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Research Article

Spectral Analysis of Surface Wave for Empirical Elastic Design of Anchored Foundations

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Helical anchors are vital support components for power transmission lines. Failure of a single anchor can lead to the loss of an entire transmission line structure which results in the loss of power for downstream community. Despite being important, it is not practical to use conventional borehole method of subsurface exploration, which is labor intensive and costly, for estimating soil properties and anchor holding capacity. This paper describes the use of an empirical and elasticity-based design technique coupled with the spectral analysis of surface wave (SASW) technique to provide subsurface information for anchor foundation designs. Based on small-strain wave propagation, SASW determines shear wave velocity profile which is then correlated to anchor holding capacity. A pilot project involving over 400 anchor installations has been performed and demonstrated that such technique is reliable and can be implemented into transmission line structure designs.

1. Introduction

Foundation is the load transfer mechanism from structure to the earth medium, and the design of foundations typically relies on the determination of soil strength, Q_u, which is then reduced by a safety factor, FS, to get the allowable stress, $Q_{\text{allowable}}$:

$$Q_{\text{allowable}} = \frac{Q_u}{\text{FS}}. \tag{1}$$

The strength variables required may include cohesion and frictional angles of soil and various shape and load modification factors. Davis and Selvadurai [1] argued that the safety factors limit the behaviors to within the elastic range (1/3 of peak stress). Hence, they suggested that there may be incidence where elastic foundation design would make sense. Since most soil/rock mechanical testing methods are associated with the determination of ultimate strengths of soil material, Davis and Selvadurai [1] further suggested using geophysical testing methods for determining *in situ* soil elastic parameters. While strong reasoning is presented, no real-life design examples were offered to reinforce the elastic design idea. Recent paper by Selvadurai [2] further extended the argument about the importance of elasticity in soil mechanics to poroelastic problems.

This paper identified power transmission structures as likely candidates for elastic-based design and suggests using an empirically based method for the elastic design of anchor foundations using a Rayleigh wave-based soil exploration technique for determining soil elastic parameters [3–5]. This approach is applied to anchor-supported transmission line structures, which are typically stabilized by helical anchors that are often installed without prior information on the underlying soil characteristics [3]. Because anchor holding capacity is dependent on the inherent resistance of soil, failure to analyze pertinent soil properties before transmission line construction could lead to disastrous anchor pullouts. Such failures may not only affect a specific transmission line structure but may also jeopardize the stability of neighboring transmission structures resulting in a domino failure mode that can cause extensive power outages for downstream communities. However, most transmission structures are erected in a rapid fashion without extensive subsurface explorations, and as a result, the anchors are usually installed with basic recommendations from the anchor manufacturer [4].

The proposed soil exploration technique, spectral analysis of surface waves (SASWs), is based on the detection of impact-induced, small-strain stress waves [5]. The method generates the shear wave velocity versus depth profiles of the tested soil and has been successfully applied to the detection of pavement thickness, characterization of shallow soil profiles, and correlation to soil liquefaction potentials [5–13]. Three technical data can be established using SASW: (1) recommended embedment depth of the anchors, (2) soil stiffness at the necessary depth, and (3) depth of bedrock. To correlate wave speed to anchor holding capacity, controlled pull tests were performed at different soil sites resulting in a linear correlation. Figure 1 shows the stress distribution of pulled anchors at different depth (after Niroumand and Kassim [14]). If sufficient safety factor is built in the design, such that the anchor system will be loaded in the elastic range, then the elastic soil parameters determined by SASW may be correlated to the actual anchor holding capacity. Figure 2 shows the schematic connection between elastic wave parameters and the ultimate anchor holding capacities for anchored structures. The correlation is established via actual geophysical and anchor pull tests at several test sites [15]. The empirical-based design approach is then validated using actual design and pull tests on transmission line in Georgia, USA.

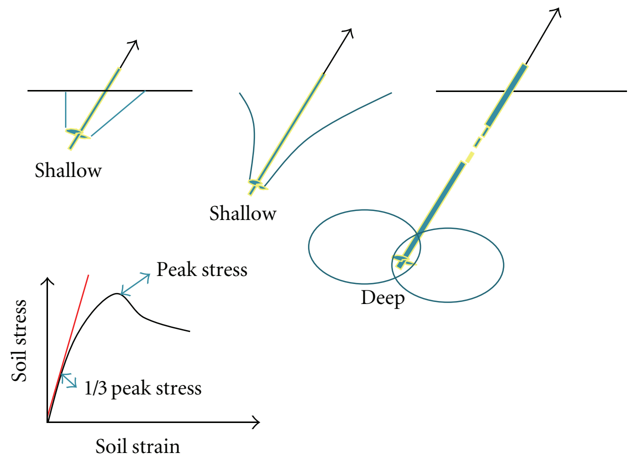

Figure 1: Basic assumption behind elasticity-based design (modified from Matthews [12]).

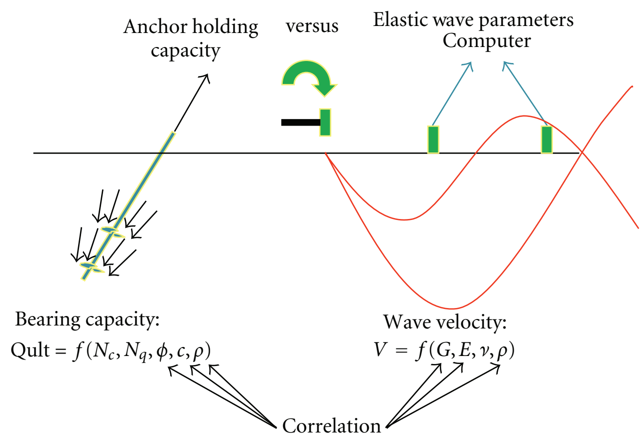

Figure 2: Correlation between anchor holding capacity and elastic wave parameters.

2. Conventional Anchor Foundation Constructions and Soil Exploration

Helical anchor foundations are tension foundations using uplift capacity of anchor to resist pullout of the anchors [16–21]. Conventional design of anchored foundations for power transmission structures relies on soil ultimate strength parameters (cohesion, c, and frictional angle, Φ) which are determined using *in situ* destructive soil exploration techniques such the standard penetration test (SPT) [21]. Niroumand et al. summarized past experimental data on the studies of anchor plates for different soils [14, 22]. This test is labor intensive and time consuming, and it requires extensive drilling and sampling at isolated points to measure a stiffness parameter known as the N-value, which may or may not be representative of the entire underlying area where the structure would be built. This scenario becomes a serious problem in areas with highly heterogeneous soils, especially at multilayered soil systems. The high cost and inherent inaccuracies of SPT necessitated current practices of installing anchors without soil exploration, which is a "hit-or-miss" strategy that incorporates an anchor pull test.

In the anchor pull test, a helical anchor is usually installed until it reaches a specified torque rating or deformity [23]. Once installed, the anchor is then pulled by backing a bulldozer coupled to a dynamometer to measure the anchor holding capacity (Figure 3). Despite being time consuming, this strategy obviously circumvents the need to perform SPT. However, the anchors installed with this method are severely deformed; hence, its original properties may have been perturbed. Pulling on the anchor to perform the test may also disturb the surrounding areas where the other helical anchors are to be installed. Moreover, because the stiffness of the soil is unknown, anchor installation depth can vary from 3 m in sand to more than 30 m in swampy soil conditions. Such unpredictability can be expensive: instead of anchoring at 30 m, prior soil exploration may reveal an area where anchoring can be accomplished at lesser depths, leading to the use of fewer extension rods. The relative hazard and unpredictability of this anchor pull test approach, as well as the drawbacks of SPT, warrant the development of inexpensive, nondestructive, and accurate means to measure soil stiffness.

3. Spectral Analysis of Surface Waves

Survey of potential nondestructive, geophysical testing methods suggested that spectral analysis of surface waves (SASWs) offers a viable alternative for measuring soil stiffness [3]. By subjecting soil to a propagating impact wave, a characteristic shear wave velocity is generated. This shear wave velocity is a function of the elastic properties of the soil; hence,

FIGURE 3: Bulldozer coupled with dynamometer to measure anchor holding capacity.

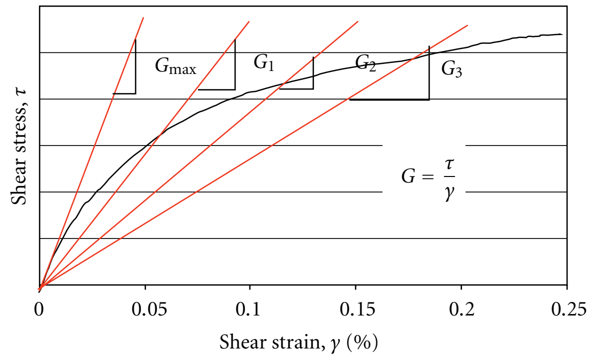

FIGURE 4: Change in shear moduli at different levels of shear strain [10, 11].

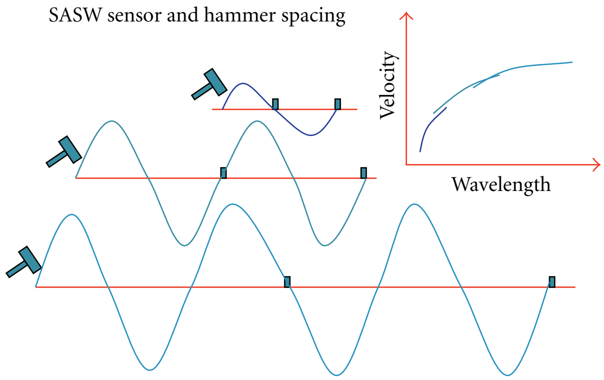

FIGURE 5: SASW test setup and sensor spacing arrangements.

this technique may provide a descriptive profile of soil stiffness with depth. The theoretical shear wave velocity profile, obtained through such a process, corresponds to the maximum shear modulus at small strains of the test site. Figure 4 shows the effect of strain magnitude effect on shear modulus in a typical shear stress, τ, versus shear strain, γ, curve. Strain rate of 0.05% is typically defined as small strain rate [24]. The method consists of three phases: (1) field testing and data collection, (2) evaluation of the field Rayleigh wave dispersion curve, and (3) inversion of the dispersion curve to obtain the shear wave velocity profile. SASW testing involves a mechanical excitation (i.e., hammer impact) and two low-frequency receivers. During testing, the two receivers are placed on the soil surface such that the distance from the impact source to the first receiver (D) is equal to the distance between the two receivers (D), which is a function of the wavelength of the excited waves. These receivers are connected to a data acquisition system. Using impact excitation, small-strain stress waves with a broad spectral content are generated which when passing through the equally spaced receivers would allow corelatable signals to be captured. Testing is typically performed in both forward and reverse directions in order to generate an average dispersion curve. General configuration for SASW testing setup is shown in Figure 5.

Also shown in Figure 5 is the idea that widening sensor spacing generates deeper waves and hence detects soil properties at deeper soils. The spacing of these two sensors (L) is equal to the distance between the impact source to the nearest receiver. Each recorded time series signal from the receivers is transformed into frequency domain by the Fourier transformation. After each test, the frequency spectrums from the two receivers are then compared to determine the phase angle shifts at different frequencies. The phase difference between two signals is then determined, and the travel time (t) between the two receivers at each frequency can be obtained as [25]

$$t = \frac{\varnothing}{2\pi f}, \quad (2)$$

where $\varnothing$ is phase difference at a given frequency f. The surface wave velocity (V_s) can be obtained from (3), where L is distance between the two receivers

$$V_s = \frac{L}{t}. \quad (3)$$

The corresponding wavelength (λ) is then determined as

$$\lambda = \frac{V_s}{f}. \quad (4)$$

Calculations are performed at each frequency component and result in dispersion curves. These dispersion curves are then used to determine the theoretical shear wave velocity profile through an iterative process of matching the experimental dispersion curve to the assumed theoretical shear wave velocity curve [25]. The layering of the site and shear wave velocity of each layer was assumed based on the experimental dispersion curve.

For the anchor foundation study, different size hammers and 4 Hz geophones have been used for the ground vibration sensing. The tests were conducted at spacing ranging between 0.5 m, 1.0 m, 1.8 m, 3.6 m, 7.3 m, and 14.6 m. At each location, more than 5 hits were conducted, and the average signal is then used.

4. Anchor Holding Capacity Correlation

Since the anchor holding capacity, Q_{ult}, is a function of the ultimate strength parameters, c and Φ, material density, ρ, and strength modification factors, N_c and N_q, and so forth [26]. Equation (5) through (7) shows the uplift capacity of an anchor in sand, silt, and clay, respectively:

$$Q_{\mathrm{ult}} = \pi\gamma' K_u \tan\varphi \cos^2\frac{\varphi}{2}\left[\left(\frac{D_1 H_1^2}{2}\right)+\left(\frac{H_1^3\tan(\varphi/2)}{3}\right)\right] + \left(\frac{\pi}{2}\right)D_a\gamma'\left(H_3^2-H_1^2\right)K_u\tan\varphi + W_s, \tag{5}$$

$$Q_{\mathrm{ult}} = \gamma' H_1 A_1 N_{qu} + A_1 c N_{cu} + \left(\frac{\pi}{2}\right)D_a\gamma'\left(H_3^2-H_1^2\right)K_u\tan\varphi' + \pi D_a c\left(H_3-H_1\right) + P_s H_1\left(\frac{\gamma'}{2}\right)H_1 K_u \tan\varphi' + P_s H_1 C_a, \tag{6}$$

$$Q_{\mathrm{ult}} = A_1 c N_{cu} + \pi D_a c\left(H_3-H_1\right) + P_s H_1 C_a, \tag{7}$$

where

Q_{ult} = ultimate anchor uplift capacity (lb),
γ' = effective unit weight of soil (lb/ft^3),
H_1 = depth to top of helix (ft),
N_{qu} = uplift capacity factor for cohesionless soils (unitless),
D_a = average helix diameter (in.),
H_3 = depth to bottom of helix (ft),
K_u = coefficient of lateral earth pressure in uplift for cohesionless soil (unitless),
P_s = perimeter of anchor shaft (in.),
C_a = adhesion on anchor shaft (unitless),
A_1 = area of top helix (in.^{2}),
φ = internal friction angle for cohesionless soil ($^\circ$),
φ' = internal friction angle for cohesive soil ($^\circ$),
N_{cu} = uplift capacity factor for cohesive soil (unitless),
c = cohesion at helix plate (lb/ft^2),
W_s = weight of soil in failure zone (lb).

Kulhawy et al. stated that all anchors behave in the same basic manner and listed the following failure modes: (1) the cone resistance failure mode assumes that the uplift resistance is provided by the weight of the soil within the cone of anchor; (2) the shear failure mode assumes that a failure occurs along a cylindrical shear surface; (3) the bearing capacity failure mode assumes that a cavity forms above the bottom plate or helix, providing the failure surface [16]. Niroumand et al. [14, 22] showed that the stress distribution is actually a function of embedment depth and can be differentiated into shallow and deep anchors (Figure 1).

The complexity of (5) and the rapid construction of anchored foundations warrant simplified and quick design approaches [15]. However, the propagating wave velocities, V, are functions of elastic material constant, G (shear modulus), E (Young's modulus), ν (Poisson's ratio), and material density, ρ. The elastic design approach assumes that the wave velocity and holding capacity can be correlated, since at small strain, soil does not show any degradation of stiffness both with strain level and with loading/unloading cycles, and linear elastic model is a good approximation.

To establish the correlation between shear wave velocities and anchor holding capacity, a total of 62 SASW tests, 29 soil boring with SPT, and 97 anchors pull tests were conducted throughout southeastern parts of the United States. The test anchors were installed at different depths and stiffness (determined by SASW), and pull tests were conducted to determine their holding capacity [27]. The soil stiffness and condition from the SASW were also validated with SPT data. Two types of anchors were investigated at this project

Table 1: Typical Shear Wave Velocities [22].

Soil classification	Shear wave velocity (m/sec)
Very soft soil	84–106
Soft soil	107–137
Medium soil	138–183
Stiff Soil	184–274
Very stiff soil	275–366
Soft rock/cemented soil	367–610
Rippability limit	670
Rock	>670
Concrete	2,286–2,438

Table 2: Selected anchor pull test results.

Anchor number	Depth (m)	Torque/no torque	Pull load to failure (kN)
T1	4.3	No torque	133.5
T2	5.2	No torque	177.9
T3	7.3	No torque	222.4
T4	9.1	Torque	355.9 (held)
T5	2.1	No torque	133.5
T6	9.8	Torque	355.9 (held)
T7	9.8	Torque	355.9 (held)
T8	6.4	Torque	334.5 (held)
T9	7.3	No torque	111.7
T10	9.1	No torque	197.9
T11	13.7	Refusal	117.2
T12	14.9	Refusal	83.8
T13	15.8	Refusal	93.4
T14	3.0	No torque	191.7
T15	3.0	No torque	191.7
T16	3.7	No torque	244.7
T17	5.2	Torque	244.7
T18	5.8	Refusal	99.6
T19	5.5	Refusal	169.0

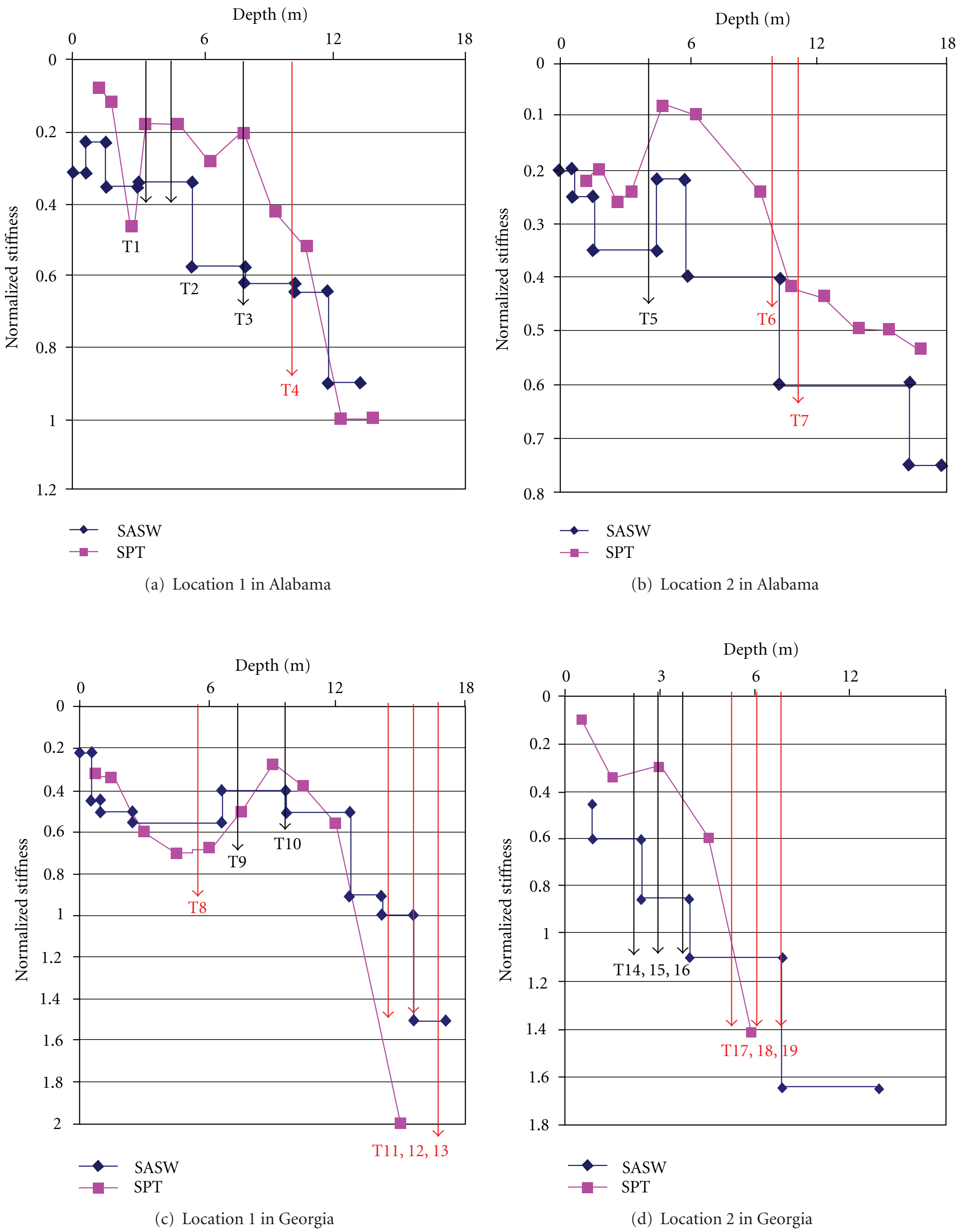

Figure 6: Field tests results (SASW, SPT, and anchor pull tests).

(torsion capacities of 6.78 kN-m and 9.49 kN-m). These anchors are the ones most frequently used by the power companies.

Selected results are plotted in Figure 6, which represent the comparison of SASW shear wave velocity and SPT N-values. These values represent normalized stiffness between the two parameters where shear wave velocity was divided by 670 m/sec (typical shear wave velocity for rock (Table 1 [24])), and N-values were divided by 50 (auger refusal). It is also shown in Figure 6 and marked with arrows for T1

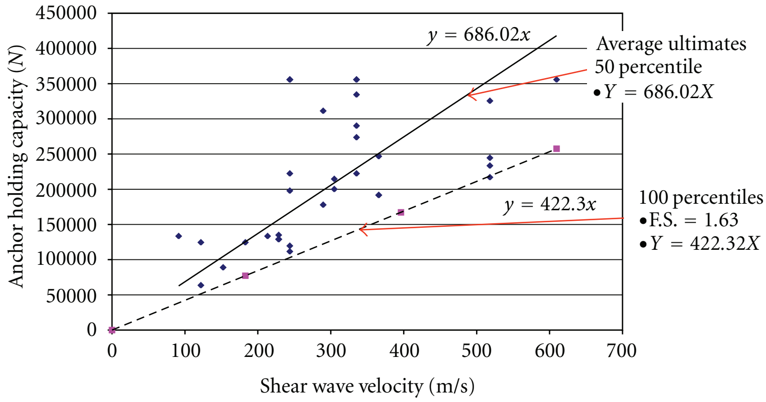

FIGURE 7: Anchor holding capacity versus shear wave velocity with 50 percentile and 100 percentile linear correlations.

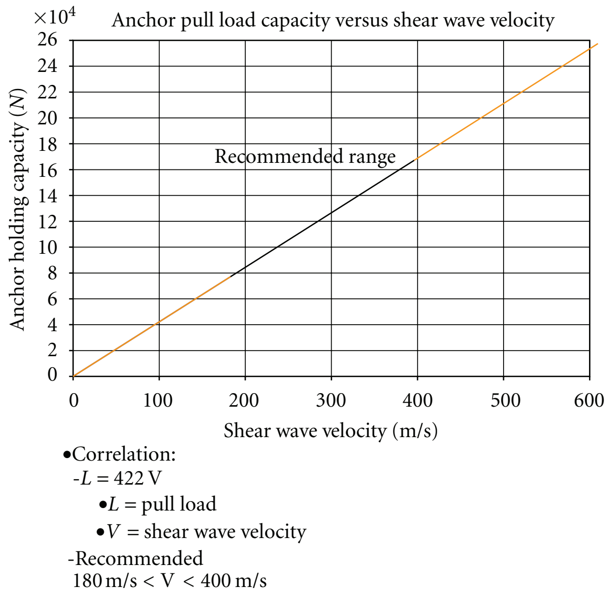

FIGURE 8: Recommended range for anchor pull load capacity versus shear wave velocity.

through T19 anchors that were installed to respective depths. Table 2 shows the representative anchor pull tests results. All anchors were subjected to pull to failure or 356 kN. Failure indicates that the anchor has a total creep of more than 100 mm [27].

Based on all the collected anchor pull test data, a linear trend line is plotted in Figure 7 to show an average pull load capacity versus shear wave velocity with a linear equation of

$$L = 686.02 V_S, \tag{8}$$

where L = anchor − holding capacity (lb) and V_S = shear wave velocity (ft/sec).

However, it should be noted that the correlation has a very low R^2 value (0.1393). This low statistical fit may be due to the fact that the correlation does not differentiate between cohesive or frictional soils.

Because this equation is based on the average results, safety factors of different ranges are added to (8) to determine variations of anchor holding capacity versus shear wave velocity. This addition is to ensure that all the anchors will meet the minimum holding capacity. Figure 7 shows the variations of anchor holding capacity at different factors of safety. Equation (9) shows the calculation for a safety factor (FS) of 1.63, which is the maximum passing safety factor for the one-hundred-percentile linear regression line. The line will meet a minimum holding capacity from the collected test results

$$\text{S.F.} = \frac{\text{Ultimate}_{\text{AVG}}}{\text{Allowable}} = \frac{686.02}{422.32} = 1.63. \tag{9}$$

The following equation shows the factored correlation between the anchors holding capacity versus shear wave velocity:

$$L = 422 V_S. \tag{10}$$

Figure 8 shows the line for (10), in which the center range represents a recommended range (180 to 400 m/sec) for

Table 3: Summarized of anchor installation and anchor pull tests at the recent pilot tests.

Transmission structure no.	Anchor installation			Anchor pull tests		
	Anchor installed	Installed to predicted depth	Twist prior to recommendation depth	Total	Passed	Failed
1	20	20	0	6	6	0
2	13	N/A	N/A	6	6	0
3	12	12	0	6	6	0
4	16	16	0	9	9	0
5	20	20	0	9	9	0
6	20	16	4	8	8	0
7	24	23	1	10	10	0
8	20	17	3	8	8	0
9	12	11	1	0	0	0
10	20	17	3	8	8	0
11	20	20	0	12	12	0
12	18	18	0	0	0	0
13	16	15	1	0	0	0
14	20	13	7	0	0	0
15	20	17	3	9	9	0
16	18	18	0	8	8	0
17	24	24	0	12	12	0
18	20	20	0	12	12	0
19	20	19	1	14	14	0
20	24	24	0	8	8	0
21	24	20	4	0	0	0
22	16	N/A	N/A	0	0	0
23	10	10	0	4	4	0
24	12	12	0	5	5	0
Total	439	382	28	154	154	0
Percentage		93.17	6.83		100	0

anchors to be installed. If an anchor is to be installed below at <180 m/sec, the soil strength at this region may not provide a sufficient or minimum amount of holding capacity. This recommended range is to satisfy the requirement by the Southern Company that all anchors are installed at a minimum holding capacity of 75 kN of working load. On the other hand, if the anchor is installed at >400 m/sec, rock fragments may be encountered and cause refusal (unable to penetrate and does not torque out). As a result, an anchor must be installed with caution, especially outside the range represented by the bold black line.

Figure 9 shows a summary of the design approach where SASW testing technique determines the soil stiffness profile and based on (10), the embedment depth and the pull capacity can be determined. Using Table 1, it is also possible to project depth to bedrock using the wave velocity value. Since the soil testing technique determines elastic soil parameters, the method is considered as an elastic design. Aside from being totally nondestructive, the SASW technique is also rapid, relatively easy to perform, portable, and inexpensive.

5. Field Validation Test

A full-scale field validation testing was conducted in Georgia, USA, to verify the correlation of anchor holding capacity prediction based on the SASW results. The site is intended or an operating transmission line between Covington and Eatonton, GA. Figure 10 shows the extent of the validation project site. Based on field SASW tests and (10), a set of recommendations for anchor installation was provided, which included (1) soil stiffness versus depth; (2) number of extensions required for each anchor to be installed to desire depth.

A total of 439 anchors were installed for the transmission line, which all are installed according to the recommendations. Table 3 summarized anchor installation and anchor pull tests results. 93.17% of a total anchor installed reached recommended depths and only 6.83% (28 anchors) torque out prior to reaching recommended depths. Among those anchors, which reached full torque before reaching recommended depth, 82% (23 anchors) of them lacked one extension. A total of 154 pull tests up to either 71 kN or 85 kN

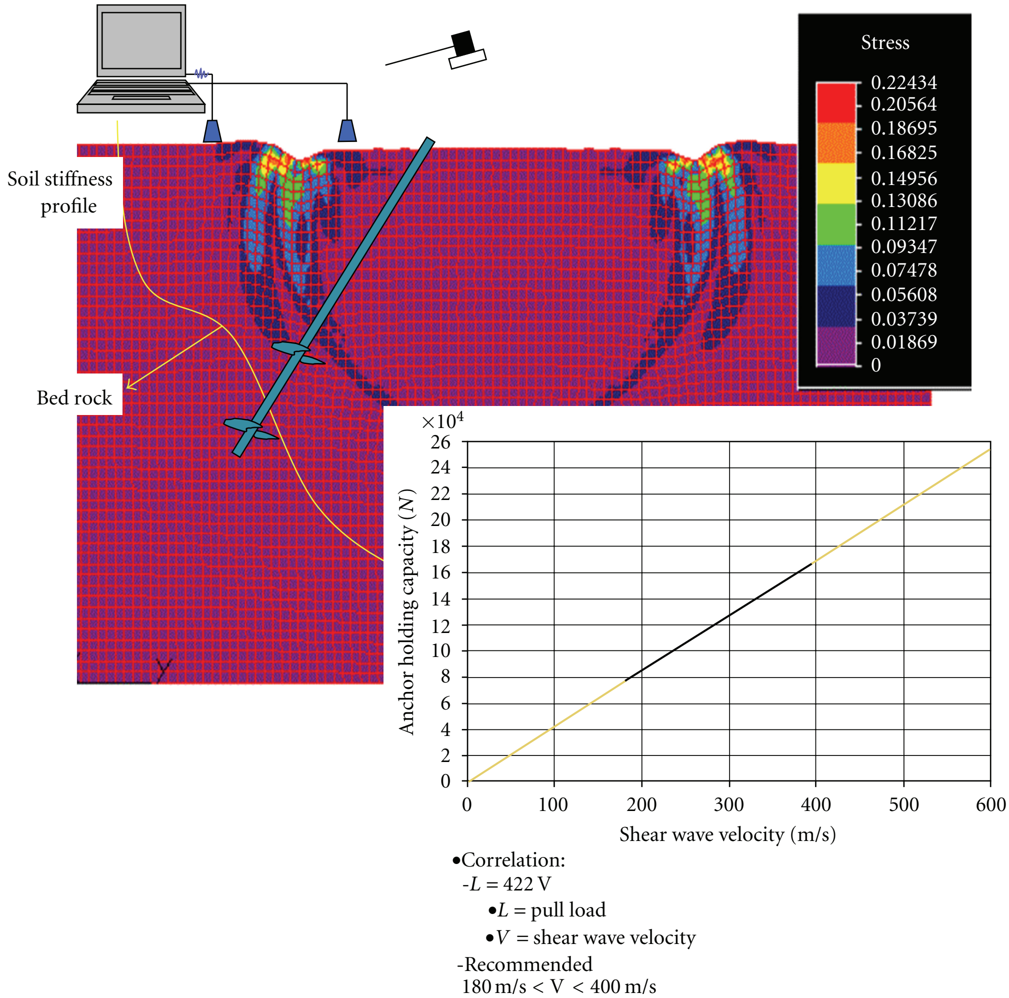

Figure 9: Elastic design of anchors based on surface wave soil testing.

Figure 10: Validation project site in Georgia, USA.

were conducted on these selected anchors. These loads are based on ultimate working loads. All anchors tested sustained the ultimate working pull load without failure.

6. Conclusion

An empirical-based elastic design approach for anchored foundation for transmission line structures is proposed in this paper. The design method relies on the use of elastic soil properties derived from SASW soil testing method, which is nondestructive and easy to perform and predicts the embedment depth and holding capacities of the buried anchors. The results of this study show that SASW testing can provide reliable prediction of depth to bedrock, and the correlated soil strengths and holding capacities of the anchors have been validated with anchor pull tests. A recently completed pilot project has demonstrated that such technique is reliable and can be implemented into transmission line structure designs.

SASW is valuable as an engineering tool for rapid geotechnical investigation since it identifies soil stiffness profile and has excellent correlation to SPT values [12, 13]. It has also been used for detection of soil anomalies including hardpan layer, bedrock, and sinkholes. However, the poor statistical fit for the derived anchor holding capacity and shear wave speed correlation indicates that there needs to be further investigations of the relationship between elastic soil properties and foundation ultimate capacity. It also should be cautioned that elastic methods do not account for soil conditions change throughout the life of the structure, which may pose great limitations on where the technique may be applicable.

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