Egyptian Geophysical Society
EGS Journal, Vol. 15, No. 1, 165-173 (2017)

CALCULATING THE TRUE SEISMIC VELOCITY OF THE DIPPING INTERFACES USING A NEW GENERALIZED ALGORITHM

*M. Rabei**

* Exploration Division, Nuclear Material Authority, Cairo, Egypt.
P. O. Box: 530 Al-Maadi, Cairo, Egypt, Email: mrabeia@hotmail.com

حساب السرعة السيزمية الحقيقية للأسطح البينية المائلة باستخدام خوارزمية عامة جديدة

الخلاصـــة: يتم استخدام تقنية الانكسار السيزمي الضحل على نطاق واسع لتحديد معاملات المرونة والأعماق الحقيقية للطبقات التحت سطحية عن طريق حساب السرعات الحقيقية للموجات الزلزالية التى تمر من خلال هذه الطبقات، تلك السرعات التي تعتبر بالغة الأهمية فى التطبيقات الجيوتقنية.عند الأسطح البينية المائلة، فان حساب السرعة السيزمية الحقيقية يعتبر عملية صعبة للغاية الى ان تم استخدام متوسط السرعة التوافقي للسرعات الظاهرية وذلك لمعرفة السرعة السيزمية الحقيقية. ومع ذلك، فان تلك الطريقة تفشل فى تحديد السرعة الحقيقية للأسطح البينية المائلة عندما تكون زوايا ميل الطبقات مساوية أو أكبر من زوايا السقوط الحرجة.

تقدم هذه الدراسة خوارزمية عامة جديدة لحساب متوسط السرعة التوافقي لأي سطح مائل باستخدام صيغة جديدة تهدف الى تقديم تقدير جيد للسرعة الحقيقية لهذه الأسطح المائلة. فحساب متوسط السرعة التوافقي باستخدام الخوارزمية الجديدة المقترحة لا يقلل نسبة الخطأ بين متوسط السرعة التوافقي المحتسب والسرعة الحقيقية فقط، ولكنه نجح أيضا في تحديد متوسط السرعة التوافقي حتى عندما تكون زوايا الميل للأسطح البينية المائلة مساوية أو أكبر من زوايا السقوط الحرجة.

اثبتت التجارب على البيانات الزلزالية الاصطناعية والحقيقية التي تمثل نماذج الأرض الشائعة والأكثر واقعية، أن السرعات التوافقية المقدرة باستخدام الخوارزمية العامة تتناسب مع سرعات النموذج الحقيقية مع قدر لا بأس به من نسبة الخطأ، والتي يمكن أن تظل دون ٠,٧٪ خلال البيانات الاصطناعية و ١,٥٪ خلال دراسات الحالة الحقيقية.

ABSTRACT: *The shallow refraction seismic technique is broadly used to determine the elastic moduli and true depths of the underlying layers by calculating the true velocities of seismic waves travelling through these strata, which are critical to engineering investigations. At dipping interfaces, computing the true seismic velocity is so difficult until the harmonic mean velocity approximation of the apparent velocities is used to figure out the true velocity. However, the harmonic approximation fails to determine the true velocity of the dipping interfaces when the dipping angles of the interfaces are equal or greater than the critical angles.*

This study presents a new generalized algorithm to compute the harmonic mean velocity of any dipping interface using a new formula aiming at providing us with a good estimation for the true velocity of these inclined interfaces. This does not only maintain the error percentage between the calculated harmonic mean velocity and the true velocity, but it also succeeds in determining the harmonic mean velocity even when the dipping angles of the dipping interfaces are equal or greater than the critical angles. The trials experienced on the provided synthetic and real seismic data, representing most realistic earth models, establish that the harmonic velocities estimated using the generalized algorithm to fit the actual model velocities with a fair measure of error percentage, can be remained below 0.7% within synthetic data and 1.5% within real case studies.

INTRODUCTION

Seismic refraction theory is a cornerstone in shallow geophysical investigations. As a consequence, its basics and limitations have been intensively discussed in many previous studies (e.g., Ewing, et. al., 1939; Slotnick, 1959; Grant & West, 1965; Griffiths & King, 1965; Musgrave, 1967; Dobrin, 1976; Telford, 1976; Parasnis, 1979; Mooney, 1981; and Sjögren, 1984). Determination of the true velocity of inclined layers occupies a major part of these studies. Many authors proposed different ways to estimate the true seismic velocity of the inclined layers. Most of these studies suggest using of harmonic mean velocity, for the second interface only (Redpath, 1973; Sjögren, 1984; Parasnis, 1986), while some authors suggest using the arithmetic average of the apparent velocities of the layer (Telford, *et. al*., 1990).

Seisa (1991) introduced an approach to calculate the harmonic mean velocity of the second layer by using the double distance existed between the shot point and the point at which the forward and reverse slopes of the second layer are intersected, divided by the time difference between the intercept time and the reciprocal time of the second layer. Thereby, it is significantly evident that Seisa (1991) used a special case to calculate the harmonic velocity, by which the interpreter has to measure the distance between two certain points (shot point and intersection point). Thus, this simple approach presented a limited choice (i.e. a case of one dipping layer with one form), which is a special case in the present study. Accordingly, the current investigation introduces a generalized algorithm that can fit to several cases, and provides determination of the true velocity, not only for the first inclined refractor, but also for the other underlyingones centering on different distance-time ratios.

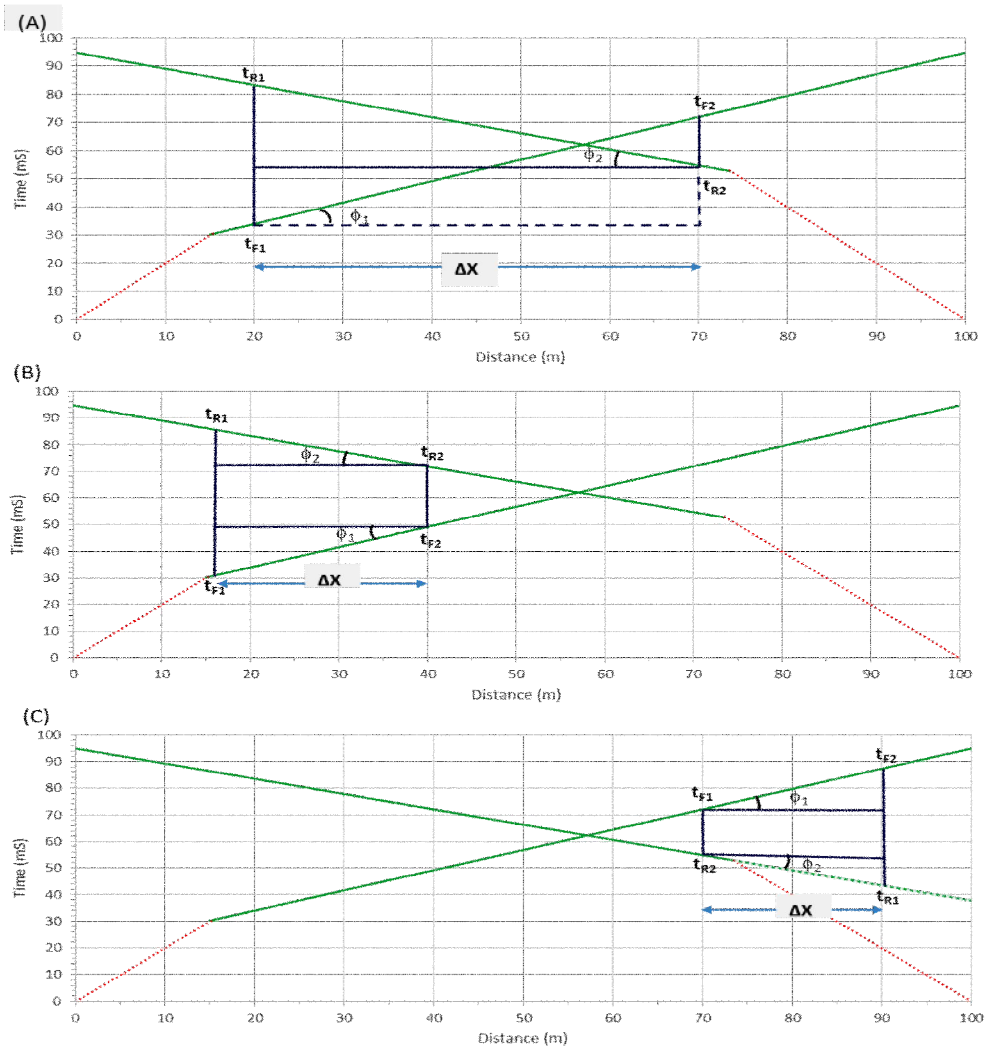

Figure (1): Traveltime graph of a dipping layer: A) calculation of the harmonic velocity when the intersection point lies inside the used distance (ΔX), B) the intersection to the right of the measurements, and C) the intersection to the left.

Methodology:

a) Computing the harmonic velocity using distance-time difference ratio for the dipping interfaces:

Consider two segments of a travel time graph of a reversed refraction spread that represents the up and down-dip of the apparent velocities of a dipping interface of any layer (n) beneath the ground surface, as shown in equation (1).

In all different cases (A, B, and C) illustrated in Figure 1:

$$\tan \phi_1 = {}^{1}/_{V_{dn}} = \frac{(t_{F2}-t_{R2})+(t_{R2}-t_{F1})}{\Delta X} \quad (1)$$

$$\tan \phi_2 = {}^{1}/_{V_{un}} = \frac{t_{R1}-t_{R2}}{\Delta X} \quad (2)$$

Where:

V_{un}: Up-dip apparent velocity of the interface (n),

V_{dn}: Down-dip apparent velocity of the interface (n),

t_{F1}: Arrival time at point (x_1) of the forward shot of the interface (n),

t_{R1}: Arrival time at point (x_1) of the reverse shot of the interface (n),

t_{F2}: Arrival time at point (x_2) of the forward shot of the interface (n), and

t_{R2}: Arrival time at point (x_2) of the reverse shot of the interface (n),

By summation of equations (1) and (2), then:

$$\frac{V_{dn}+V_{un}}{V_{dn}*V_{un}} = \frac{(t_{R1}-t_{f1})+(t_{F2}-t_{R2})}{\Delta X} = \frac{\Delta t}{\Delta X} \quad (3)$$

Where: $\Delta t = (t_{R1} - t_{f1}) + (t_{F2} - t_{R2})$, Since the harmonic velocity (V_{hn}) of the interface (n) is: $\frac{2.V_{dn} * V_{un}}{V_{dn} + V_{un}}$,Then:

$$V_{hn} = \frac{2\Delta X}{(\Delta t)} \quad (4)$$

Equation (4) can be applied for any dipping interface(n) to calculate the harmonic velocity (V_{hn}) by computing the distance-time difference ratio ($\frac{2\Delta X}{(\Delta t)}$), for any two successive points along the travel time curve divided by the time difference. This ratio enables the interpreter to choose any point on the travel time curve; especially at geophone's locations, to exclude any error could come from the distance interpolation between geophone locations.

b) Relation between the true and harmonic velocity of dipping interfaces:

Depending on the well-known equations initially inferred by Ewing *et al*., (1939), that later modified by Adachi (1945), and considering Figure (2), the reciprocal of the apparent velocity ($\frac{1}{V_{dn}}$) of the dipping interface (n) at the down-dip is: $\frac{\sin(\beta_{1n})}{V_1} = \frac{1}{V_{dn}}$…. (5), Adachi (1954),

While the reciprocal of the apparent velocity ($\frac{1}{V_{un}}$) of the inclined layer (n) at up-dip is:

$$\frac{\sin(\alpha_{1n})}{V_1} = \frac{1}{V_{un}} \text{….. (6), Adachi (1954),}$$

where:

$\alpha_{in} and \beta_{in}$:The incident angles in the dipping interface numbered (i) of down-dip and up-dip respectively, that totally make the ray-path refracted at the dipping interface number (n), i.e. if i= 1 &n=4, thenA_{14} is the incident angle in the layer number (1) that totally makes the ray-path refracted at the dipping interface number (4);

V_1: Velocity of the first layer;

Equations (5) and(6) can be modified, when the ground surface is inclined by the dip angle ($\omega_1{}^{\circ}$) into:

$$\frac{\sin(\beta_{1n})}{V_1 \cos\omega_1} = \frac{1}{V_{dn}} \text{ ………………………… (7)}$$

$$\frac{\sin(\alpha_{1n})}{V_1 \cos\omega_1} = \frac{1}{V_{un}} \text{ ………………………….. (8)}$$

In the following, equations (7 & 8) can be used to derive the relation between the harmonic velocity and the true velocity.

1. Relation between the true and harmonic velocity of the second interface:

Using the symbols in Figure (2) and equations (7&8), the harmonic velocity of the second layer (where: $n = 2$)can be calculated, as follows:

Since the down-dip slope ($1/V_{d_2}$) of the inclined layer number (2) is:

$$\frac{1}{V_{d_2}} = \frac{\sin(\beta_{12})}{V_1 \cos\omega_1} \text{………. (9),}$$

Where:

$$\sin(\beta_{12}) = \sin(B_{12} + (\omega_2 + \omega_1)),$$

Moreover, the up-dip slope ($1/V_{u_2}$) of the same layer is:

$$\frac{1}{V_{u_2}} = \frac{\sin(\alpha_{12})}{V_1 \cos\omega_1} \text{ ………….. (10)}$$

where:

$$\sin(\alpha_{12}) = \sin(A_{12} - (\omega_2 + \omega_1)).$$

Summation of equations (9 &10) leads to:

$$\frac{1}{V_{d_2}} + \frac{1}{V_{u_2}} = \frac{\sin(Ic_{12} + (\omega_2 + \omega_1)) + \sin(Ic_{12} - (\omega_2 + \omega_1))}{V_1 \cos\omega_1},$$

where: $A_{12} = B_{12} = Ic_{12} = \text{critical angle.}$

By simplifying the equatin, then the harmonic velocity (V_{h_2}) of the second inclined layer equals:

$$V_{h_2} = \frac{V_2 \cos\omega_1}{\cos(\omega_2 + \omega_1)} \text{…….. (11)}$$

where: V_2 is the true velocity of the second layer.

2. Relation between the true and harmonic velocity of the third layer:

Using equations (7& 8), the harmonic velocity of the third layer can be calculated as follows:

Since the down-dip slope of the third inclined layer ($\frac{1}{V_{d_3}}$) is:

$$\frac{1}{V_{d_3}} = \frac{\sin(\beta_{13})}{V_1 \cos\omega_1} \text{ ……………………….. (12),}$$

where:

$$\sin(\beta_{13}) = \sin(B_{13} + (\omega_2 + \omega_1)).$$

Also, since the up-dip slope of the third inclined layer ($\frac{1}{V_{u_3}}$) is:

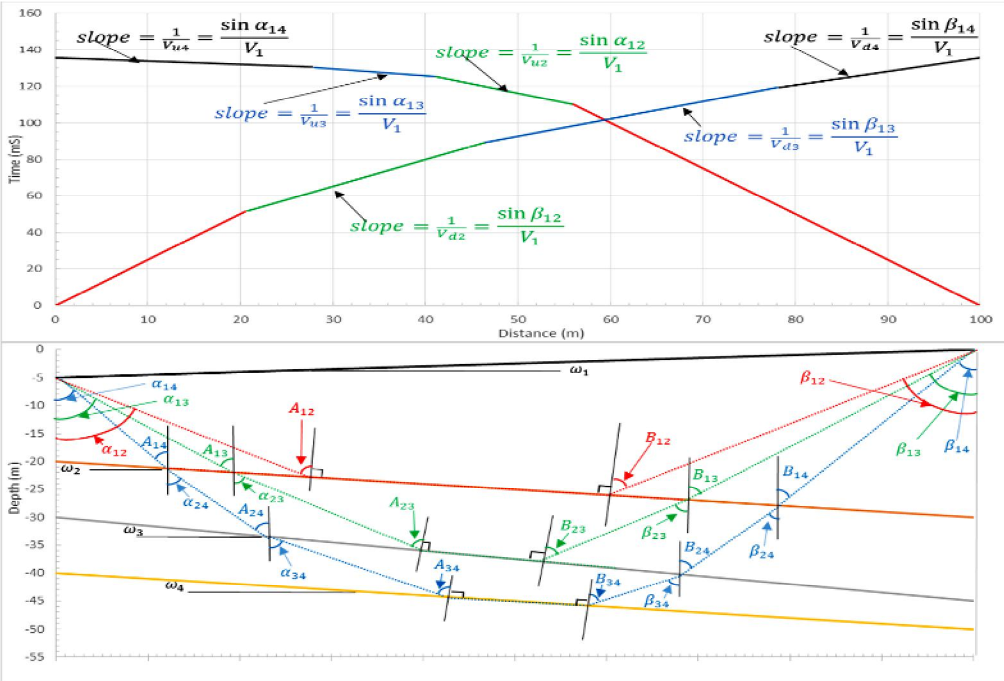

Figure (2): Travel time graph of four segments and their related layered model.

$$\frac{1}{V_{u_3}} = \frac{\sin(\alpha_{13})}{V_1 \cos\omega_1} \quad \ldots\ldots\ldots\ldots\ldots (13)$$

where:

$$\sin(\alpha_{13}) = \sin(A_{13} - (\omega_2 + \omega_1)),$$

By the summation of equations 12 and 13:

$$\frac{1}{V_{d_3}} + \frac{1}{V_{u_3}} = \frac{\sin(A_{13} - (\omega_2 + \omega_1)) + \sin(B_{13} + (\omega_2 + \omega_1))}{V_1 \cos\omega_1}$$

Then:

$$\frac{V_{d_3} + V_{u_3}}{V_{d_3} V_{u_3}} = \frac{\left[\begin{matrix}[(\sin(A_{13}) + \sin(B_{13})) * \cos(\omega_2 + \omega_1)] + \\ [(\cos(A_{13}) - \cos(B_{13})) * \sin(\omega_2 + \omega_1)]\end{matrix}\right]}{V_1 \cos\omega_1}$$

.where, the term

$$[(\cos(A_{13}) - \cos(B_{13})) * \sin(\omega_2 + \omega_1)]$$

can be simplified into:

$$\left[(\sin(A_{13}) + \sin(B_{13})) * \tan\left(\frac{A_{13} - B_{13}}{2}\right)\right]$$

, and while $\tan\left(\frac{A_{13} - B_{13}}{2}\right) = \tan(\omega_2 - \omega_1)$, then:

$$\frac{V_{d_3} + V_{u_3}}{V_{d_3} V_{u_3}} =$$

$$= \frac{\left[\begin{matrix}[\sin(A_{13}) + \sin(B_{13})] * \\ \cos(\omega_2 + \omega_1)\end{matrix}\right] + \left[\begin{matrix}[\sin(A_{13}) + \sin(B_{13})] * \\ [\tan(\omega_2 + \omega_1) * \\ \sin(\omega_2 + \omega_1)]\end{matrix}\right]}{V_1 \cos\omega_1}$$

$$= \frac{[\sin(A_{13}) + \sin(B_{13})]\left[\begin{matrix}\cos(\omega_2 + \omega_1) + \\ [\tan(\omega_2 + \omega_1) * \\ \sin(\omega_2 + \omega_1)]\end{matrix}\right]}{V_1 \cos\omega_1}$$

$$= \frac{[\sin(A_{13}) + \sin(B_{13})]}{V_1 \cos\omega_1 * \cos(\omega_2 + \omega_1)} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

where:

$$\sin(B_{13}) = \frac{V_1}{V_2} * \sin(Ic_{23} + (\omega_3 - \omega_2))$$

$$\sin(A_{13}) = \frac{V_1}{V_2} * \sin(Ic_{23} - (\omega_3 - \omega_2));$$

After the substitution of the values of $\sin(B_{13})$ and $\sin(A_{13})$ in equation (14):

The harmonic velocity (V_{h_3}) can be:

$$V_{h_3} = \frac{V_3 \cos\omega_1 * \cos(\omega_2 + \omega_1)}{\cos(\omega_3 - \omega_2)} \quad \ldots\ldots\ldots (15),$$

where: (V_3) is the velocity of the third layer.

3. Relation between the true and harmonic velocity of the fourth layer:

Using equations (7& 8), the harmonic velocity of the third layer can be calculated as follows:

The down-dip slope of the fourth inclined layer ($\frac{1}{V_{d_4}}$) is:

$$\frac{1}{V_{d_4}} = \frac{\sin(\beta_{14})}{V_1 \cos\omega_1} \quad \text{………………………….. (16)}$$

where:

$\sin(\beta_{14}) = \sin(B_{14} + (\omega_2 + \omega_1))$,

While, the up-dip slope of the fourth inclined layer number ($\frac{1}{V_{u_4}}$) is:

$$\frac{1}{V_{u_4}} = \frac{\sin(\alpha_{14})}{V_1 \cos\omega_1} \quad \text{…………………………... (17)}$$

where:

$\sin(\alpha_{14}) = \sin(A_{14} - (\omega_2 + \omega_1))$,

By the summation of equations (16 & 17):

$$\frac{1}{V_{d_4}} + \frac{1}{V_4} = \frac{\sin(B_{14} + (\omega_2 + \omega_1)) + \sin(A_{14} - (\omega_2 + \omega_1))}{V_1 \cos\omega_1}$$

Then:

$$\frac{V_{d_4} + V_{u_4}}{V_{d_4} V_{u_4}} == \frac{[(\sin(B_{14}) + \sin(A_{14})] * \cos(\omega_2 + \omega_1)] + [(\cos(B_{14}) - \cos(A_{14}) * \sin(\omega_2 + \omega_1)]}{V_1 \cos\omega_1}$$

$$= \frac{(\sin(B_{24}) + \sin(A_{24}))}{V_1 \cos\omega_1 * \cos(\omega_2 + \omega_1)}$$

Since:

$$\sin(B_{14}) = \frac{V_1}{V_2} * \sin(B_{24} + (\omega_3 - \omega_2))$$

$$\sin(A_{14}) = \frac{V_1}{V_2} * \sin(A_{24} - (\omega_3 - \omega_2))$$

Then:

$$\frac{V_{d_4} + V_{u_4}}{V_{d_4} V_{u_4}} == \frac{[\frac{V_1}{V_2} * \sin(B_{24} + (\omega_3 - \omega_2))] + [\frac{V_1}{V_2} * \sin(A_{24} - (\omega_3 - \omega_2))] * \cos(\omega_2 + \omega_1)}{V_1 \cos\omega_1 * \cos(\omega_2 + \omega_1)}$$

$$= \frac{[(\sin(B_{24}) + \sin(A_{24}))}{V_2 \cos\omega_1 * \cos(\omega_2 + \omega_1) * \cos(\omega_3 - \omega_2)}$$

By the simplification and substitution of the values of $\sin(A_{24})$ and $\sin(B_{24})$, as the previous steps, then:

$$\sin(A_{24}) = \frac{V_2}{V_3} * \sin(Ic_{34} - (\omega_4 - \omega_3)),$$

$$\sin(B_{24}) = \frac{V_2}{V_3} * \sin(Ic_{34} + (\omega_4 - \omega_3)),$$

Also, the harmonic velocity (V_{h_4}) of the fourth layer will be:

$$V_{h_4} = \frac{V_4 * \cos\omega_1 * \cos(\omega_2 + \omega_1) * \cos(\omega_3 - \omega_2)}{\cos(\omega_4 + \omega_3)} \quad \text{…. (18)}$$

where: V_4 is the true velocity of the fourth layer.

4. The general form:

Using the equations (11), (15), and (18), a general equation can be derived to determine the relation between the harmonic velocity (V_{h_n})and the true velocity of the layer (n)is:

$$V_{h_n} = \frac{V_{Tn} * \prod_{i=0}^{n-2} \cos(\omega_{i+1} - \omega_i)}{\cos(\omega_n - \omega_{n-1})} \quad \text{…….. (19)}$$

where:

(V_{Tn}) is the true velocity of the layer (n), when $(i = 0)$, then the value of (ω_0)equals Zero.

c) Relation betweenthe true velocity(V_{Tn}) of any dippinginterface (n)and the harmonic velocity (V_{hn})computed using the distance-time difference ratio:

From equations (4) and (19), the harmonic velocity (V_{hn}) of the layer "n" is:

$$V_{h_n} = \frac{2\Delta X}{\Delta t} = \frac{V_{Tn} * \prod_{i=0}^{n-2} \cos(\omega_{i+1} - \omega_i)}{\cos(\omega_n - \omega_{n-1})}$$

Therefore, the true velocity (V_{Tn}) of the layer(n) is:

$$V_{Tn} = \frac{2\Delta X}{\Delta t} * \frac{\cos(\omega_n - \omega_{n-1})}{\prod_{i=0}^{n-2} \cos(\omega_{i+1} - \omega_i)} \quad \text{…(20)}$$

Equation (20) clarifies the general relation between the true velocity and the harmonic velocity of any layer, which can be used to compute the true velocity using the distance-time difference ratio.

Synthetic data and case studies

Five synthetic models and two case studies of different locations had been used to validate the new formula. All the synthetic models are produced using IXRefraX program (Interpex, 2010). The first three models, figures (3, 4, & 5) show that, using the proposed distance-time difference ratio construction to obtain the harmonic velocity (V_{hr}) values are more successful than using the statistical harmonic mean of the apparent velocities (V_{hs}), that fail to obtain the harmonic velocity at dipping interfaces, that have dip amounts equal to or greater than the critical angle, i.e. model 2 and model 3. Also, it is remarkably noticeable that the error percentage between the harmonic velocity and the true velocity is less than 0.7% (table 1).

The second two synthetic models, figures (6 &7) are representing the most realistic earth models that have low to moderate dip amounts. These two models illustrate harmonic velocity (V_{hr}) values close to those velocity values with error percent 0.5% (Table 1). While the new algorithm enables us to determine the harmonic velocity of all interfaces, the traditional method computed only for the fourth model.

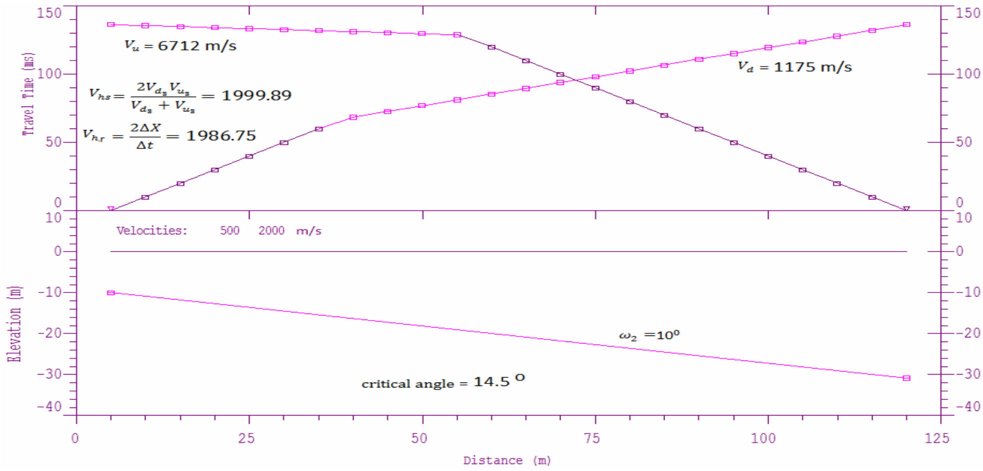

Figure (3): Travel time graph of an interface with dipping amount less than the critical angle.

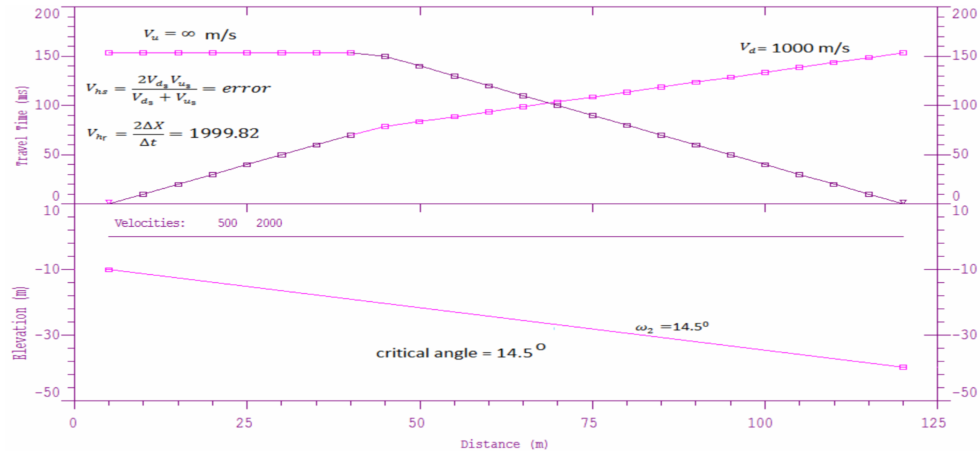

Figure (4): Travel time graph of an interface with dipping amount equal to the critical angle.

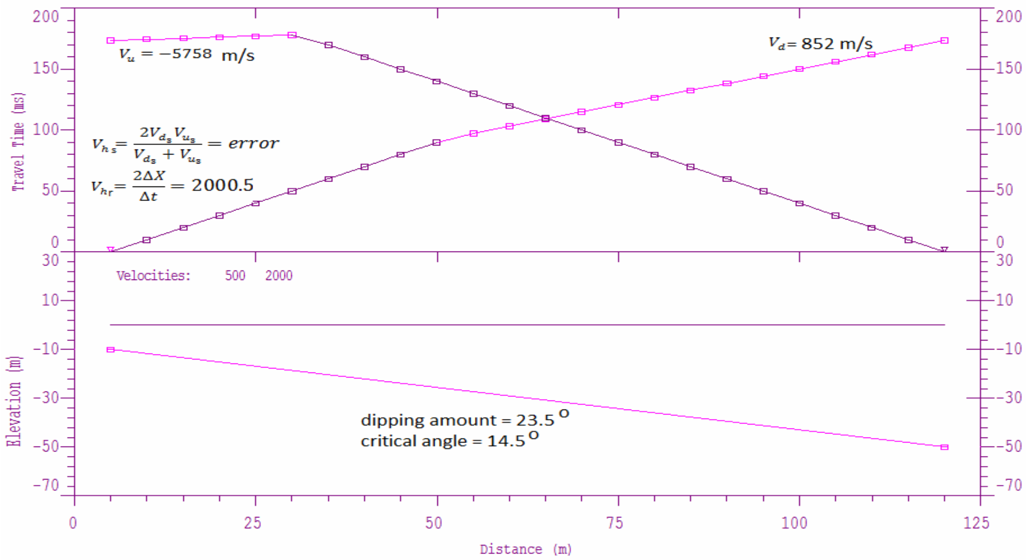

Figure (5): Travel time graph of an interface with dipping amount greater than the critical angle.

Table (1): Results of the synthetic and real case sties showing the differences between deferent type of velocity and error percentage.

	True Velocity	Harmonic Velocity $V_{hg} = \frac{2\Delta X}{\Delta t}$		Harmonic Velocity $V_{hs} = \frac{2V_{d_2}V_{u_2}}{V_{d_2}+V_{u_2}}$		Dipping amount
			error %		error %	
Model -1						
V2	2000	1986.75	0.66	1999.89	0.01	10
Model -2						
v2	2000	1999.82	0.01	error		14.5
Model -3						
v2	2000	2000.5	0.01	error		23.5
Model -4						
v2	1500	1503.06	0.15	1493.72	0.42	3.4
v3	2500	2510.06	0.4	2509.78	0.39	5.7
v4	3500	3515.01	0.43	3514.93	0.43	2.9
Model -5						
v2	1000	1000.08	0.01	error		11.3
v3	2000	1999.4	0.03	error		16.7
Case - 1						
v2	1665	1683	1.1	1660	0.3	1.8
Case -2						
v2	1136	1152	1.4	1167	2.7	0.14
v3	3155	3187	1	3152	0.1	0.19

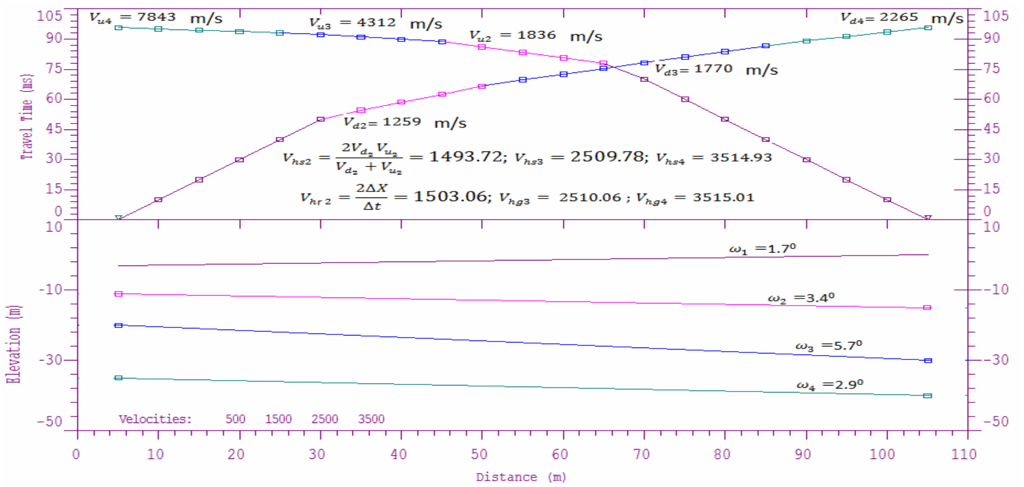

Figure (6): Synthetic travel time graph for four-layered model.

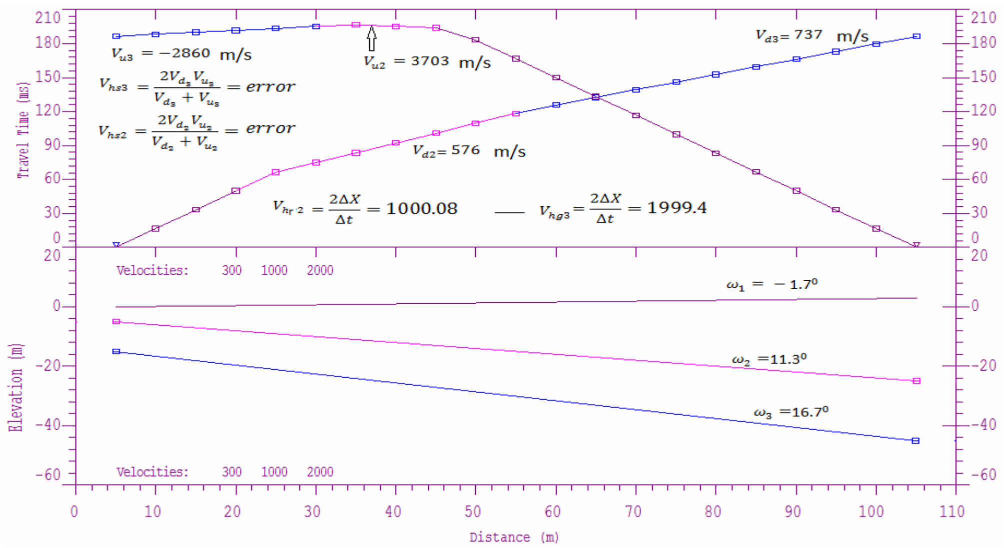

Figure (7): Synthetic travel time curves for three-layered model.

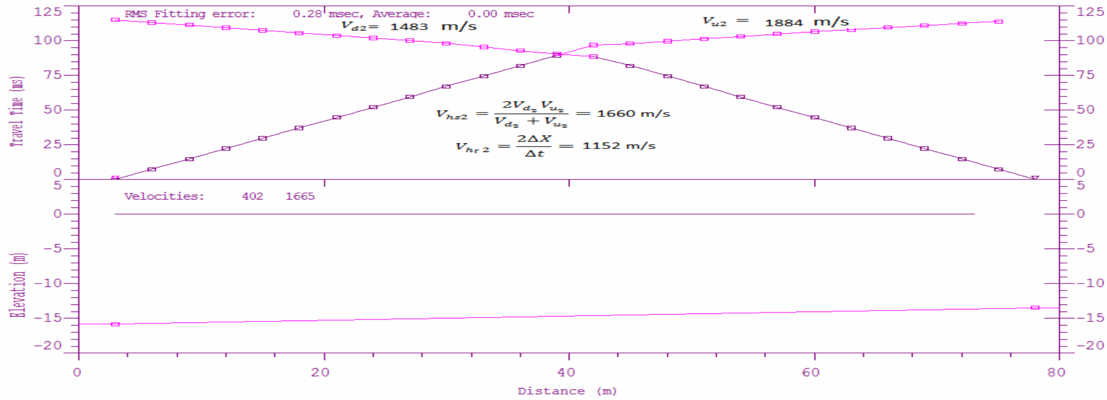

Figure (8): Travel-time graph for and the obtained geo-seismic model of Asylum Lake case study.

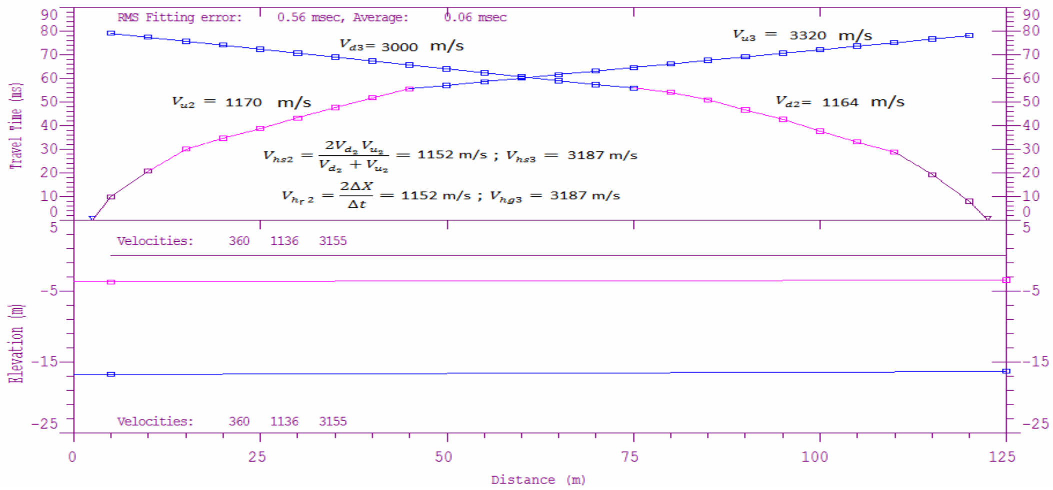

Figure (9): Travel-time graph and the obtained geo-seismic model of WadiNogros case study.

The first case study is located at Asylum Lake, near Kalamazoo, MI, USA. This location is a geophysical test site belonging to Western Michigan University. These data were collected using 24 vertical geophones with 3 m interval, and two end shots with3 m offset. The investigated area consist of two layers: the first represents dry glacial deposits and the second is a saturated glacial deposits consists mainly of sands. As shown in Figure (8), the harmonicvelocity (V_{hr}) value (1683 m/s) is close to the true velocity value (1665 m/s) obtained by the used program with error percent of 1.1% (Table 1).

The second case study is locatedin Wadi Nugros area, at the central Eastern Desert, Egypt. This data were collected using 24 vertical geophones with 5 m interval, and two end shots with 2.5 m offset. The investigated area consists of three layers: the first one is represents unconsolidated alluvial deposits and the second layeris a saturated alluvial deposit consisting mainly of sands, silt and gravels, while the third layer is represents the basement rocks. As shown in Figure (9), the harmonic velocities of layer 2 and 3 have values of (1152; 3187 m/s)close to the true velocity values(1136; 3155 m/s) obtained by the program, with error percent less than 1.5% (table 1).

SUMMARY AND CONCLUSIONS

This research presents new generalized algorithm to calculate the harmonic velocity of the dipping interfaces, using the distance-time difference ratio. The previous approaches failed to compute it at certain cases, when the dipping angles of the interfaces are equal or greater than the critical angles, while the new formula succeeded to calculate it in such and all cases with a minor amount of error. The synthetic data show that, the error percentage below 0.7% of the dipping amounts could be greater than the critical angle of the dipping interface. Real case studies also show error percent less than 1.5%. In addition, the study also presents a novel algorithm, that enables the interpreter to calculate the true velocity of the dipping interfaces depending on the calculated harmonic velocity of the proposed generalized form, but within reasonable expectations of precision, the harmonic mean is till more than adequate. In other words, corrections for dip, which are cosine functions, are rarely necessary for common realistic earth models.

Acknowledgement:

My thanks to Dr. W. Suack, who provided me with the data of Asylum Lake and for his helpful review. Also, to my colleagues in the Egyptian Nuclear Materials Authority (NMA) for their good efforts.

REFERENCES

Adachi R. 1954. On a Proof of Fundamental Formula concerning Refraction Method of Geophysical Prospecting and some Remarks. Kumamoto Journal of Science. Ser. A, Mathematics, physics and chemistry 2, (1), 18-23.

Dobrin M. B. 1976. Seismic Stratigraphy - New Kind of Geophysical Interpretation. Aapg Bulletin-American Association of Petroleum Geologists 60, (12), 2179-2179.

Maurice Ewing, George p. Wool lard, and A.C. Vine, 1939. Geophysical investigations in the emerged andsubmerged Atlantic coastal plainpart iii: Barnegat bay, New Jersey, section.Geological Society of America Bulletin, V50, P 257-296.

Grant F.S. & West G.F. 1965. Interpretation theory in applied geophysics. New York. McGraw-Hill.

Griffiths D.H. & King R.F. 1965. Applied geophysics for engineers and geologists (1st ed.). Oxford, New York. Pergamon Press.

Interpex Limited 2010. IXRefraX Instruction Manual, Version 1.3, Interpex Limited.

Mooney W.D. 1981. IASPEI Workshop. Seismic Modeling of Laterally Varying Structures. Eos, Transactions American Geophysical Union 62, (2), 18-19.

Musgrave A.W. 1967. Seismic refraction prospecting. Tulsa, Okla. Society of Exploration Geophysicists.

Parasnis D.S. 1979. Principles of applied geophysics (3rd ed.). London, New York. Chapman and Hall. ISBN 0470264802.

Parasnis D. S. 1986. Principles of applied geophysics (4th ed.). London, New York. Chapman and Hall. ISBN 0412283204

Redpath B. 1973. Technical report E-73-4.Seismic refraction exploration for engineering site investigations. Springfield, Va., National Technical Information Service. ISBN 0412283204.

Seisa H.H. 1991. A contribution to the interpretation of shallow refraction seismic data. TUBerlin.

Sjögren B. 1984. Shallow refraction seismics. London New York, Chapman and Hall. ISBN 0412242109.

Slotnick M.M. 1959. Lessons in seismic computing, a memorial to the author. Tulsa Okla. Society of Exploration Geophysicists.

Telford W.M. 1976. Applied geophysics. London, New York. Cambridge Univ. Press. ISBN 0521206707.

Telford W.M. Geldart L.P. & Sheriff R.E. 1990. Applied geophysics(2nd ed.). Cambridge England, New York. Cambridge Univ. Press.