Ground modulus measurement and interpretation for wind turbine foundations

Mesure et interprétation au sol de module pour des bases de turbine de vent

D. Wang
Ph.D, P.E, General Project Manager, 5th Division, CMEC, Beijing, China
C. Harris
P.E., Principle, Renewable Resource Consultants LLC, Round Rock, TX 78665, US
A. Fowler
Sr. V.P., Renewable Energy System-Americas, Broomfield, CO 80021, US

ABSTRACT
The focus on the development of renewable wind energy technology has gained in popularity due to sky-rocketing petroleum costs as the direct result of increased energy consumption. Such demand has lead to the investments of billions of dollars in wind farm projects throughout the world. These projects require high level of engineering expertise due to significant overturning moments and shear forces caused by wind loads. The wind turbine manufacturers also require stringent rotational stiffness requirements, which often limit the foundation deflection to less than ten millimeter or less. Therefore, collecting in-situ field measurement such as the subgrade modulus can be useful in determining the stiffness and settlement of bearing stratum of foundations. In this paper, the practicality of two in-situ test methods, pressuremeter test and vertical seismic profile (VSP), which are often used to determine the subgrade modulus, are discussed. Some technical issues, such as data collection techniques, interpretation of different modulus by cyclic loading and static loading, measured and interpreted modulus of small strain, are discussed. Based on the projects completed to date, correlation between the modulus measured with these two methods was studied and analyzed.

RÉSUMÉ
Le foyer sur le développement de la technologie renouvelable d'énergie éolienne a gagné dans la popularité due aux coûts montants en flèche de pétrole comme le résultat direct de la consommation d'énergie accrue. Une telle demande a pour mener à plusieurs milliard de dollars d'investissements dans des projets de ferme de vent dans le monde entier. Ces projets exigent à niveau élevé de l'expertise de technologie due aux moments significatifs de renversement et aux forces de cisaillement provoqués par des charges de vent. Les fabricants de turbine de vent exigent également les conditions de rotation rigoureuses de rigidité, qui limitent souvent le débattement de base moins de dix millimètres ou moins. Par conséquent, le rassemblement de la mesure sur le terrain in-situ telle que le module de sous-grade peut être utile en déterminant la rigidité et le règlement de la strate de roulement des bases. En cet article, le caractère pratique de deux méthodes in-situ d'essai, l'essai de pressuremeter et le profil séismique vertical (VSP), employés souvent pour déterminer le module de sous-grade sont discutés. Quelques questions techniques, telles que les techniques de collecte de données, interprétation de module différent par le chargement cyclique et le chargement statique, ont mesuré et ont interprété le module de la petite contrainte, sont discutées. Basé sur les projets accomplis jusqu'ici, la corrélation entre le module mesuré avec deux méthodes principales a été étudiée et analysée.

Keywords : foundation, wind turbines, rotation stiffness, modulus, small strain, pressuremeter, geophysical testing

1 INTRODUCTION

Recent advancement in wind turbine technology has led to much larger turbines, blades and tower heights. Typical wind turbine generators (2.0 and 3.0 MW) weigh as much as 2500 to 2900 kN (560.8 to 650.5 kip). Tower hub heights are typically between 70 and 80 meters (229.7 to 262.5 ft). The foundational materials including the weight of reinforced concrete, backfill above foundation base or soil/rock masses around foundation must be able to resist characteristic overturning moments which are on the order of 50000 to 60000 kN-m (36790 to 44150 kip-ft) and have sufficient rocking stiffness typically on the order of 40 to 50 GN-m/Rad. The rocking stiffness is of particular importance because it determines if a wind turbine will develop vibration related frequencies that would be detrimental to the wind turbine tower system. If natural frequencies are attained, resonant vibration will occur and it could lead to the collapse of the entire system.

Given the above stringent demands, the performance of the foundation system is extremely important. Therefore, proper investigative techniques should be applied to determine and qualify the subsurface conditions to be able to support a wind turbine foundation.

2 SUBSURACE INVESTIGATIVE TECHNIQUES

Besides the typical geotechnical investigative techniques, the design of wind turbines require extensive in-situ strength characteristic testing which include the use of pressuremeter and geophysical testing.

2.1 Pressuremeter Testing

Pressuremeter testing measures both the strength and stress-strain properties of all soil types including soft rock. A pressure regulator facilitates accurate pressure control and a direct readout of guard cell pressure is provided. The pressuremeter is used primarily to calculate bearing capacity of shallow and deep foundations; settlement of foundations; deformation of laterally loaded and sheet piles and resistance of anchors. Figures 1 and 2 illustrate pressuremeter and testing procedures.

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Figure 1. A boring is being drilled prior to the beginning of pressuremeter testing (Courtesy of Kleinfelder Austin Office, 2006)

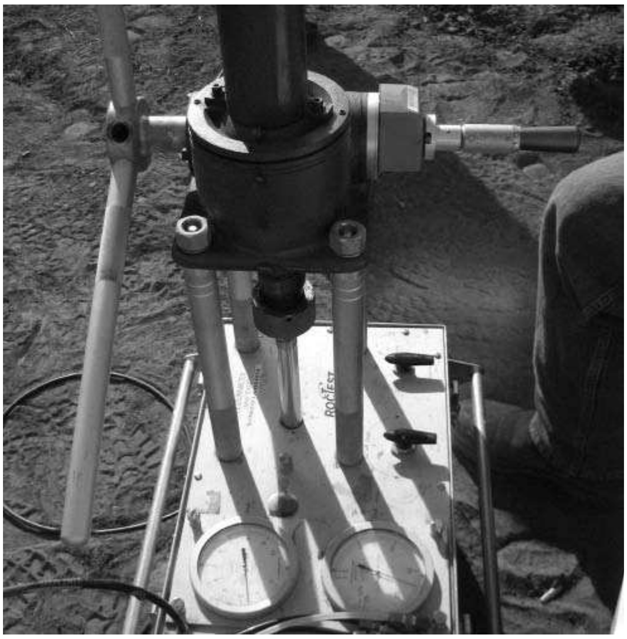

Figure 2. Pressuremeter gauges (Courtesy of Kleinfelder Austin Office, 2006)

"The probe is placed at the test depth in a pre-drilled borehole obtained by a method adapted to the soil conditions: augering, rotation with drag bit and bentonite, shelby tube driving, etc. The test is run either with a constant rate of deformation, by using a uniform rate of rotation of the actuator, or with equal increments of pressure as for the Ménard pressuremeter test." (Roctest, 2005)

Of the many useful information derived from the pressuremeter testing, deformation moduli (including presssuremeter modulus and shear modulus) is of particular interest for foundation design of wind turbines. Deformation modulus is calculated from the following equations based on pressuremeter gauge readings:

$$E_0 = \frac{(1+\nu) * 2V * \Delta P}{\Delta V} \quad (1)$$

$$G = \frac{\Delta P}{2 * \Delta(radial\_displacement / radius)} \quad (2)$$

Where: ν = Poisson's Ratio
V= Cavity volume at the middle of the elastic zone
ΔV= Change in volume measured by pressuremeter
ΔP= Change in Pressure measured by pressuremeter
E_0 = Pressuremeter Modulus
G = Shear modulus

Typical pressuremeter testing curve is illustrated in Figure 3.

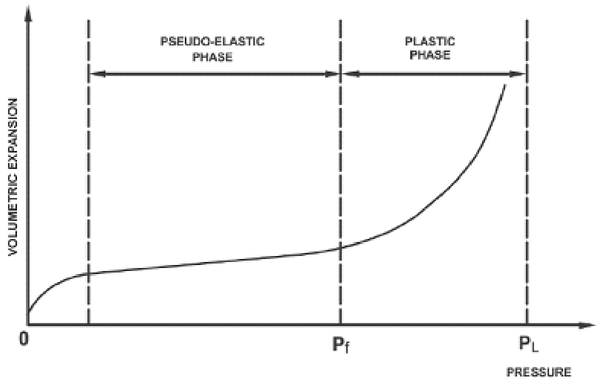

Figure 3. Typical pressuremeter testing curve

The deformation modulus is useful in determining the stiffness of soil or soft rock. Coupled with strain rate data obtained from the pressuremeter testing, particular deformation modulus can be developed with any given amount of strain.

2.2 Geophysical testing

Geophysical testing and analyses can also provided moduli values. Vertical seismic profile (VSP) is based on theory of wave propagation in linear material, and generally operate at strain levels that are not large enough to induce significant nonlinear stress-strain behavior in the soil, typically at shear strains below about 0.01% (Kramer 1996). Vertical Seismic Profile (VSP) is performed by lowering a geophone connected to a seismograph down a borehole and recording the time required for both compression and shear waves to propagate through the soil and rock mass from a sound source, which may be generated by explosive sources, vertical impact and horizontal impact as shown by Figure 4.

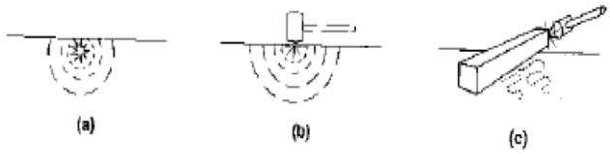

Figure 4. Different methods for creation of impulsive disturbances for seismic geophysical tests (a) shallow explosives; (b) vertical impact; (c) horizontal impact (Kramer 1996)

In our case, the sound source is a slug hammer, hitting a "strike plate", which triggers the clock within the seismograph. The data is collected on a portable computer and processed to eliminate "background noise". Both compressional (P) and shear (S) wave velocities are then computed based on the time the waves take to propagate from the strike plate to the geophone. P and S waves take longer to propagate through softer soil compared to rock.

The processed shear velocities are used to determine certain soil and rock characteristics based on simple equations. Since most seismic geophysical testes induce shear strains lower than about $3x10^{-4}$ %, the soil/rock rigidity, or shear modulus can be calculated using the following equation (Kramer 1996):

$$G = \rho * V_s^2 \quad (3)$$

Where: G = Shear Modulus (psf)
ρ = Mass density (pcf/(ft/sec^2))
V_s = Shear velocity (ft/sec)

Young's Modulus, E, can also be calculated from the compression and shear velocity using the following equation:

$$E = 2G * (1 + \nu) \quad (4)$$

Where: E = Young's Modulus (psf)
ν = Poisson Ratio, typically 0.25 for hard rock and 0.3 to 0.4 for stiff to soft soil
G = Shear Modulus (psf)

3 COMPARISON OF MUDULUS BASED ON VERTICAL SEISMIC PROFILE AND RESSUREMETER TESTING RESULTS

Values of stiffness in real soils however measured are strain level and stress level dependent. Translating between pressuremeter values and Young's Modulus is complex though worth pursuing. Due to the amount of the data, this paper will only compare actual test results from three wind farm projects where both pressuremeter and geophysical techniques were used to determine deformation modules instead of building a model to translate the two moduli. Site of Whirlwind Energy Center Project, located in Floydada County, Texas, primarily consist of lean and fat clay with varying amounts of sand and silt. Vertical seismic profile (VSP) testing was performed at five turbine locations from depth 1.524 m (5 feet) to 7.62m (25 feet) below ground surface while pressuremeter testing was performed at three locations which two of them are parallel to the holes for vertical seismic profile testing at a depth around 8 ft and 12 ft below ground surface. Site of Sweetwater Phase 4B Wind Farm, located in Nolan County, Texas, primarily consist of lean and fat clay and limestone with varying degree of weathering. Vertical seismic profile was performed at five holes from depth 1.839m (6 feet) to about 9.144m (30 feet) below ground surface, while pressuremeter testing was performed in 6 holes at varying depth from 2.134m (7 feet) to 3.962m (13 feet). One of the pressuremeter testing holes is parallel to Vertical Seismic Profile hole. Mesquite Wind Farm, located in Shackelford County, Texas, has the similar subsurface conditions with Sweetwater 4B Wind Farm. Vertical seismic profile was performed at 10 locations from ground surface to about 3.048m (10 feet) depth, and pressuremeter testing was performed at 10 holes from depth 1.524m (5 feet) to 4.572m (15 feet). Among the holes for vertical profile and pressuremeter testing, five holes are parallel. The comparisons are summarized in Tables 1, 2 and 3.

4 SHEAR MODULUS VS STRAIN LEVEL

Table 4 in next page lists the pressuremeter testing data for one of our wind farm projects in Washington State, which consists of weathered to competent basalt rock in subsurface.

Table 1 Comparisons between Vertical Seismic Profile and Pressuremeter testing for Whirlwind Project

Whirlwind -TX		VSP					Pressuremeter Testing	Result
Hole/ depth	Soil Type	Velocity Vs (ft/sec)	Density (pcf)	Mass Density (pcf (ft2/s))	Shear Modulus G (psi)	Young's Modulus, E (psi)	Pressure meter Modulus E_0 (psi)	Ratio E/E_o
S4/8.5ft	sandy lean clay, SPT N is about 50	1063.9	115	3.6	28072.5	72988.5	4200	17.4
S4/11.5ft	" "	1135.8	115	3.6	31995.1	83187.2	5100	16.3
S16/8.5ft	Lean clay with sand, SPT N is about 35	932	115	3.6	21543.3	56012.5	3450	16.2
S16/11.5ft	N is about 43	1089.5	115	3.6	29439.7	76543.3	9650	7.9

Table 2 Comparisons between Vertical Seismic Profile and Pressuremeter testing for Sweetwater 4b Project

Sweetwater 4b - TX		VSP					Pressuremeter Testing	Result
Hole/ depth	Soil Type	Velocity Vs (ft/sec)	Density (pcf)	Mass Density (pcf(ft2/s))	Shear Modulus G (psi)	Young's Modulus, E (psi)	Pressure meter Modulus E_0 (psi)	Ratio E/E_o
F14/7ft	Lean clay with silt, limestone gravel, SPT N is above 50	1865.9	115	3.6	86348.8	224506.8	3890	57.7
F14/13ft	Highly weathered limestone	4152.9	135	4.2	502132.5	1305545	230000	5.7

Table 3 Comparisons between Vertical Seismic Profile and Pressuremeter testing for Mesquite Project

Mesquite - TX		VSP					Pressuremeter Testing	Result
Hole/ depth	Soil Type	Velocity Vs (ft/sec)	Density (pcf)	Mass Density (pcf(ft2/s))	Shear Modulus G (psi)	Young's Modulus, E (psi)	Pressure meter Modulus E_0 (psi)	Ratio E/E_o
T15/5ft	very stiff lean clay with limestone fragment, N is about 20	1700	120	3.7	74791.7	19000	2368.1	8
T15/10ft	Hard tan silty clay with limstone seams and fragments	2700	135	4.2	212222.2	530625	2562.5	207.1
T34/6ft	Hard silty clay with limestone fragment	1200	120.1	3.7	37291.7	94652.8	11763.9	8
T34/12ft	Tan to light gray limestone with weathered and marly seams	2950	135	4.2	253402.8	633402.8	4055.6	156.2
T42/5ft	Hard tan silty clay with limstone fragments	1100	120	3.7	31319.4	94652.8	2750	34.4
T42/11 ft	Hard tan silty clay with limestone fragments	2260	135	4.2	148680.6	371736.1	6027.8	61.7
T51/11ft	Very stiff lean clay with limestone seams and fragments	3000	135	4.2	262013.9	655069.4	7611.1	86.1
T79/6ft	Very stiff to hard reddish brown to tan silty clay with limestone fragments	3000	135	4.2	262013.9	655069.4	4750	137.9

Figure 5 (in next page) shows the trend of interested shear modulus versus the strain level.

5 DISCUSSIONS

The data listed in the first three tables indicated that the tested and interpreted stiff modulus with vertical seismic profile and pressuremeter testing method varies greatly. Generally, in stiff clay soil, the Young's Modulus, E, based on vertical seismic profile testing is at least 8 times higher than pressuremeter testing modulus, E_0. In the case where the soil is mixed with fragments or weathered rock, the Young's Modulus based on vertical seismic profile testing are much higher than the modulus based on pressuremeter testing. The difficulty of performing the pressuremeter tests accurately in fragments-mixed soil and weathered rock could be the reason to cause the difference. In some cases of our practice, the pressuremeter rarely reaches the limit pressure of the material in such soil conditions, and our data suggests that the strain level is much lower in hard soil and rock masses than that in soft soil. The trend indicated by the data in this paper is consistent with a finding in one publication (Mathew et al, 2000), which suggested that the ratio of modulus determined by geophysical methods and large plate load tests are 0.85 for hard soil and weak rock, while the ratio is 0.5 for soft soil, even though the magnitude of the ratio is much different.

Table 4 Pressremeter testing data in a wind farm in WA

Test Hole	Depth (ft)	Soil Type	Initial Average Shear Modulus (psi)	Unload-reload Shear Modulus (psi)	Strain
WCB01	32.9	Basalt	140000	210000	0.60%
WCB02	14.5	Basalt	12000	150000	2.10%
WCB02	16	Basalt	7000	210000	6%
WCB03	12	Basalt	200000	1300000	0.60%
WCB03	14.2	Basalt	200000	1300000	0.60%
WCB04	33	Basalt	700000	1300000	0.60%
WCB04	31.5	Basalt	700000	130000	0.50%
WCB06	29.2	Basalt	700000	700000	0.60%
WCB06	31.9	Basalt	300000	1300000	0.50%
WCB07	30	Basalt	35000	150000	1%
WCB07	28.5	Basalt	20000	150000	1%
WCB08	22	Basalt	25000	150000	3.80%
WCB08	20.5	Basalt	7000	190000	3.00%

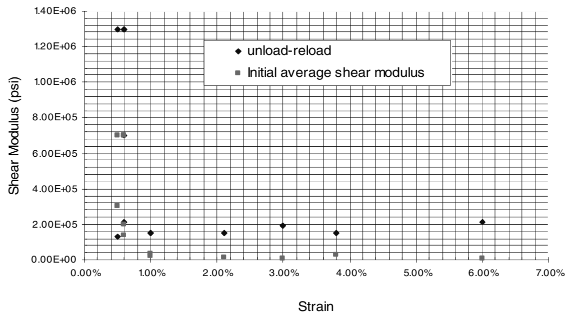

Figure 5. Shear modulus vs strain in basalt rock with pressuremeter testing

Figure 5 indicates when the strain level is less than 1%, the measured shear modulus vary steeply, and is considerably higher than that measured with greater strain levels. When the strain level is greater than 1%, the shear modulus measured become relatively low and flat. This is consistent with the findings depicted on Figures 6 & 7 on right column: with strain enlarging, the shear modulus becomes flat no matter what type of soils.

6 CONCLUSION AND RECOMMENDATIONS

In conclusion, ground modulus can be measured and interpreted from geophysical and/or pressuremeter testing data. However, discrepancy measured from the two methods is observed. Based

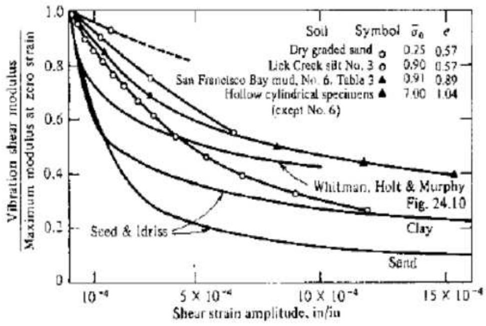

Figure 6. Effect of shearing strain amplitude on shear modulus from tests on hollow samples of sand (after Drnevich, Hall and Richart 1967, tabulated from Winterkorn H and Fang H, 1975)

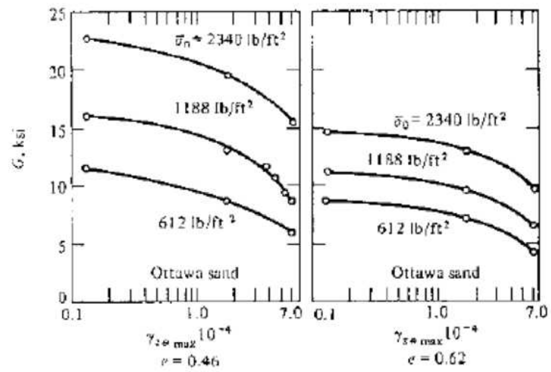

Figure 7. Normalized diagram, effect of shearing strain amplitude on shear modulus (after Hardin and Black, tabulated from Winterkorn H and Fang H. 1975)

on the field data, it appears that the pressuremeter testing could lead to lower modulus than geophysical method. In addition, it appears that geophysical testing is more applicable where the strain values are known to be low, which could be performed in rock, hard soils etc. When the strain levels are high, for example, measurement performed in soft soil, a reasonable reduction would be required or pressuremeter testing should be used. It will be valuable to cautiously interpret the testing data both from geophysical method and pressuremeter testing to assure the foundation design is reliable as well as cost-efficient.

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