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Evaluation of a Fast Proxy of Vs30 (Vs30m)

Muhammad Saqlain (110382605@cc.ncu.edu.tw)
National Central University
UMAR ZADA
University of Engineering and Technology Peshawar
Wakeel Hussain
China university of Geoscience

Research Article

Keywords: Vs30, Model Dispersion Curve, Rayleigh wave.

Posted Date: April 26th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1545864/v1

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Abstract

The most frequent parameter used to quantify seismic site response in ground motion models is time-averaged shear wave velocity in the top 30 m of a site (Vs30), used by many engineering design codes and most recently by published empirical-scaling equations to estimate the amplitudes of strong ground motion. The current study explores the potential comparison of the results from the predictive equations and formula recommends by the international building code. In order to avoid forward modeling and inverse modeling, 53 synthetic and real data models with distinct types of Vs profile were used, to determine the theoretical dispersion curves. In the prediction equation, V_R36 and V_R40 were employed to estimate Vs30. Furthermore, the use of V_R40, based on the 53 different models, shows a good agreement with Vs30. The correlation is significantly influenced by the thickness of the first layer. The findings calculated by the correlation are not in the acceptable zone for layer thicknesses of $10 < H < 20$ m and thin layers at shallow depths with lower shear wave velocity.

1) Introduction

Different proxies are used to define the site effect for site with few information. The most common one is the time-averaged shear-wave velocity over the first 30 meters, Vs30.In particular shear wave velocity (Vs) in important parameter for evaluating dynamic behavior of soil. In geotechnical engineering the shear wave velocity Vs is an important parameter for evaluating the dynamic behavior of soil. The average shear-wave velocity of the upper 30 meters of a soil profile (Vs30) is used as an important parameter for most earthquake ground-motion prediction equations (GMPEs), site-classifications studies, seismic hazard assessment, and the development of seismic micro zonation maps (Boore et al. 1993; Anderson et al. 1996; Castro et al. 1997; BSSC 1998; Park and Elrick 1998). Borcherdt (1994a, b) and Martin and Dobry (1994), (lee and Tasi, 2008). Table 1 shows seismic site classifications based on the Vs30 from European (Code, p, 2005), Spanish (De Fomento, M, 2002), and American (American Society of Civil Engineers, 2017) seismic codes and structural standards.

Table 1. Classification based on V_S30 for seismic codes and standard regulations from Europe, Spain, and United States.

Eurocode 8 (Europe)			NCSE-02 (Spain)			ASCE 7-16 (USA)		
Soil Type	**Description**	**V_S30 (m/s)**	**Soil Type**	**Description**	**V_S30 (m/s)**	**Soil Type**	**Description**	**V_S30 (m/s)**
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	V_S > 800	I	Compact rock, very dense cemented or granular soil.	V_S > 750	A	Hard Rock	V_S > 1500
						B	Rock	750 < V_S £ 1500
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterizes by a gradual increase of mechanical properties with depth.	360 < V_S £ 800	II	Very fractured rock, dense or cohesive hard granular soil.	400 < V_S £ 750	C	Very dense soil and soft rock	360 < V_S £ 750
C	Deep deposits of dense or medium dense sand, gravel, or stiff clay with thickness from several tens to many hundreds of meters.	180 < V_S £ 360	III	Granular soil of medium compactness or cohesive soil of firm consistency to very firm.	200 < V_S £ 400	D	Stiff soil profile	180 < V_S £ 360
D	Deposits of lose-to-medium cohesion- less soil or of predominantly soft-to-firm cohesive soil.	V_S < 180	IV	Loose granular soil or soft cohesive soil.	V_S < 200	E	Soft soil profile	V_S < 180
	A soil profile consisting of a surface alluvium layer with V_S values of type C or D and thickness varying	□	□	□	□			□

E	between about 5 m and 20 m, underlain by stiffer material with Vs > 800 m/s.					F	Other, see ASCE 7-16 Table 20.3-1	
S1	Deposits consisting of or containing a layer at least 10 m thick of soft clays/silts with a high plasticity index (PI > 40) and high water content.	V_S < 100	□	□	□	□	□	□
S2	Deposits of liquefiable soils, sensitive clays or any other soil profile not included in types A-E or S1	□	□	□	□	□	□	□

Traditionally, Vs30 is determined by the seismic measurement in the borehole, for instance, downhole, cross-hole, or suspension logging methods. These methods are time-consuming and uneconomical. Faster, accurate, and cost effective method is needed to efficiently measure the Vs30. Non-invasive surface waves methods, for instance, spectral analysis of surface waves (SASW), multichannel analysis of surface waves (MASW), and array microtremor and refraction microtremor techniques are proven, nondestructive seismic methods that can be used to determine the variation of V_S with depth (Stokoe et al., 1994; Brown, 1998; Park et al., 1999; Okada, 2003 and Louie, 2001). These methods are cost effective and don't require borehole, are widely used for the determination of Vs30. The basis of surface wave methods is the dispersive characteristic of Rayleigh waves (V_R) when propagating in a layered medium. These surface waves methods consist of collecting surface-wave phase data in the field to determine the dispersion curve. The variation of phase velocity V_{ph} with Rayleigh wave V_R or frequency is called dispersion. The Rayleigh wave phase velocity depends on the site characteristics for instance, shear wave velocity, compression wave velocity, density, Poisson's ratio. After determination of the dispersion curve by using iterative forward or inverse modeling techniques to back-calculate the corresponding V_S profile. From the V_S profile, V_S30 can be calculated.

Due to non-uniqueness problem in the inversion analysis, and based on the comprehensive study Brown et al, (2000) and Martin and Diehl, (2004), proposed a two predictive equation for the fast determination of Vs30 by using Rayleigh wave velocity at wavelength 36m and 40m.

These predictive equation was derived by using linear regression analysis on a set of Rayleigh-wave dispersion curves and Vs30 values that were calculated from seismic velocity profile.

These velocity profile was estimated by downhole, P-S suspension logging and each velocity profile contained shear wave velocity and compression wave velocity.

To verify these predictive equation, 53 ironic velocity profile as shown in (Fig 1) were selected. For each V_S, VP profile, the fundamental-mode Rayleigh-wave dispersion curve was calculated. When determining the fundamental mode dispersion curve, the corresponding density for each layer were used. Reasonable variations in mass density have a negligible effect on dispersion. The evaluation of predictive equation based on different synthetic and real data velocity profile is thoroughly discussed below.

2) Methods

To compare the results from the predictive equations, developed by Brown et al, (2000) Eq. 2.1 and Martin and Diehl, (2004) Eq. 2.2, for wavelength corresponding to the Phase velocity of Rayleigh wave at 36 m (V_R36) and 40 m (V_R40) respectively, with the result from the formula recommends by the international building code 2000 equation 2.3 for the fast determination of Vs30. We set up fifty-three simple synthetic and real data typical earth velocity profiles to determines its theoretical dispersion (model dispersion) curve. Because only one point V_R36 or V_R40 is needed in the dispersion, these fifty-three models divided into three different groups. As illustrated in Fig. 1, Group A, consists of twenty-five synthetics, two layered earth profile with (a) weak soft layer overlaying stiff soil Fig (1a), (b) A weak soft layer overlaying soft rock (Fig 1b), (c)A weak soft layer overlaying rock (Fig 1c), and (d) A weak layer overlaying hard rock (Fig 1d). Group B, consist of six constant gradient synthetic earth profile frequently encountered in the field as shown in (Fig 1e). and Group C, twenty-seven real data models, taken from Puerto Rico Seismic Network (Odum et al.,2007), As illustrated in (Fig 1f). When performing modal dispersion curve analysis, the typical densities corresponding to the stiffness of each layer were used. For each Vs, Vp profile, fundamental mode Rayleigh-wave dispersion curve was determined by the famous dynamic stiffness matrix method (Kausel and Roesset, 1981). In a layered medium, for the given velocity profile, the wave equation leads to a characteristic equation, in which for a single frequency, multiple possible root of phase velocity (V_{ph}) or Wavelength can be found. These solutions are the model dispersion curves, in which the lowest phase velocity (V_{ph}) and frequency are the fundamental mode and higher phase velocity are the higher mode. Modeling was done in wavelength domain instead of frequency domain.

$$Vs30 = 1.076 * V_R36 \qquad (2.1)$$

$$Vs30 = 1.045 * V_R40 \qquad (2.2)$$

$$Vs30 = \sum di / \sum ti = 30 / \sum (di / Vsi) \qquad (2.3)$$

2.1) Theoretical Dispersion Curve

The matrix approach devised by (Thomson, 1950; Haskell, 1953) and global stiffness matrix formulation for a layered system, which originate in the work of (Thomson, 1950; Haskell, 1953), are used to generate theoretical dispersion curves in most circumstances (Kausel and Roesset, 1981). The more stable global stiffness matrix approach was employed to compute theoretical dispersion curves in this study. For a horizontally layered medium, an elements stiffness matrix was constructed for each layer including the half space by assuming axial symmetric motion (i.e., ground motion subjected to circular vertical loading). The elements stiffness matrix of a given layer, which relates stresses at the upper and lower surfaces of the layer to related displacement, can be computed in frequency (W) and Wave number (k) using the general solution of the wave equation. In a manner similar to the finite elements methods, the global stiffness matrix "*K*" can be determined by subsequently assembling of an elements stiffness matrix, corresponding to each the nodal forces to the nodal displacements at the layer interfaces. For non-trivial solution, the determinate of the global stiffness matrix $K(w,k)$ should be zero. For a constant frequency, the value of wavenumber (K), the phase velocity $V_{ph}=w/k$ can be determined by setting the determinant of the global stiffness matrix method equal to zero. The global stiffness matrix method is basically a root finding method. The different wavenumbers k (or phase velocities V_{ph}) determined at a given frequency corresponds to dispersion curves with different modes. For instance, the largest wavenumber, hence the lowest phase velocity, for a frequency belongs to the fundamental mode and the second largest wavenumber belongs to the second mode. An open-source software, MASWaves (**Olafsdottir et al. 2017),** has included a function (MASWaves_theoretical_dispersion_curve.m) to compute the fundamental-mode dispersion curve in terms of wavelength vs. phase velocity was used in this study.

3) Result And Discussion

Our discussion will concentrate on whether V_R36 or V_R40 should be used in the predictive equation to determine the fast proxy of Vs30 for various synthetic and real data velocity profiles. Based on the dynamic stiffness of 53 velocity profiles, the fundamental-mode of Rayleigh wave dispersion curves were calculated. The value of Vs30 calculated by the predictive equation is compared to the actual value of Vs30 determined by the formula recommended by the international building code, as shown in (Eq. 2.3). With the exception of a few exceptional cases, the difference between the actual and predictive values of Vs30 is usually within +/- 10% error bonds. The following result will summarize the selection of a more suitable predictive equation, as well as the evaluation of Vs30 proxy.

3.1) GROUP A

As shown in Figure 1 (a, b, c, d), there are twenty-five 2-layer synthetic earth profiles with varied velocity contrast. The fundamental-mode model dispersion curve was calculated using the dynamic stiffness matrix method on the first layer with varied depth and constant shear wave velocity (120 m/s), with varying half space shear velocity to a depth of 30 m. The choices of V_R36 or V_R40 in the predictive equation for determining Vs30 will be summarized in the following section.

3.1.1) Weak soil layer overlaying stiff soil

Figure (1a) shows the two-layer constant velocity profile with varying depth of the 1st layer. Due to the low velocity contrast, overall the actual Vs30 have a good correlation with the Vs30 determined by the both the predictive equation and lies within the +/-10% error bond, but the Vs30 calculated by using V_R40 in the predictive equation is closely related to the actual Vs30 as shown in (Fig 2). By using V_R36 and V_R40, at a height of (H15 Top layer height) 15 m and (H20) 20 m both results are underestimated.

3.1.2) Weak Soil Layer Overlying Soft Rock

Fig. 1b illustrates the weak soil overlaying on the soft rock in a similar way to Fig. 1a. The results of the Vs30 and Rayleigh wave phase velocity (V_R36, V_R40) correlations point to the same conclusion. Vs30 was determined by applying V_R36 and V_R40 in the prediction equations at heights of 5 m and 25 m, and the results of Vs30 are in +/-10 percent error bonds. The Vs30 computed by V_R36 is underestimated for heights of 10 m, 15 m, and 20 m. Overall, V_R40 is in good agreement with genuine Vs30, as shown in the graph (Fig.3).

3.1.3) Weak Layer Overlaying on Rock

Fig. 1c represent the case of weak layer over rock. Result shows that, due to high velocity contrast, Vs30 calculated by the predictive equations are underestimated and the correlation between Vs30 and V_R at a wavelength of 36 m and 40 m are not in a reasonable range. The results are basically dominated by using V_R50 in the predictive equation as shown in (Fig. 4).

3.1.4) Weak Layer Overlaying on Hard Rock

In the way similar of the other two-layer velocity profile, velocity of the 1st layer was keep constant with variable height as shown in (Fig. 1d). Due to high velocity contrast between the two layers, it is clear from the results that the Vs30 calculated by the predictive equation by using Rayleigh wave velocity at V_R36, V_R40 is not promising and not even a single data point lies within +/-10% acceptable error bond. Vs30 estimated by using V_R50, two velocity profile, for instance, H20, and H25 is in +/-10% bound as shown in (Fig 5).

3.2) Synthetic Data Representation

Synthetic data representation as illustrated in Fig.6 is the most sophisticated correlation, to obtained a quick idea about the selection of the Rayleigh wave velocity at a specific wavelength for instance, V_R36, V_R40, and V_R50, to use in the predictive equations, for the calculation of Vs30 within the acceptable +/-10% error bound zone. The Rayleigh wave velocity at a wavelength of 50 m i.e. V_R50 covered more area for instance, high velocity contrast than V_R40 and V_R36 respectively. When the velocity contrast is not significantly higher between the 1st layer and half space, as shown in Fig. 1(a) with 1st layer thickness 22 m < H < 13 m, Vs30 determined by the predictive equation, by using the Rayleigh wave velocity at wavelength of V_R36 lies within the acceptable zone. In this case, by using V_R40, the Vs30 lies in the acceptable zone as shown by dark black circle on the V_R40 line. In case of weak layer over soft rock, the Vs30 calculated by the predictive equation by using V_R36 and V_R40 will lies in the acceptable error bound zone only, if the thickness of the 1st layer lies between 22 m < H < 10 m and 20 m < H < 10m respectively, but on the other hand, V_R50 will be in the acceptable zone. As the velocity contrast between the top layer and the haft space becomes more significant, as shown in Fig. 1(c,), by using V_R40, and V_R50, Vs30 will be in acceptable zone, if the height of the 1st layer H > 22 m and 5 m > H > 10 m respectively. For weak soil over hard rock, due to a very high velocity contrast, Vs30 calculated by V_R50 lies in the acceptable zone as shown in the figure below.

3.3) Group B Synthetic Gradient Models

At many sites, under typical geological conditions, soil stiffness increases gradually with depth due to its geological age, cementation, compaction, overburden pressures etc., and the effect of the non-fundamental mode Rayleigh wave energy on the dispersion curve is minimal. In this situation the common expectation includes engineering fill over stiff sediments, asphalt, concrete, and soft lose material on the compacted base materials or soft soil over shallow soft rock. To represent these condition in field, six gradient synthetic models were selected as illustrated in Fig.1(e), to calculate its theoretical dispersion curves. Vs30 was determine by the predictive equations using V_R36, V_R40 and V_R50. From the results as shown in (Fig. 7) it is concluded that Vs30 has a very good correlation with the phase velocity of Rayleigh wave at a wavelength of 36 m i.e. V_R36. All the data points are in the acceptable zones. The Vs30 calculated by using V_R40 and V_R50 in the predictive equation are overestimated.

3.4) Real Data Models

As indicated in Fig. 1, twenty-seven genuine data models were acquired from the survey report of the University of Puerto Rico in collaboration with the US Geological Survey (1f). They investigated near-surface shear wave velocity and compressional wave velocity using noninvasive seismic refraction-reflection profiling techniques. The average shear waves velocity at the top 30 meters was computed using Eq. 2.3, and the findings were compared to those obtained from the prediction equation using V_R36 and V_R40. The majority of the results are acceptable, with a few exceptions as shown in Fig. (8) and Fig. (9). (9). The two-layer synthetic technique is used in real-world data models. The results are not always acceptable due to high velocity contrast.

4) Conclusion And Suggestion

The application of VR40 indicates a good agreement with shear wave velocity, i.e. Vs30, based on the 53 distinct models. The velocity contrast increases as you move from stiff soil to hard rock, affecting the correlation. The predicted value of Vs30 is not within the permitted range. The thickness of the first layer has a considerable impact on the correlation. The results predicted by the correlation are not in the allowed zone for layer thickness between 10 H 20 m and thin layer at shallow depth with lower shear wave's velocity. Vs30 is more sensitive to shallow top lower Vs, but VR36 and VR40 are less sensitive to shallow top Vs. As a result, for seismic hazard zonation studies and site categorization, it is recommended to explore VR rather than Vs at different wavelengths. Even if the VS30 approach is used to evaluate the data, it may be practical to collect a complete set of sounding data while performing surface wave investigations at a single place for determining VS30 for site categorization. If anticipated VS30 is within 10% of a class border, a complete surface wave dispersion curve would be available for forward/inverse modelling.

Declarations

Conflict of interest:

The authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this paper.

Funding:

Not applicable.

Availability of data and materials:

Not applicable.

Code availability:

Not applicable.

Authors' contributions:

All authors have contributed equally in this research work.

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Figures

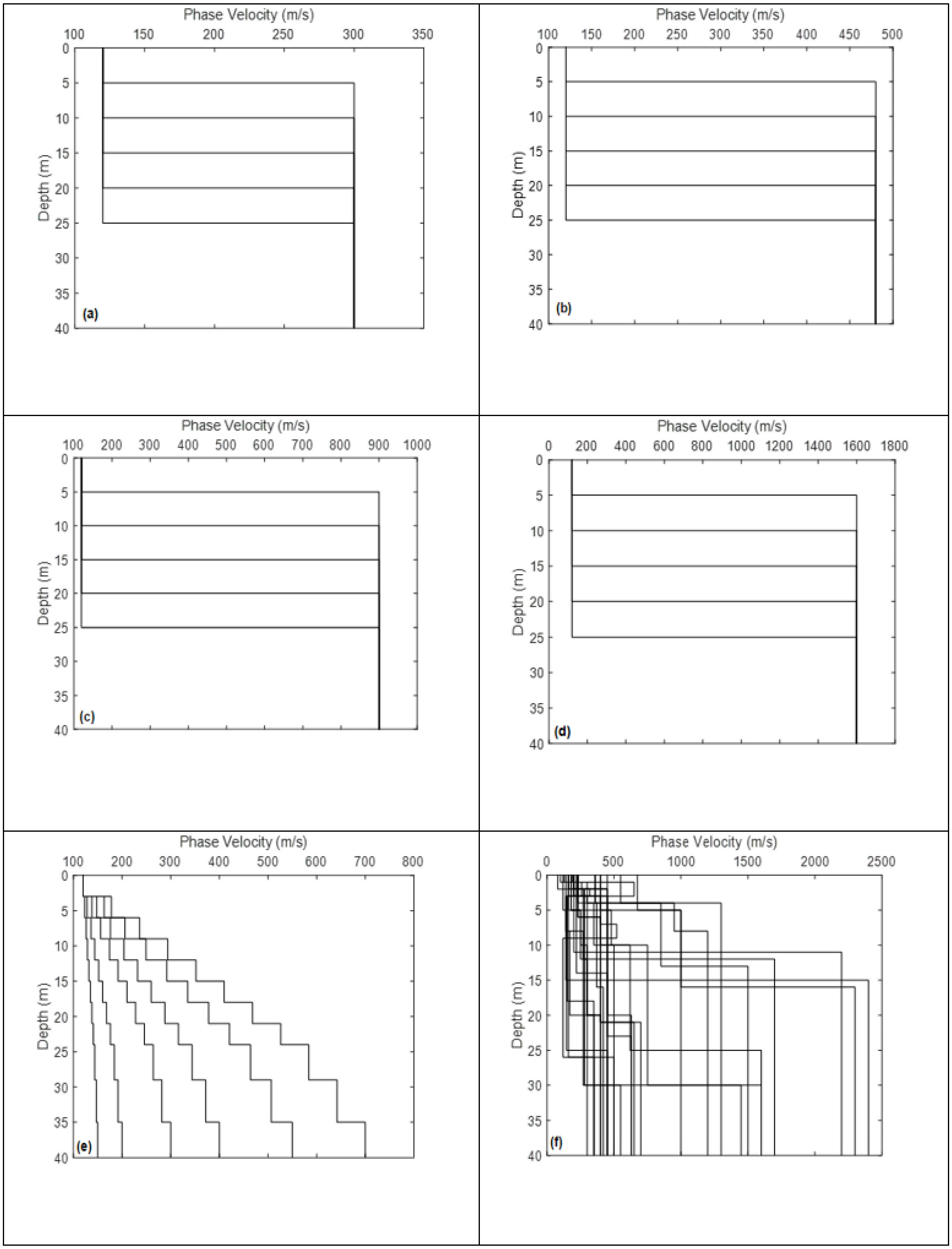

Figure 1

Shows the illustration of the different models

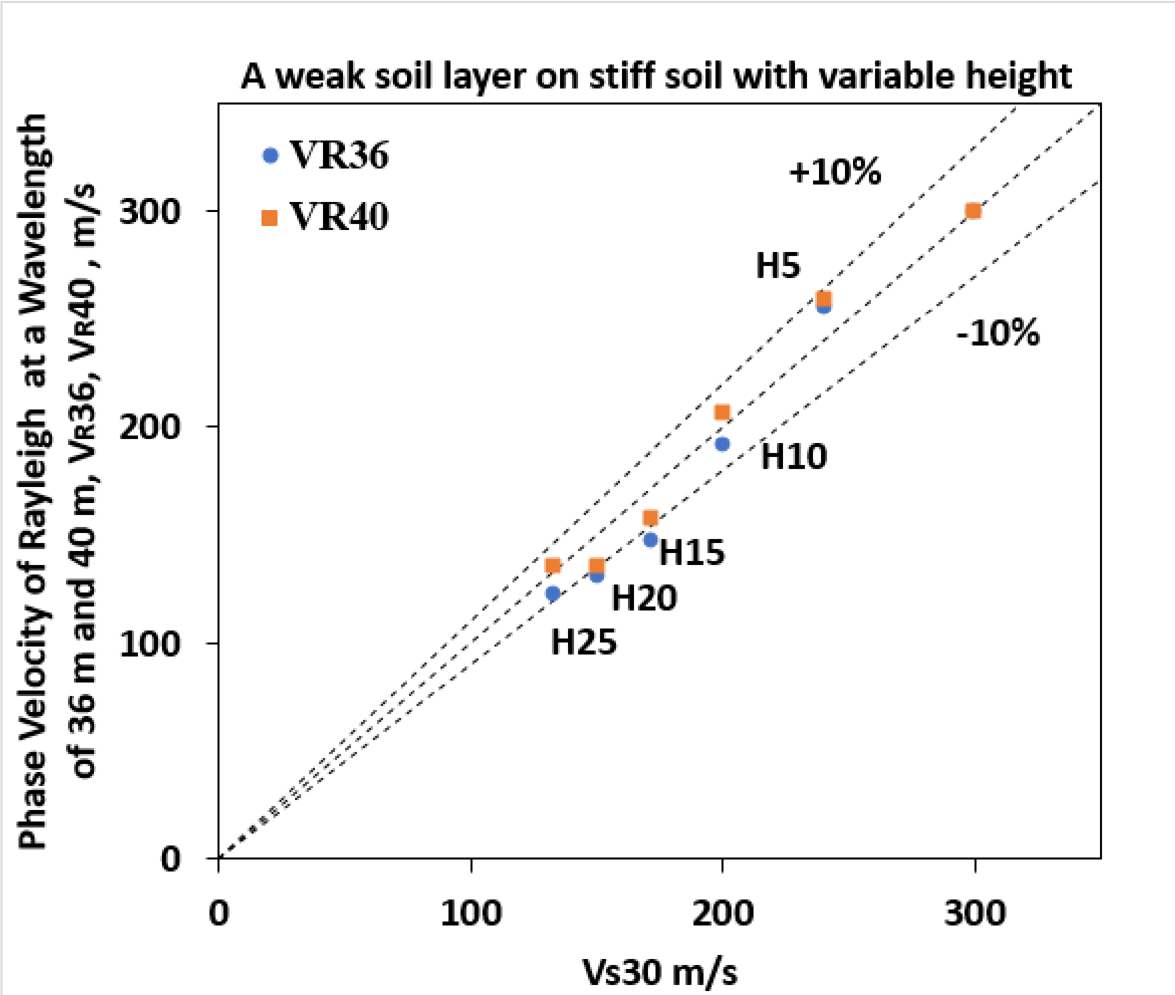

Figure 2

Weak soil layer over stiff soil layer with variable depth of the 1st layer.

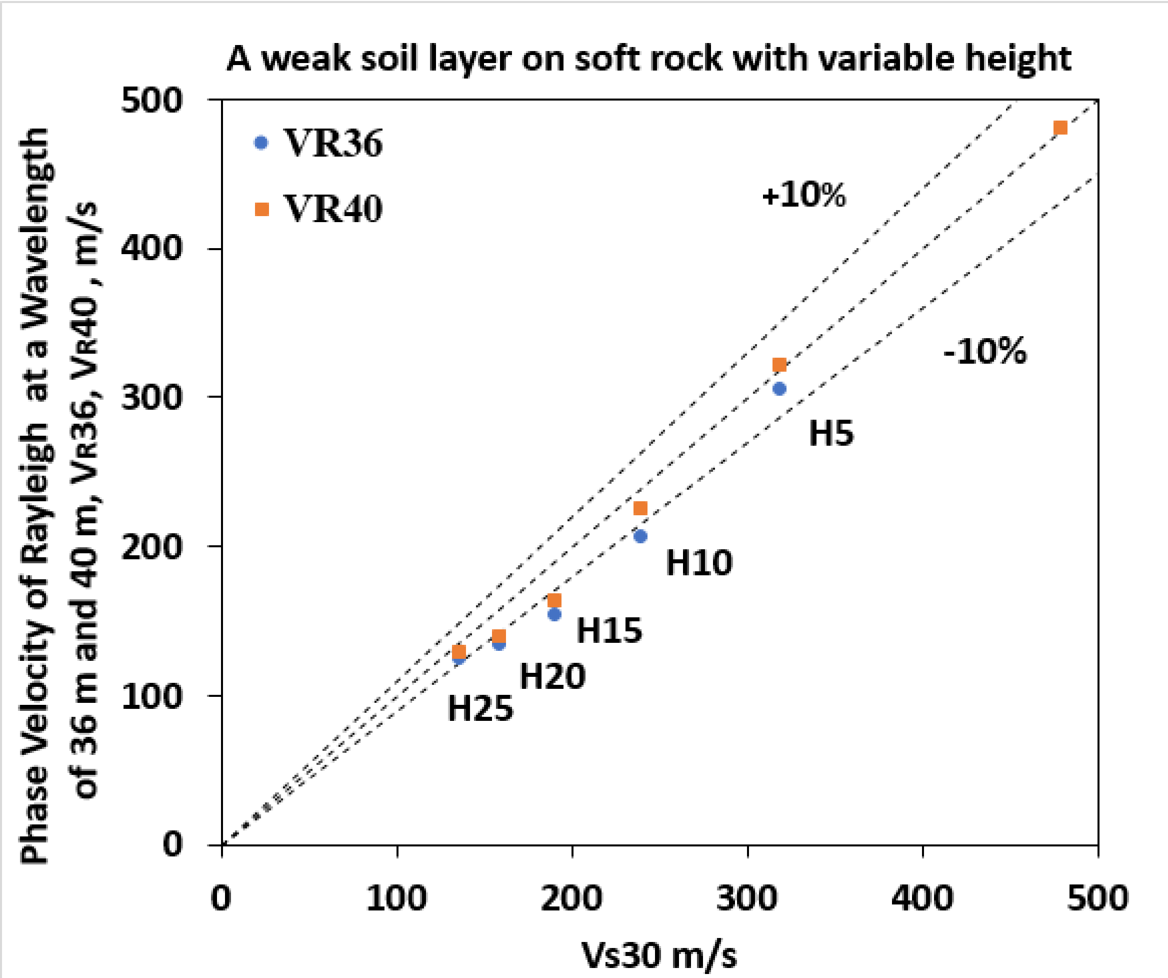

Figure 3

Weak soil layer on soft rock with variable depth of 1st layer.

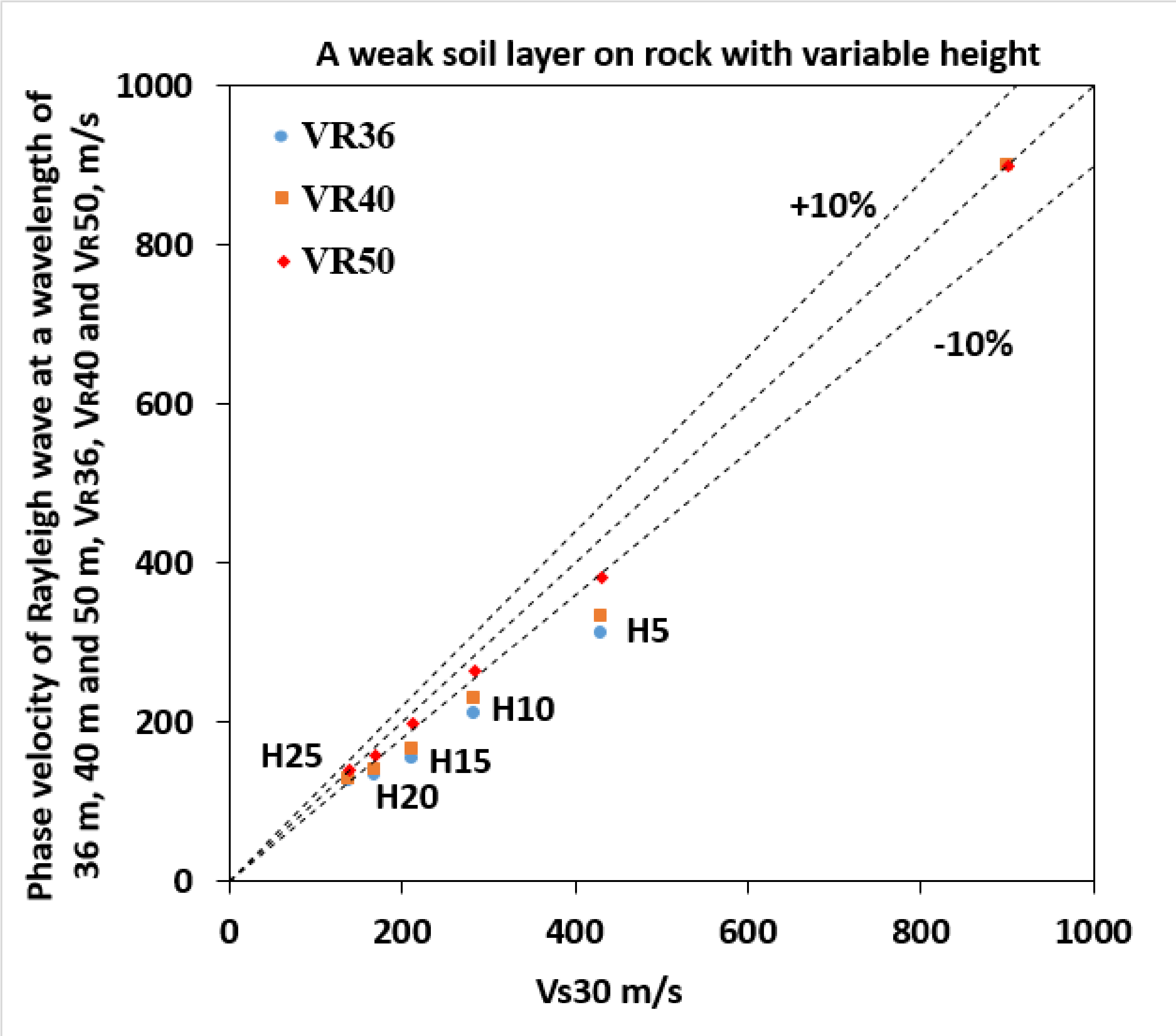

Figure 4

Weak soil layer overlaying rock.

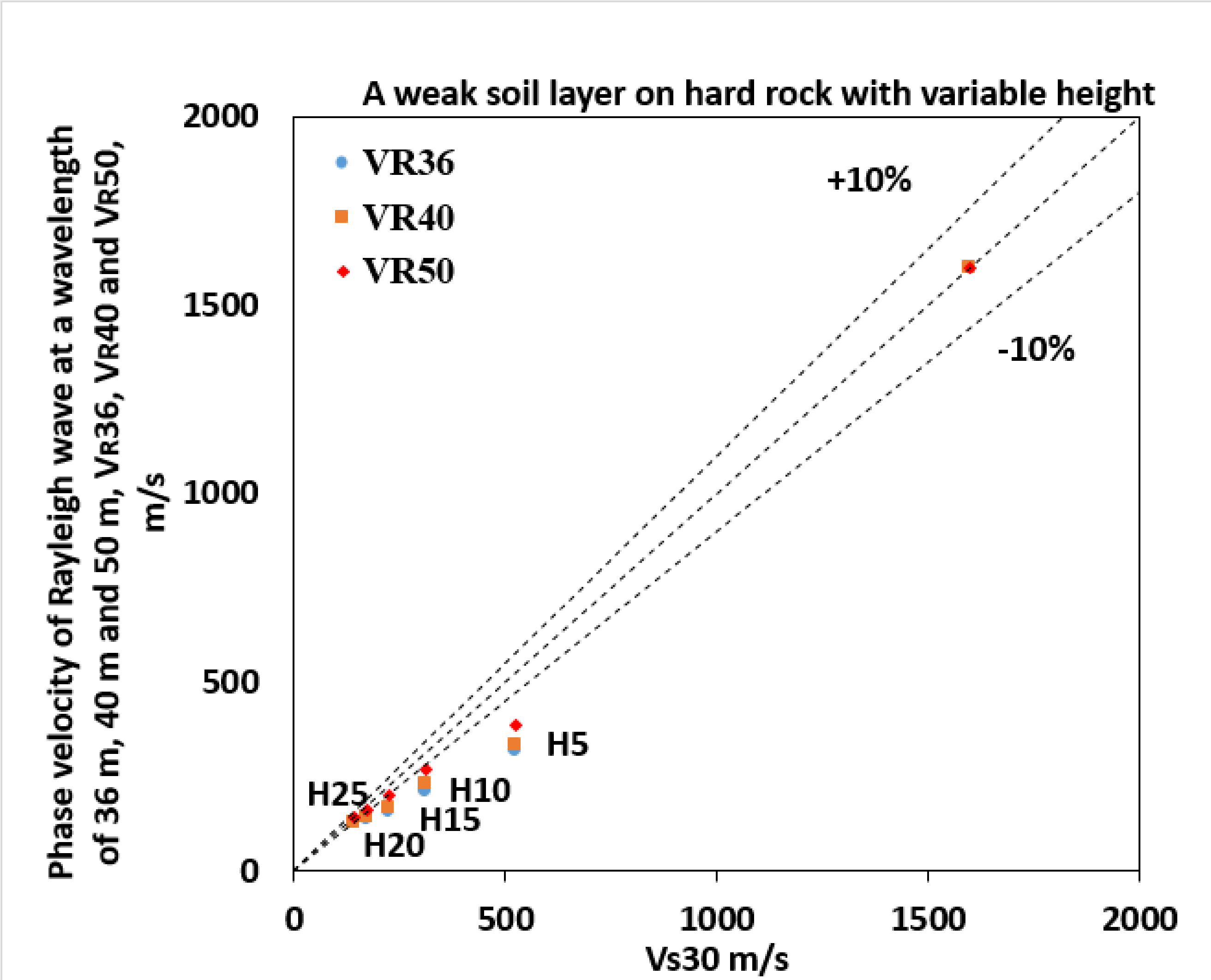

Figure 5

Weak Soil Overlaying on the Hard Rock.

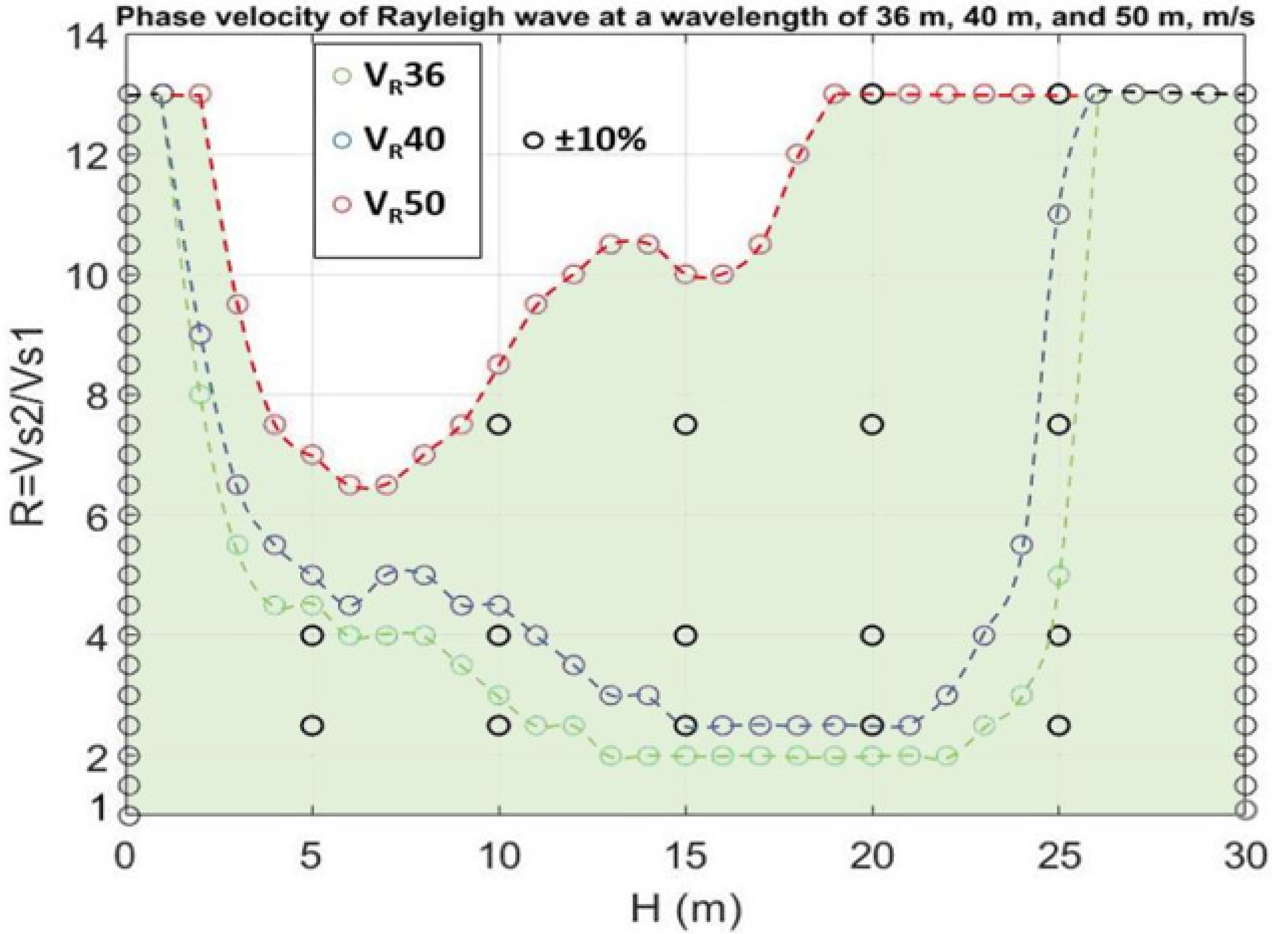

Figure 6

2-layer Synthetic Representation Models

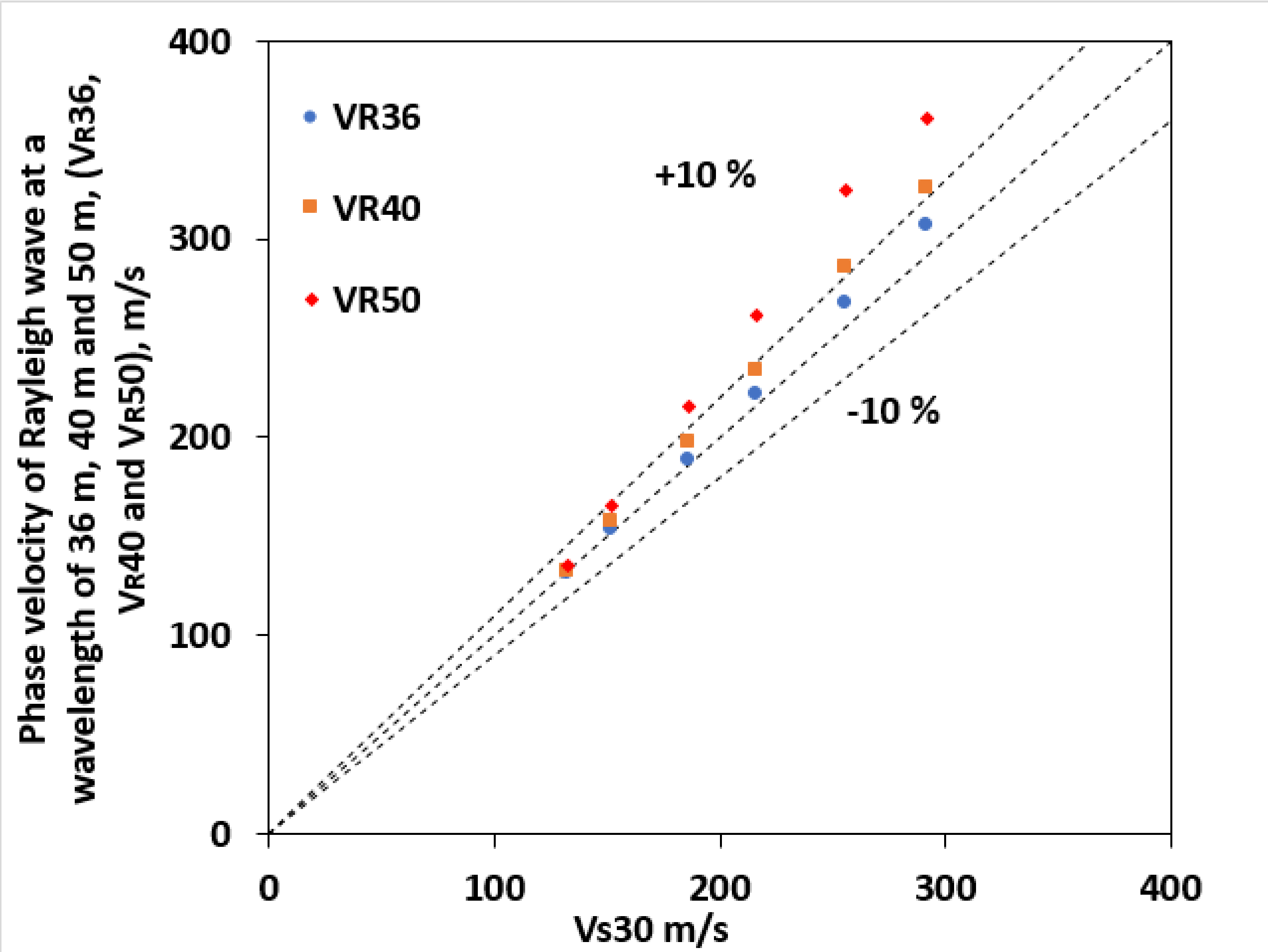

Figure 7

Shows the result of synthetic gradient models

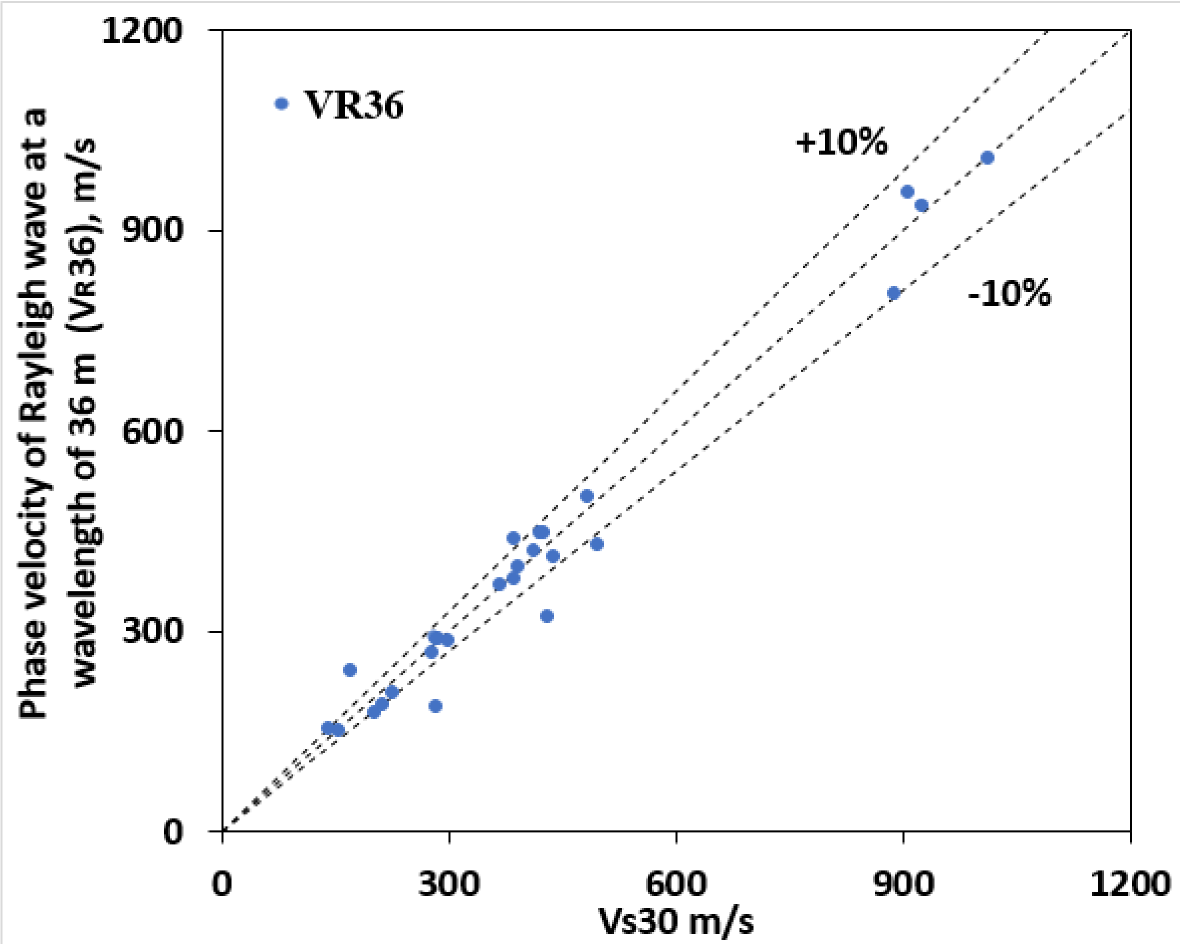

Figure 8

Results of Real data models by using V_R36

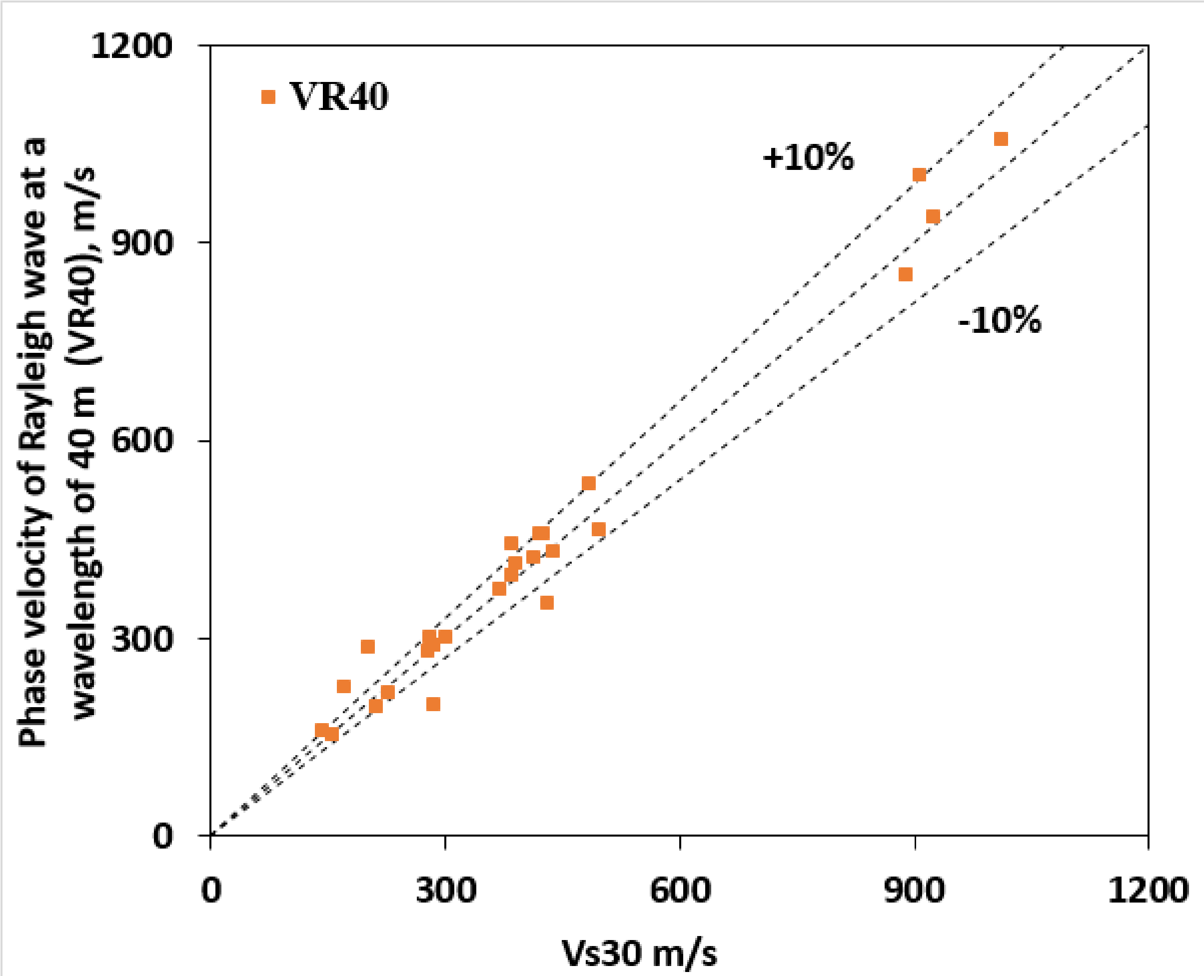

Figure 9

Results of Real data models by using V_R40.