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Full Length Research Paper

Geotechnical and geophysical studies for wind energy systems in earthquake-prone areas: Bahce (Osmaniye, Turkey) case

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Wind energy structures are systems related to the conversion of wind energy into useful form by wind power. They are subjected to strong dynamic and static loads. For this reason, an integrated site/soil investigation is required for all phases of project. In this context, there are several geotechnical/geophysical criteria and requirements such as settlement criteria, stiffness requirements, ground water and dewatering requirements, excavation criteria, etc. Geotechnical and geophysical studies should include possible degradation of soil and rock due to cyclic loading over expected years of operation, bearing capacity, surcharge soil erosion due to drainage of storm water, differential settlements and consolidation settlements, etc. All soil layers that influence settlement and stiffness of foundation must be investigated. Study area is seismically active region and bounded in Bahçe district of Osmaniye City, in Turkey. The geodynamics of the region are controlled by the collision of the Arabian and Eurasian Plates. The East Anatolian Fault Zone, major seismogenetic source of project area is a 550 km-long, approximately northeast-trending, left lateral strike-slip fault. An (deterministic and probabilistic) earthquake hazard analysis was applied to region to estimate the ground motion level in engineering bedrock. Several geotechnical/geophysical tests and boreholes were performed in area to obtain better settlement, stiffness, bearing capacity, degradation properties.

Key words: Wind energy systems, geotechnical earthquake engineering, Turkey.

INTRODUCTION

Civil engineering structures for wind energy systems are related the conversion of wind energy into useful form by wind power. These structures are subjected to strong dynamic and static loads. For this reason, an integrated site/soil investigation is required for all phases of project. Geological observations, geophysical measurements, soil explorations, in-situ tests and laboratory tests have been performed over the study area. This survey has been realized in order to be able to decide basic systems in an element, which is one of the turbine locations of Wind Power Plant (135 MW) that is planned to be constructed in Bahçe county of Osmaniye province and in order to be used as a basis for the superstructure loads to be transferred to the soil in detail. Presentation of the location map of the site with several cities and main seismogenetic fault described in Figure 1a.

Geological framework

From the structural point of view; Amanos Mountain is located over the intersections of the tectonic zones or within the impact area of these zones which are well known world wide. At Nur Mountain, characteristic folding

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Table 1a. Equations for rapture length and magnitude estimations.

Researcher	M (magnitude)	Magnitude type
Ambraseys and Zatopek (1969)	M = (0,881 LOG(L))+5,62	Ms
Douglas and Ryall (1975)	M = (LOG(L)+4,673)/0,9	Ms
Ezen (1981)	M = (LOG(L)+2,19)/0,577	Ms
Toksöz et al. (1978)	M = (LOG(L)+3,62)/0,78	Ms
Wells and Coppersmith (1994)	M = 5,16+(1,12 LOG(L))	Mw

Table 1b. Selected two fault model (A : fault rapture length is 50 km) and B : fault rapture length is 245 km) within East Anatolian Fault Zone.

Researchers	M (magnitude) Estimations For A Model	M (magnitude) Estimations For B Model
Ambraseys and Zatopek (1969)	7.1	7.5
Douglas and Ryall (1975)	7.1	7.6
Ezen (1981)	6.7	7.5
Toksöz et al. (1978)	6.8	7.4
Wells and Coppersmith (1994)	7.1	7.6

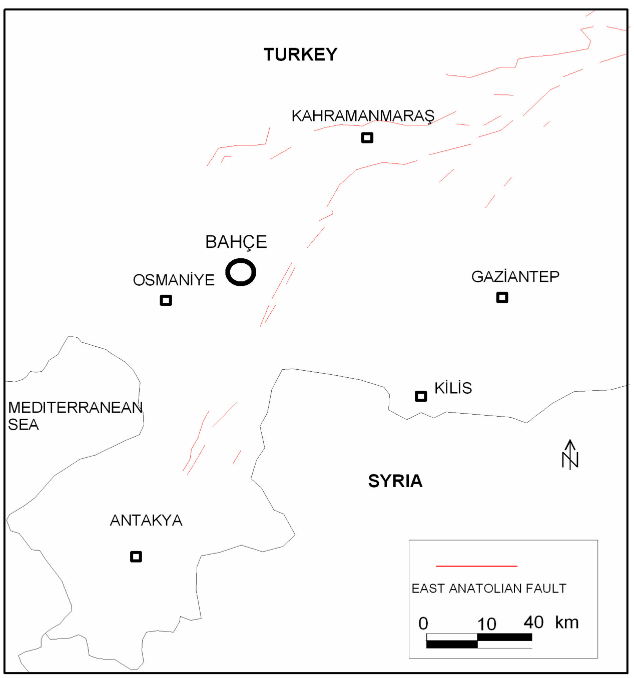

Figure 1a. Presentation of the location map of the site with several cities and main seismogenetic fault.

and faulting properties are being observed. Overturned, overthrust and canted folding in different scales are observed. Spring water and percolating water are becoming dense in the western part and are being observed over discontinuity zones depending on the structural geology. These springs and percolations have resulted important amount of decomposition over the main rock. The engineering properties of the geological units differ from one region to another depending on the structure and hydro-geology and types of rocks. Study area is near the Eastern Anatolia Fault zone which is strike slip fault zone. Eastern Anatolia Fault has not been formed of only one single fault but has been formed of as a complex fault system or zone.

SEISMIC HAZARD ANALYSYS OF REGION

Seismic hazard analyses aim at assessing the probability that the ground motion parameter at a site due to the earthquakes from potential seismic sources will exceed a certain value in a given time period (Erdik et al., 1999, 2004). Deterministic and Probabilistic approaches are used in developing ground motions in professional practice. The deterministic approach is based on selected scenario earthquakes and specified ground motion probability level, which is usually median ground motion or median-plus-one standard deviation. The probabilistic approach encompasses all possible earthquake scenarios, all ground motion probabilities and computes the probability of the ground motion to be experienced at the site exceeding a certain value in a given time period. Empirical attenuation relationships are generally employed in the quantification of seismic hazard in either deterministic or probabilistic approaches (Seismic Microzonation for Municipalities: Manual, 2004).

For deterministic seismic hazard analysis, two fault model are selected namely A (fault rapture is 50 km) and B faults (fault rapture is 245 km) within east Anatolian fault Zone (Table 1a and b).

Earthquake ranges for analysis were taken from 4.5 - 7.5 about 100 km radius (Table 1c).

Table 1c. Earthquake Magnitude ranges in study area about 100 km radius. Data are obtained by BU KOERI, compiled by Kalafat et al., 2007).

Magnitude Ranges	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$
Number of Earthquakes	34	9	6

Table 2a. Used Acceleration Attenuation Relationships in this Study

a = Acceleration Value (cm/sn^2) **PHA = Pick Horizontal Acceleration** **M = Earthquake Magnitude** **D = Epicentral Distance (km)** **R = Radial Distance from Focal depth (km)**	**Researchers**
.$a = 1300\, e^{0.67M} (R + 25)^{-1.6}$	Donovan (1973).
.$\log a = 3.09 + 0.347\, M - 2 \log (R + 25)$	Oliviera (1974).
$\log (a/g) = -1.02 + 0.249\, M - \log R - 0.00255\, R + 0.26$ where; $R = (D^2 + 7.3^2)^{0.5}$	Joyner and Boore (1981).
$\ln (a_H) = (-3{,}512+0{,}904M-1{,}328 \ln [(R_{seis}{}^2)+(0{,}149\, e^{0{,}67M})^2]^{0{,}5} + (0{,}44-(0{,}171 \ln(R_{seis}))+(0{,}405-(0{,}222 \ln(R_{seis})))$ where, M is moment magnitude; R_{seis} is shortest distance to seismogenetic fault	Campbel (1997).

Table 2b. Earthquake occurrence probability (%) for D (Year) by poison distribution in the study area.

	Probability (%) For D (Year)				Average Return Period
Magnitude	**10**	**50**	**75**	**100**	**(Years)**
5	90,5	100,0	100,0	100,0	4
5,5	56,1	98,4	99,8	100,0	12
6	25,0	76,3	88,5	94,4	34
6,5	9,6	39,6	53,1	63,5	98
7	3,5	16,2	23,3	29,7	281
7,5	1,2	6,0	8,8	11,6	802

Gutenberg-Richter recurrence relationships was determined as

$$\mathrm{Log}(N) = a - b\, M \tag{1}$$

Earthquake occurrence probability were given by using

$$Rm = 1 - e^{-(N(M)\,.\,D)}$$

Where Rm = Risk value (%); D, duration; N(M) for M magnitude (1) equation value.

Attenuation relationship was defined by several attenuation models (see Table 2a). From a set of attenuation relationships, the average acceleration values of the cities was calculated with exceeding probability of 10% in 50 years by using several attenuation models as shown in Table 2b and c.

Figure 1b shows active fault zones, earthquakes in historical and instrumental periods near study area. Seismic hazard analysis for the region are carried out on the earthquakes bigger than 4.5 for 106 years of period.

Poisson probabilistic approach is applied to earthquake data. Table 2b shows earthquake probability (%) for selected year by Poison distribution in the study area, and Table 2c shows ground motion level at the site exceeding (10%) in a given time period (50 years).

SITE INVESTIGATIONS

Test pits

Information has been obtained from observation purpose superficial excavations and in the laboratory evaluations, drilling samples have been used.

Table 2c. Ground motion probabilities show the probability of the ground motion to be experienced at the site exceeding (10%) in a given time period (50 years).

	D (year)	Probability of exceedence (%)	M (magnitude)	
	50	10	7.2	
	Δ, Epicentral Distance (km)	H, Focal depth (km)		
	25	15		
	Donavan (1973)	Oliviera (1974)	Joyner and Boore (1981)	Campbell (1997)
Estimated a (g)	0.26	0.19	0.59	0.45

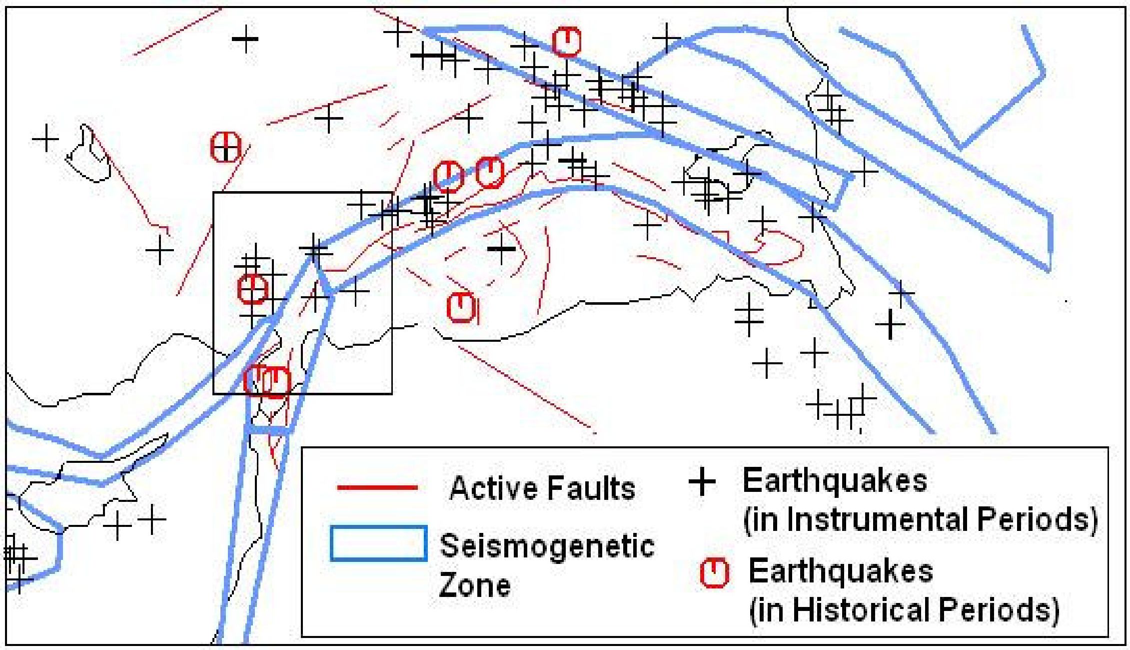

Figure 1b. Active fault zones, earthquakes (M larger than 5.5) in Historical and Instrumental time intervals around the Study Area (a quadrangle) [map is redrawn by Erdik et al. (1999)].

Drilling wells

As a result of the observations and analysis performed over the survey area and near environment, it has been planned and realized 2 drilling (SK-1 on the middle of the base, SK-2 at the edge of the base) wells with 30 meter over the area at which the construction base will be settled (Table 3).

Surface and ground water

There is no ground or superficial water danger which could affect the basic systems of the turbine planned to be constructed over the survey area. However, the contact and interaction of the superficial water and standing water which can accumulate during and after the construction of the foundations of the turbine as a result of the seasonal precipitations should be prevented.

Field tests

SPT tests and core evaluations: Since the survey area is formed by rock units even from the surface (not suitable for SPT experiment), core samples obtained from drillings have been evaluated.

Geophysical tests

(a) Seismic tests: In the seismic studies which have been performed over the soil of the survey area, mainly seismic refraction method which is used in direct and reverse shooting has been applied. Seismic measurements have been made by measuring both longitudinal (or compressional), Vp and also transversal (or shear), Vs wave velocities. Vp has been measured in order to determine the underground structural locations in horizontal and lateral directions, Vs has been measured in order to know the elastic properties. Geophone intervals in

Table 3a. Lithology according to the drilling results.

Borehole	Depth (m)	Lithology
SK-1	0.00 – 7.50	gray colored, faulted and fractured, melted cellular from place to place limestone with rarely calcite filled faults, calcite grained, with brown colored decomposition surfaces.
	7.50 – 30.00	gray colored, melted cellular limestone with brown colored decomposition surfaces, calcite grained from place to place, fractured, medium sometimes thick layered.
SK-2	0.00 – 7.50	gray colored, faulted and fractured, melted cellular from place to place limestone with rarely calcite filled faults, calcite grained, with brown colored decomposition surfaces.
	7.50 – 30.00	gray colored, melted cellular limestone with brown colored decomposition surfaces, calcite grained from place to place, fractured, medium sometimes thick layered.

Table 3b. Average geotechnical parameters obtained by seismic tests.

Vp Velocity (m/s)	Vs Velocity (m/s)	Vp/Vs	Density (gr/cm3)	Poison Rate	Shear Module (Kgf/cm²)	Dyn. Ela. Mod. (Young) (Kgf/cm²)	Soil Amplifications (Borcherdt et al 1991)	Soil Preddminant Period To (s)
1811	834	2.17	2.1	0.37	14.922	40.750	0.7	0.16
1835	791	2.32	2.1	0.39	13.419	37.195	0.8	0.17

Table 3c. Soil resistivity and corrosion level according to Turkish standards.

Resistivity Value	Corrosion Degree
Resistivity < 10 ohm.m	More Corrosive
10 < Resistivity < 30 ohm.m	Corrosive
30 < Resistivity < 100 ohm.m	Medium Corrosive
100 ohm.m < Resistivity	Not Corrosive

seismic measurements have been selected as 2 m. Table 3b shows geotechnical parameters obtained by seismic tests.

(b) Electric resistivity applications: In the resistivity studies which are made in order to clarify the lithological structure of the soil of the survey area, SAS (signal Average System) resistivity measurement system has been used. Soil resistivity is being changed depending on the grain size, water content, porosity and permeability. At the survey area, the variation of the apparent resistivity with the depth has been analyzed by applying Vertical Electric Drilling, in the Schlumberger permutation technique with 2 AB/2 = 40 m expansion and so the structural disorder, depth, lithology, thickness of layers, underground water capacity, corrosion degree which is especially important in the structuring have been analyzed by using the resistivity differences (Table 3c).

The results of the measurements obtained in survey area and the soil curves formed by the apparent resistivity values which are varied according to the depth have been evaluated manually and by using computer. The resistivity values of the survey area are as follows (Table 3d).

LABORATORY TESTS AND ANALYSIS

Index/physical properties of the soil/rock

The tests which are complying with the R.T. Ministry of Public Works norms and TS1900 have been performed over the soil / rock core samples which have been taken from the boreholes that had been drilled during field surveys.

Table 3d. Resistivity Values of the units in survey area.

Schedule B2: Resistivity Values of the units in survey area		
Unit	**Thickness(m)**	**Resistivity (Ohm.m)**
First Layer	7 - 8	345 - 360 Ohm.m
Second Layer	50	1083 - 1217 Ohm.m

ENGINEERING ANALYSIS AND EVALUATIONS

Determination of soil-structure relation

Foundation system: Required laboratory studies have been made over the observations, soil excavations, geophysical applications about the mentioned foundation soil which has been analyzed regarding geotechnical perspective and the obtained parameters have been specified in the above sections.

The planned structures (wind towers) are high towers having rigid bearing systems. Raft foundation will be a proper foundation solution for this project since this kind of a foundation will provide safety against differential settlements, will protect the integrity of the bearing system under the earthquake loads and dynamic wind load, as well as static loads.

Bearing capacity: Allowable bearing capacity calculations regarding the related parameters about either soil / rock or structure have been made separately in different approaches by taking into account land data, laboratory experiment results and drilling core observations and Rock Quality Designation (RQD) values. The rock and soil formations of the environment have been taken into account in the selection of the calculation methods. At the soil / rock locations which are not convenient to provide samples proper for the experiments required for the method (especially in rock tri-axial experiment required for the Bell method), values which have been obtained from the other locations of the same unit or the known technical literature values have been taken into account.

Settlements: Even it is not expected to occur the Settlements which exceeds the acceptable limits under the load to the soil as a result of the structuring over this soil of which most parts that the structure foundation will be based are clay, silt the Settlements value of the medium which has been calculated according to the elasticity module (dynamic) and Poisson ratio values.

Special attention should be given not to place the foundation over the excessive splitted, weak durable or decomposed units except the survey points during the foundation excavation and not to place the foundation over differentiated units. Before the construction and after the excavation, and during and after the construction, it is required to protect the foundation area from the superficial waters and rains and adequate discharging system should be designed.

Table 4. Soil groups according to Turkish earthquake design code.

Soil Group	Shear Wave Velocity (m/s)
(A)	> 700
(B)	400 - 700

Liquefaction: There is no ground water danger in a depth up to 20 m which can negatively affect the foundation structure over the survey area.

Soil class and other parameters: The soil of the survey area is rock formed of faulted, fractured, layered limestone units, Vs shear wave velocity (if the thin layer in the surface is ignored) which has been obtained from the Geophysical - Seismic studies has been measured in between 791 - 834 m/s. According to the Turkish Earthquake Code, these velocities correspond to Soil Group (A), Local Soil Class (Z1) but since these units are fractured and have frequent discontinuity intervals, it is better to classify them as B group Z2 soil class. A little bit more clarification explaining the difference between both classes is given Table 4 and 5. Spectrum characteristic periods which are regarded according to the selected foundation type TA and TB are respectively 0.10 - 0.40 (s). Soil dominant vibration period has been calculated as 0.16 s.

Conclusions and Suggestions

The following results have been obtained after the geological, geophysical, geotechnical studies performed over the area at which the Wind Power Plant turbine (Osmaniye Bahçe) will be constructed;

(a) In the performed observational geological surveys; as a result of the laboratory experiments performed over the core drilling applications of which the survey depth is 30 m, geophysical seismic velocity measurements and electric sounding (resistivity) applications, samples / drilling cores obtained from the soil.
(b) It has been found out that there are limestone units which are gray colored, cracked and fractured, melted cellular from place to place, with rarely calcite filled cracks.

Table 5. Local site class and spectrum characteristic periods (TA , TB) according to Turkish earthquake design code.

Local site class	Soil Group according to Table 6 and Topmost Layer Thickness (h1)	Spectrum Characteristic Periods (TA , TB)
Z1	Group (A) soils Group (B) soils with h1 ≤ 15 m	Between 0.10 and 0.30 s
Z2	Group (B) soils with h1 > 15 m Group (C) soils with h1 ≤ 15 m	Between 0.15 and 0.40 s

(c) Calcite grained, with brown colored decomposition surfaces up to 7.5 m and from this depth until 30 m.
(d) It has been found out that there are limestone units which are gray colored, melted cellular, with brown colored decomposition surfaces, calcite grained from place to place, fractured, medium sometimes thick layered.
(e) The point load bearing of the ponderous samples of the units are in between 19,83 - 58,78 kg/cm² values and the uniaxial pressure bearing are in between 125.44 - 358.64 kg/cm² values. Cohesion value against the main rock is (Si) = 6.72 Mpa and internal friction angle is (Ø) = 34.80. These data are obtained by laboratory measurements.
(f) Over the survey area, there is no natural disaster risk such as floods, landslides, flows, avalanches, rock fallings are not observed.
(g) Over the survey area, there is no underground water which could negatively affect the foundations of the turbine. There is no liquefaction hazard.
(h) Even it is not expected to occur the settlements which exceed the acceptable limits under the load to the soil as a result of the structuring over this soil of which most parts that the structure foundation will be based are limestone. The cracked, fractured, decomposed units at the upper parts should be removed gradually and in a controlled manner during the foundation excavation. Special attention should be given not to place the foundation over the excessive splitted, weak durable or decomposed units except the survey points.

It is required to inform the designing company whenever a situation such as undesirable due to the foundation structuring or poor durability, micro faults, etc., is met different than the soil profile described in logs, in order company to get necessary precautions on time and in required locations.

Raft (spread) foundation will be a proper foundation solution in order to be on the safe side against cracks and discontinuities, since this kind of a foundation will provide safety against differential settlements, will protect the integrity of the bearing system under the earthquake loads and dynamic wind load, as well as static loads.

After the foundation excavations are completed, the upper surface of the foundation soil should be smoothly leveled and the foundation construction (in order to increase the friction) should be started by concreting over the natural soil surface.

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