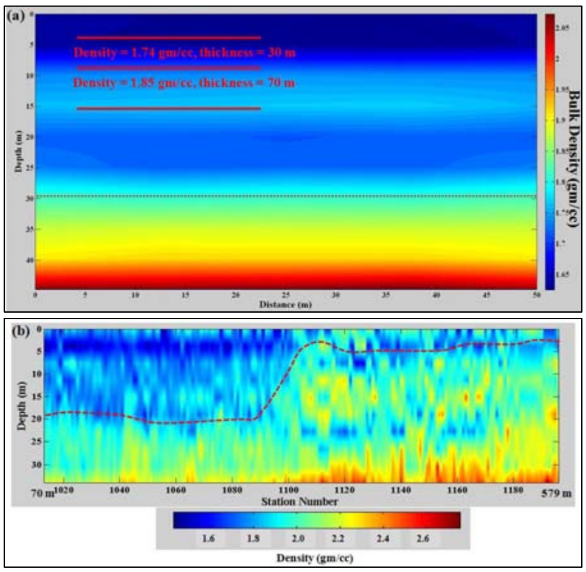


Figure 5. 2D bulk density profiles for (a) the numerical model, and (b) the Barringer Crater site. The red dashed line in (a) shows the transition from layer1 to layer 2 (1.75-1.85 gm/cc) and the dashed red line in (b) is the same as in Figure 4b.

vary from 1.85-2.4 gm/cc. Though, we have very few known densities for the crater site. A summary of the predicted bulk densities for each data set has been provided in Table 2.

Conclusions

We have assessed a modification to Gardner's relationship to predict density from S-wave velocity. It provides some

Table 2. A summary of known and predicted bulk densities.

Bulk density (gm/cc)	Numerical Model	Physical model	YBRA, Montana	Barringer Crater
Known	1.75-1.86	2.6	1.8-2.4	1.85-2.4
Predicted	1.65-2.05	2.5-2.65	1.8-2.38	1.65-2.3

reasonable results. We used a noninvasive method to predict bulk densities from S-wave velocities and compared with known densities. In some cases (Barringer Crater) known density data points are less and scattered. All predicted densities are consistent with known values with an error of maximum 0.5 gm/cc. We also changed the exponent values to minimize the error. The exponent *b* varies from 0.21 to 0.234 compared to suggested value of 0.22 with a deviation of 4.35-6.36 %. The method worked well for very low velocities also. Though, experiments with much more data points are required to establish the modified Gardner's relation for regular use

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EDITED REFERENCES

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