# GREAT LAKES WIND ENERGY CENTER FEASIBILITY STUDY

## GEOLOGICAL AND GEOTECHNICAL DESKTOP STUDY

prepared by

DLZ

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**NOTICE:**

This report contains findings from the Geological Desktop Study. **The Geological Desktop Study is just one of several studies within the Great Lakes Wind Energy Center Feasibility Study. Conclusions drawn from a single report are strictly preliminary.**

The Great Lakes Wind Energy Center Feasibility Study is being conducted by JW Great Lakes Wind LLC (JWGL), with its parent company juwi GmbH, on behalf of the Cuyahoga County Great Lakes Energy Development Task Force. Please direct questions regarding the Great Lakes Wind Energy Center Feasibility Study to Ryan Miday at p4rm1@cuyahogacounty.us or (216) 299-9326.

# 1.0 INTRODUCTION

## 1.1 Project Description

The Great Lakes Wind Energy Center (GLWEC) Feasibility Project is a study to explore the potential for establishing a Great Lakes Wind Energy Research Center ("Center") in Cuyahoga County, Ohio. The Center is envisioned to potentially include the following principal elements:

- A Pilot Project Site consisting of a 5-20 MW wind turbine pilot project with 2-10 wind turbines installed in Lake Erie near Cleveland.
- A Test Center that would allow manufacturers to test new product designs.
- A Certification Center where the technical acceptability of new wind-related equipment could be certified.
- An Advanced Research Center for innovative wind energy research and technology development by public, private and/or academic institutions.

The goals of the overall feasibility study, of which this report is a part, are to identify where the offshore elements of the Center can be constructed and to present the conceptual design, preliminary designs and specifications of wind farm layout, wind turbines, platforms and foundations, onshore logistics for electrical connections, and other documents illustrating the requirements for constructing the Pilot Project Site. The feasibility study is expected to include recommendations as to the types of wind turbines, platforms and foundations that will be feasible for the Center as well as preliminary technical designs for these elements.

Based on the preliminary designs and data developed, the feasibility study is further expected to present cost estimates detailing the costs of the construction, operation, and maintenance of each of the Center's elements; a marketing assessment of the wind industry's needs that should be addressed by the Center's elements, and how industry participants should participate in its financing and ongoing costs; a business plan for the Center, including projections on costs and revenues, and corresponding recommendations on financing and an outline of options for ownership and operation of Pilot Project Site; and whether the Center will provide economic development for the community, including an assessment of potential supply chain creation and job creation. At the completion of the study, it is also expected that the project manager, JW Great Lakes Wind, LLC, and the County will have collaborated to determine the regulatory requirements for securing approvals and permits from the appropriate regulatory agencies necessary to construct and operate the Pilot Project.

## 1.2 Purpose and Scope

The purpose of the GLWEC Geological and Geotechnical Desktop Study is to provide preliminary subsurface information for the Pilot Project Site and, based on this information, to identify and evaluate potential foundation types suitable for supporting the Pilot Project.

In support of the GLWEC Feasibility Study, this desktop study report presents the geologic history and generalized subsurface conditions of the lakefront and offshore areas along the shore of Lake Erie in Cuyahoga County, Ohio based on a review of existing literature, geologic references and other relevant information. In addition to the documented geologic, stratigraphic and lakebed conditions, this report also provides descriptions and preliminary recommendations and opinions regarding potential foundation alternatives for supporting wind turbines in Lake Erie up to approximately five miles off the Cuyahoga County shoreline.

This report is not intended for use in final design or construction. Additional geotechnical studies, reports, and services will be needed if the project proceeds to design or construction.

# 2.0 GEOLOGIC CONDITIONS

The study area for the Pilot Project is located in the Central Basin of Lake Erie and can generally be described as a band three to five miles (five to eight kilometers) off the Cuyahoga County shore. The study area is illustrated on Figure 2.0-1. Geologic information within the Central Basin of Lake Erie has not been well documented by the Geologic Surveys of the United States, Canada, the State of Ohio or the Province of Ontario. While some limited information is available in the publications reviewed, much of the information was inferred from information collected from onshore data.

## 2.1 Physiographic Setting

Cuyahoga County lies on the boundary between the Central Lowland and Appalachian Plateaus Physiographic Provinces. The shoreline and northern and western portions of the county fall within the Huron-Erie Lake Plane Section of the Central Lowland Province. The northern portion lies in the Erie Lake Plane Region of the section. This Region is characterized by the low relief features that were within or along the margins of Pleistocene Age lakes, which were the precursors of Lake Erie.

## 2.2 Lake Elevation and Bathymetry

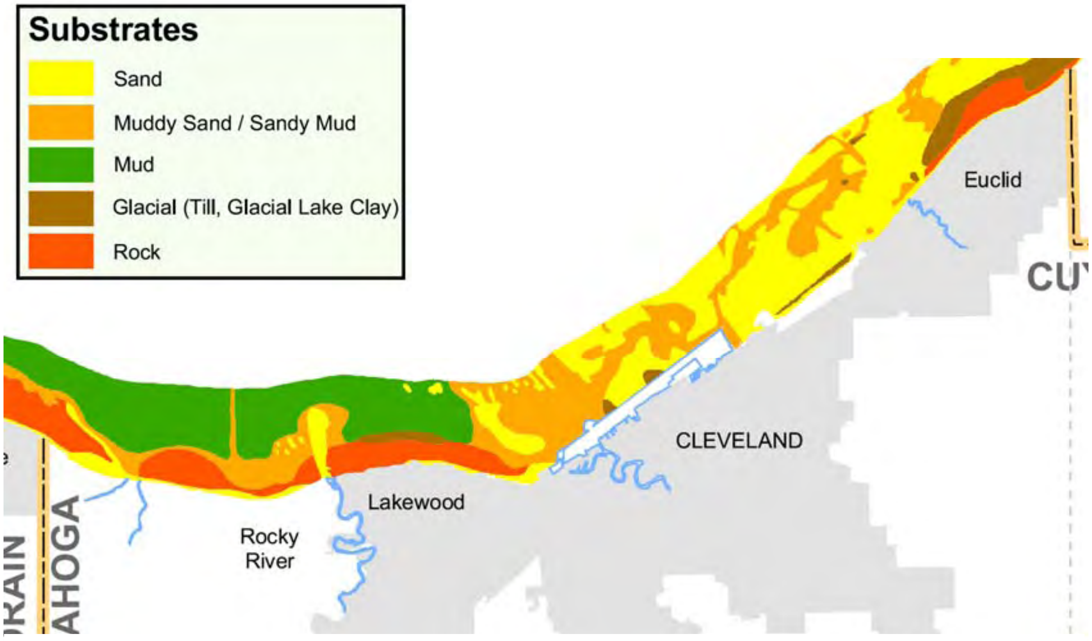
The long term mean surface elevation of Lake Erie, based on data from 1860 to present, is approximately 571 feet above seal level. Over this same period, the average lake level has generally fluctuated between elevations 568 and 574 feet.

Bathymetric data collected for the mid-lake airport feasibility study suggest that, over most of the study area, the water depth is between 40 and 70 feet (12 and 21 meters) deep. The information also indicated that the bathymetric contours are roughly parallel to the shore. The water depths observed in the area three to five miles offshore for the airport feasibility study varied from about 40 feet (12 meters) to a little more than 50 feet (15 meters). This data is generally consistent with more recently compiled bathymetric contour mapping available from NOAA [1]. Bathymetric contours off the Cuyahoga County shoreline are presented on Figure 2.2-1.

## 2.3 Recent Sediments

Sediments were deposited during the postglacial period following Pleistocene, which is also referred to as the Holocene Epoch, approximately 10,000 years ago to present. These more recent sediments include soils derived from the weathering process of existing rock and sediments into finer particles. These sediments on land are typically the near surface soils derived from the break down of the parent rock and soil into finer material though physical and chemical weathering processes. These soils can also be the result of soil deposition by movement, colluvium, and deposition by flowing water, alluvium. The soils vary from clays to large boulders depending on the environment. Coarse grained sediments are found in the Rocky River Valley, east of Cleveland, where deeply incised stream channels result in the cleaving of larger rocks from the steeper side walls while the less energetic, nearly level, till plains around Cleveland are covered with finer grained soils developed in the tills and beach sands.

Lake sediments have been laid down over the older material from the previous epoch. These sediments also vary in consistency from very fine mud, organic muck and clays to sands and gravels associated with the beach environments. Rivers, streams and sewers flowing to the lake also contribute sediment to the lake bottom. In general, the higher the energy, the coarser the sediments encountered. Typically this translates into coarser sediments being found in shallow water with higher wave action and finer grained materials in deeper water with low water movement. Generally, boulders are not found in recent age sediments; however, rafting of near shore materials by ice is also a possibility. Due to the temperate nature of the climate in this epoch, the movement of large boulders by ice rafting is not likely. A generalized map of the near shore substrates is presented below. A more detailed presentation of the postglacial sediments off the Cuyahoga County shore is shown on Figure 2.2-1.



*Cuyahoga County near shore substrate map from the Ohio Coastal Atlas [16]*

## 2.4 Glacial Sediments

Near surface geological conditions of the area have been influenced by numerous factors over the ages. The most recent, regional reshaping of the area was the result of glaciation occurring during the Pleistocene. The Pleistocene, also referred to as the Ice Age, occurred between approximately 1.8 million to 10,000 years ago. During that period, the continental ice sheet moved across Ohio at least four times. Often, the later phases of glaciation remove or cover the features created by the earlier glacial activity. It is widely believed that, during this epoch, the basin, which contains Lake Erie, was gouged from an existing ancient river (Erigan River) valley by the movement of the ice sheet. Evidence of the glacial process in the lake is visible in the Glacial Grooves State Park on Kelley's Island where the limestone outcrop has been deeply incised by the ice movement.

*Grooves in limestone, Glacial Grooves State Park, Kelley's Island*

Unconsolidated sediments that resulted during the Pleistocene can be classified into four general groups on the basis of the environment in which they were deposited. These types are tills, outwash, glacio-lacustrine (lakebed deposits) and glacial beach sediments. Tills are typically a mixture of fine and coarse-grained sediments laid down beneath the ice and in end moraines of glaciers. Outwash deposits are typically coarse sediments consisting of sands and gravels that are derived from flowing water and typically contain fewer fine-grained sediments. Outwash deposits can be large or can also be interspersed as layers or lenses within the tills. As the glaciers retreated out of the current basin in which Lake Erie is contained, lakes formed against the retreating ice margin and ice and sediment formed dams impounding the glacial melt water and precipitation in the basin. Sediments derived from these processes include the lacustrine sediments on the ancient lake bottom. These ancient lakes formed beaches along their shores at levels generally higher than the present lake level. West of Cleveland in Lakewood, prominent beach ridges are set back from one-half to three miles (0.8

to 5 kilometers) from and approximately parallel to the present day shoreline. Beach ridges have also been mapped east of Cleveland but are now concealed by dense urban cover. Depending on the energy of the beach environment in the area, sand and/or gravel beach deposits were formed along the ancient lake margins. In some cases, these deposits can be quite extensive. Generalized geologic profiles of the glacial sediments in the study area, both parallel and perpendicular to the shoreline, are presented on Figures 2.4-1and 2.4-2. The approximate alignments of the profiles are shown on Figure 2.0-1.

The occurrence of boulders and cobbles in both tills and lacustrine sediments is also common. Individual large boulders, called glacial erratics, can be released from the ice in moraines or beneath the glacier. Boulders and cobbles can also be deposited as a somewhat discrete layer within the till as well. Cobbles to large boulders can also be encountered in lacustrine deposits. These are typically the result of sediments that are entrained in the ice and released as the ice melts. These large coarse sediments could also have been rafted into the lake by icebergs, which then released the sediments as they melted some distance away from the retreating ice sheet. Glacial erratic cobbles and boulders ranging in diameter from several inches to more than six feet (0.1 to more than 2 meters) are widely scattered at the surface in Cuyahoga County.

## 2.5 Bedrock

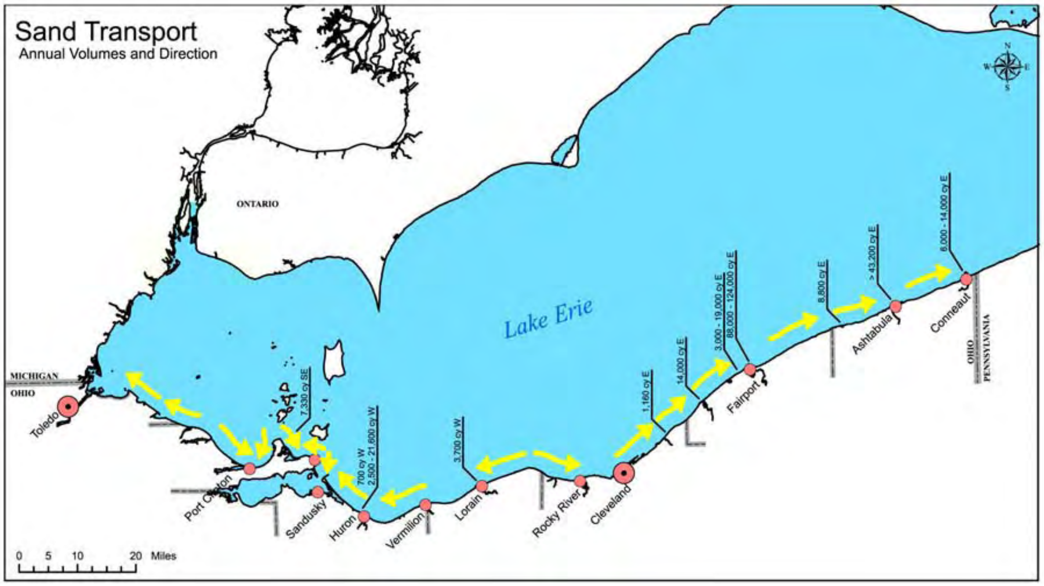
Due to depositional and erosion processes, the youngest bedrock encountered in northern Cuyahoga County and within the bounds of the County within the lake is Devonian in age, approximately 360 million years before present. The uppermost Devonian bedrock units off the Cuyahoga County shoreline include the Cleveland, Chagrin and Huron Members of the Ohio Shale formation. In the study area, the surface of these units typically ranges from elevations of 400 to 500 feet (122 to 152 meters) above mean sea level with their lower contact with the Hamilton Group bedrock more than 350 feet (107 meters) below mean sea level near the shore. However, due to the tilted bedding of the bedrock, the elevation of the bottom of the shale units may be around 300 feet (91 meters) above mean sea level near the Canadian border. The approximate top of bedrock profile within the study area is presented on Figures 2.4-1 and 2.4-2.

The underlying Hamilton Group includes the Olentangy Shale as its basal unit. Ohio Department of Natural Resources (ODNR) structure maps of the area indicate that the contact between the Olentangy formation and the underlying Onondaga limestone is between 300 and 480 feet (91 and 146 meters) below sea level from the northwest corner to southeast corner of the study area, respectively. The bedrock below these formations includes, in descending order, the Devonian Delaware group, Dundee Formation and the Silurian units Bass Island Formation and seven sub units of the Salina Formation, units A though G. The base of the Salina in the Cleveland area lies at an elevation of in excess of 2,000 feet (610 meters) below the ground surface.

In the Cuyahoga river valley of downtown Cleveland and the coastal area north of Cleveland, salt resources of the F unit of the Salina have historically been mined from a depth of approximately 1700 feet (518 meters) below the ground surface. The Cleveland salt mine extends from downtown Cleveland approximately 2.3 miles north beneath Lake Erie. The mine is operated from the Whiskey Island Peninsula just west of the Cuyahoga River. A majority of the mined area is located beneath the lake as depicted on Figure 2.0-1. Maps of the Cleveland mine indicate that it is a room and pillar configuration with columns remaining to support the overlying rock. The mine reportedly exploits the upper halite (rock salt) deposits of the Salina Formation. The mining activities, based on the reported depth and location of the mine, are not anticipated to affect the site selection or foundations for the pilot project.

## 2.6 Coastal Processes

The term coastal processes refer to the normal evolution of the near shore environment due to natural and manmade influences. The driving force in the coastal process is water action in the near shore environment. This includes wave action and near shore currents. These activities account for the breakdown of rock and sediment and the transport of the sediment in the near shore environment. As depicted in the image below, the littoral currents (near shore currents) move sediments along the shoreline. In the Cleveland area this movement is from west to east.



*Sand Transport Map [47].*

The movement is a natural process, which transports sediments from one location to another, resulting in erosion in some areas and deposition in other areas. The natural erosional processes have also been altered by man through the installation of near shore current obstacles including marinas, jetties, breakwaters, and groins or altering the lake floor by dredging. Changes to the littoral currents by these manmade alterations have larger impacts away from the structures. Installation of groins and jetties result in sediment accretion on the up current side while sediment erosion occurs on the down current side.

*Images depicting impact of manmade structures (jetties and groins) on near shore sediment transport*
*Modified images from http://www.ocean.udel.edu/mas/wcarey/monthlyquestions/april04.html*

## 2.7 Lake Floor Conditions

Lake floor conditions have been documented in the area of the proposed pilot project by several other investigations. These have included a mid-lake airport feasibility study, offshore sand resource studies and a wider ranging seismic reflection and vibracore study of the regional geology of the southern Lake Erie bottom off the Ohio shore. Probably some of the best available subsurface information in Lake Erie near Cleveland is presented in the 1974 geotechnical report prepared by Dames & Moore for the Airport Feasibility Study [20].

The Dames & Moore study included geophysical surveys, vibracores and soil borings. The vibracores extended as deep as 40 feet (12 meters) while the soil borings ranged from 70 to nearly 100 feet (20 to 30 meters) below the lake bottom. The study area for the airport feasibility exploration can be generally described as a rectangular area approximately 10 miles wide by 20 miles long (16 by 32 kilometers), beginning 3 to 5 miles (5 to 8 kilometers) from shore and generally parallel to the Cuyahoga County shoreline. Vibracore studies conducted in this area indicated that soft clay deposits covered the northernmost portion of the floor of the lake within the study area. The extent of the soft clays is illustrated on Figure 2.7-1. However, a majority of the study area was covered with stiff to very stiff silty clay. Analysis of the cores from this study suggested that the soft clays would not be adequate to support the high fill that was proposed for the airport. A medium stiff silty clay layer typically lies beneath the soft clays and appears to be a transition layer between the stiff to very stiff silty clay with small gravels (glacial till) that lies below. Both materials were assessed for the airport study, which found that, while the intermediate material was relatively compressible, the underlying silty clay with sand and small gravel had good shear strength at depth. In addition, consolidation tests conducted on these deeper soils indicated that they are preconsolidated and have moderate compressibility. The airport study also indicated that sand, gravel and silt are interspersed in the area and was reported to generally occur in thin layers.

Sand resource studies in the same area indicate similar findings; however, the depth of these investigations was only between 10 and 20 feet (3 and 6 meters) below the lake floor. The sand survey also indicated the presence soft to medium stiff silty clays. One boring in the study area encountered hard silty clay with minor gravel at a depth of 10 feet (3 meters) below the lake floor.

A geophysical and vibracore study was performed in the Ohio waters of Lake Erie from Marblehead to Conneaut in 1977 and 1978 under direction of the Department of the Army, Coastal Engineering Research Center [17]. This study found that postglacial sediments, about three miles offshore from Cleveland west to Lorain, ranged from 0 to 6.5 feet (0 to 2 meters) in thickness and consisted mainly of soft mud. From Cleveland, east to the Grand River in Lake County, the study indicated the lake floor consisted of glacial till and generally lacked appreciable postglacial sediment. East of the Grand River to Conneaut, postglacial sediment thickness five to six miles offshore ranged from approximately 30 to 50 feet (9 to 15 meters), consisting of “muddy sand” and “sandy mud”.

Results of seismic surveys and exploratory borings conducted for other studies indicate that bedrock (shale) is generally encountered at elevations of between 400 and 500 feet (122 and 152 meters) above sea level within the study area. The bedrock topography in the study area, compiled from various sources, is presented on Figure 2.7-2.

Based on the investigations conducted previously, conditions on the lake floor can vary considerably over relatively small intervals of depth and horizontal distance.

## 3.0 Natural Hazards

### 3.1 Natural Gases

In Cuyahoga County, the Cleveland and Chagrin Shales are known to contain pockets of gas. Encounters with natural gas have been recorded in several exploratory borings for tunnel projects at locations scattered around the greater Cleveland area. The gases are typically encountered in borings extending 150 to 300 feet (45 to 90 meters) in depth and penetrating 50 feet (15 meters) or more into the rock formations. Natural gas has also been observed within porous, granular horizons in the glacio-lacustrine sediments and glacial tills overlying the Chagrin Shale.

Gas concentrations during exploratory drilling are typically monitored by measuring the Lower Explosive Limit (% LEL). The LEL measurements respond to several types of combustible gases including methane ($CH_4$), which is believed to be a major constituent of the natural gases encountered. Hydrogen sulfide ($H_2S$) and carbon monoxide (CO) gases have also been detected.

Often, the quantity/concentration of gas is low enough that exploratory drilling operations are unaffected. However, in some cases drilling operations were suspended from a few hours to a few weeks to allow the gas to dissipate. In a few extreme cases, gas and drilling fluids were expelled to heights of 30 to 40 feet (9 to 12 meters) above the ground surface.

### 3.2 Seismicity and Faults

Compared to seismically active areas of the United States (California or Alaska), Ohio has relatively few earthquakes. The most frequent and damaging earthquakes in the state have originated in the vicinity of western Ohio at Anna in Shelby County. During the last 100 years, this area has experienced more than 30 earthquakes. The decade of the 1930s was the most active period. During this time, 23 events were recorded, including the most severe shock ever recorded in Ohio. Figure 3.2-1 shows the earthquake epicenters in Ohio including the Anna area. Other areas of earthquake activity include northeastern, southeastern, and other western areas of Ohio. Most of these have been of minor intensity, causing little or no damage.

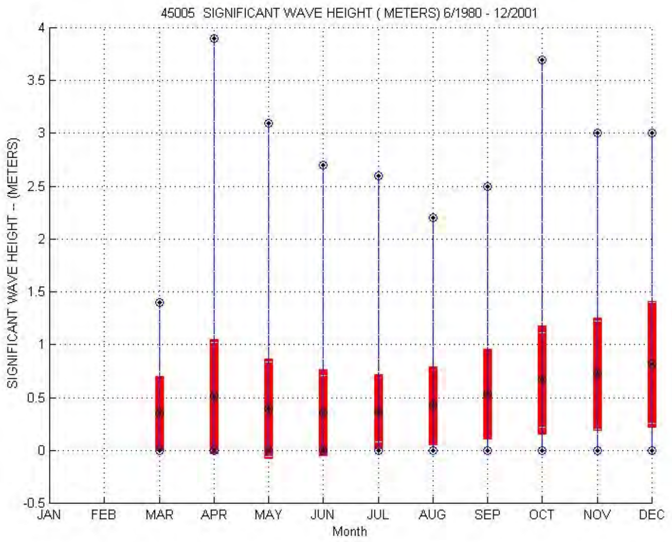
Within the past three years, the Ohio Seismic Network has reported approximately 27 small quakes in Lake Erie. Generally these quakes are about magnitude 2.0-3.8. These quakes are typically shallow and centered about 3 to 6 miles (5 to 10 kilometers) below the ground surface. The epicenters of the seismic activity appear to be located outside of the Cuyahoga County borders in the lake. Like most quakes reported in Ohio, these are considered to be minor and often result in little to no damage. According to the Ohio Seismic Network reports, these quakes are detected by seismic stations but are typically not felt by humans.

Historic quakes have been reported in close proximity to the study area. These were all identified along the Cuyahoga River Valley by the National Center for Earthquake Engineering Research. Five quakes dating from 1836 to 1924 were estimated to have had magnitudes of between 2.9 and 3.3.

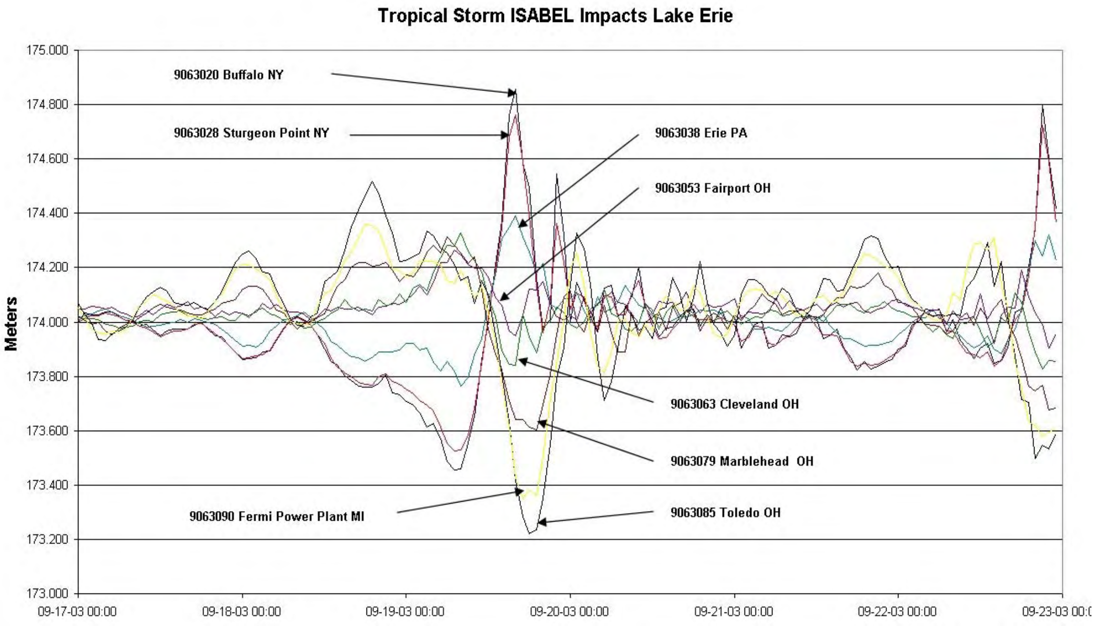
Although seismically active areas and faulting are known to exist in some portions of Ohio, faults are generally not mapped in this area of the State. An exception to this is the Middleburg fault. The Middleburg fault is located in western Cuyahoga County and extends from just south of the Medina County line north-northeast to a point approximately 3 miles inland from the Lake Erie shore. The mapped location is provided on Figure 2.0-1. The fault originates in the Precambrian unconformity in excess of 4,500 feet (1,370 meters) below mean sea level. The Middleburg fault is a normal fault with the up thrown block on the eastern side of the fault. The fault was reported and named in a 1982 paper by John Gray et-al identifying Devonian-age gas shales. Information reviewed from the Ohio Seismic Network indicates that no documented earthquakes have originated in the area of this fault.

## 3.3 Waves and Seiche

Although tidal influences do affect the lake, more significant variations in lake level are caused by wind driven waves. The long axis of Lake Erie is roughly aligned with the predominant east-west wind direction. The presence of higher wind velocities across the lake causes an increase in wave amplitude. Wave conditions reported by the NOAA National Data Buoy Center observations at Station 45005 - W ERIE, 28 nautical miles Northwest of Cleveland, Ohio (41.68 N 82.40 W) (41°40'36" N 82°23'54" W) reported swells of as much as 12.8 feet (3.9 meters) between the wave peak and trough. The following figure depicts the maximum, minimum, average wave height and one standard deviation of the waves reported by the buoy between 1980 and 2001.



While wave amplitude is a localized interaction of the wind action and barometric pressure on the water, a regional phenomenon known as seiche is also associated with the wind action on the shallow lake. Seiche is the result of the water mass of the lake being mounded on the one end of the lake by wind action and/or barometric pressure differential and then oscillating back to the other end of the lake. The phenomenon is most easily demonstrated with a long shallow pan filled with water being tipped slightly to one end and then leveled to induce a wave. The water in the pan oscillates from end to end until the energy is dissipated. Seiche within the lake has been recorded and an example of seiche as recorded by NOAA stations along the lake is presented below. Seiche combined with wind driven waves have been reported to raise the water level as much as 22 feet (6.7 meters) in Buffalo, New York. NOAA reports that the typical period of the seiche oscillation is approximately fourteen hours in Lake Erie. Conditions reported by the Cleveland NOAA observation station 9063063, noted below, show significantly less dramatic affects of seiche due to its location a near the mid point of the lake.

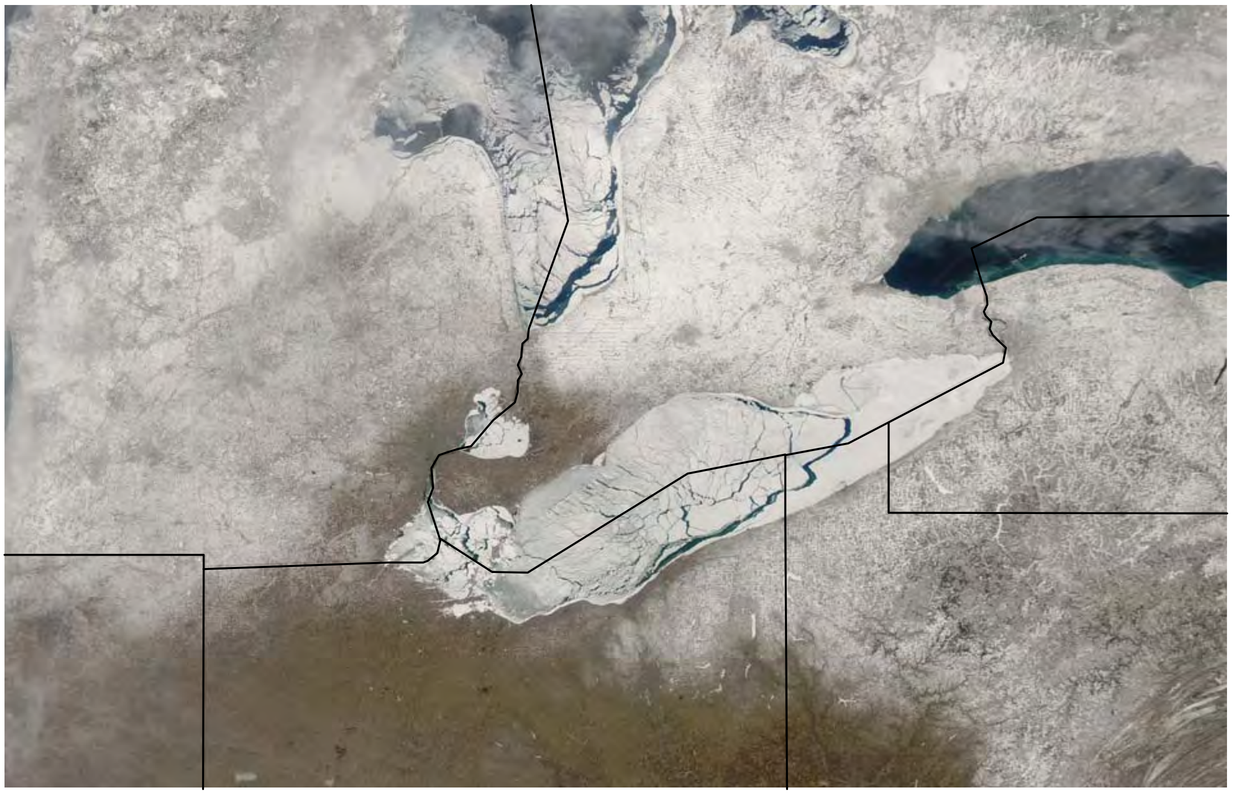


*Oscillation and storm surge on Lake Erie 17-22 September, 2003 (Times in EST).*

Rogue waves, also known as freak waves, are unique waves that are distinguished by an instant, singular and unexpected wave profile with an extraordinarily large and steep crest or trough. Rogue waves are rare phenomena that have been reported in Lake Erie. NOAA is engaged in research of rogue waves in the Great Lakes; however, at this time, limited research has been completed and published. The ODNR has indicated the following: “There are several recorded instances of so-called "rogue" waves that have suddenly swamped a comparatively small area of Lake Erie shoreline. None of these events have been associated with earthquakes and all have been confined to a local area of shoreline.”

### 3.4 Ice

Lake Erie lies in the northern part of the temperate zone of North America and is subject to the seasonal temperature variations associated with the climate. During the late fall and winter months, sub freezing temperatures are common to the region. Of the Great Lakes, Lake Erie is the shallowest and has the lowest surface area to depth ratio. Therefore, Lake Erie has the least thermal mass and is subject to freezing earlier and more completely than the other Great Lakes. Historically the lake has had 100 percent ice cover as shown in the following NOAA satellite image.



*Satellite image of Lake Erie with near 100% ice cover, March 9, 2007*

Lake ice is also subject to the same wind driven forces as the water. The predominant west to east wind flow drives ice into the eastern basin and the Niagara River. To combat the affects of ice on the easternmost shoreline of the lake and the mouth of the Niagara River, a joint Canadian-United States project using an ice boom constructed of steel pontoons has successfully been used to suppress ice movement into the bay. In addition, the predominant west to east ice flows, wave action, near shore currents and wind also move lake ice in other directions impacting the physical features of the lake bottom and coastline. Ice thickness on the lake varies with air temperature, lake temperature and precipitation; however, the affects of ice, even less that a few feet thick, can be dramatically compounded by the formation of ice ridges. Ontario Hydropower documented ice ridge formation in an investigation in February 1982. Video images of ice less than three feet (one meter) in thickness formed a ridge approximately 33 feet (10 meters) high. During formation of the ice ridge, wind driven lake ice was forced under the leading edge of the ridge and driven into the lake bottom, at a reported depth of nearly 65 feet (20 meters), before breaking off the ice sheet and adding to the ridge from beneath.

*Near shore ice ridge [21]*

A geophysical survey conducted in the area of the documented ice ridge indicated extensive lake floor disturbance had occurred. The survey, conducted in the spring of 1982, indicated that an area measuring 1.5 miles (2.5 kilometers) long by 100 feet (30 meters) wide and up to five feet (1.5 meters) deep had been gouged into the lake floor during the formation of the ice ridge. Water depth in the area was found to be between 52 and 62 feet (16 and 19 meters).

# 4.0 PRELIMINARY GEOTECHNICAL ASSESSMENT

Selection of a suitable foundation for supporting offshore wind turbines depends upon a variety of factors including subsurface conditions, water depth, loading conditions, environmental considerations and cost. This portion of the desktop study is focused on identifying feasible foundation alternatives for the site conditions, essentially water depth and soils, anticipated based upon the geologic and geotechnical information and data presented in the preceding sections and the following paragraphs.

## 4.1 General Stratigraphy

The area under consideration for potentially siting wind turbines is generally three to five miles (five to eight kilometers) off the Cuyahoga County shore. The water depth in this area ranges from approximately 40 to 55 feet (12 to 17 meters). Generalized geologic references report the stratigraphy in the area to consist of recent lake sediments overlying a complex system of interbedded glacial till, glacial outwash and glacio-lacustrine silts/clays associated with the advancing and retreating ice margins during the Pleistocene glaciation, as well as beach deposits of sand and gravel from various ancient lake stages. Shale bedrock is present beneath the glacial deposits. Generalized stratigraphic columns are presented on Figure 4.1-1, one for the area generally west of the boundary between the Cities of Cleveland and Lakewood and one from that point east representing the central and eastern portions of the study area. The stratigraphy is characterized in more detail in the following paragraphs.

### 4.1.1 Recent Sediments

As discussed previously herein, recent sediments are those materials deposited following the last glaciation (i.e. within about the last 10,000 years). The texture of the recent sediments at a given location is essentially a function of the energy of the environment in which they are laid down. Coarser grained materials are found in the lake, for example, in shallow waters with high wave action or near the mouths of fast flowing streams. In the low energy, deeper water environment a few miles (several kilometers) offshore, the sediments are correspondingly finer grained. Generalized geologic references and studies characterize these recent sediments as “sandy mud” and “muddy sand.” They are usually very soft or even semi-fluid and essentially incapable of supporting load. West of Cleveland within the study area, these materials are reportedly up to 6.5 feet (2 meters) thick while to the east, they are very thin or nonexistent.

### 4.1.2 Glacial Deposits

The four types of glacial or glacial related deposits are tills, glacio-lacustrine (lakebed deposits), outwash and glacial beach sediments. Large glacial erratic boulders are also commonly present in glacial till deposits and lacustrine sediments of glacial origin. Beaches and dune ridges formed on the shores of ancient lakes when water levels were significantly higher than at present. Consequently, these deposits are located at higher elevation on the Lake Plain south of the present day Lake Erie shore. Generalized descriptions and characteristics of the other types of glacial deposits are presented in the following paragraphs.

### Glacial Till

Glacial till is an unsorted, unstratified mixture of clay, silt, sand, pebbles, cobbles and boulders deposited directly by the ice. Characteristics of individual tills tend to remain relatively constant over limited areas.

Glacial tills in the Cuyahoga County area are generally over-consolidated, stiff to hard in consistency and have low compressibility. They are often capable of providing allowable bearing capacities of several thousand pounds per square foot (200 to 500 kilopascals) with relatively small post-construction settlement.

### Glacio-Lacustrine

Glacio-lacustrine deposits generally consist of stratified deposits of fine-grained sand, silt and clay that were laid down in lakes which formed against the retreating ice margin. Where encountered, these deposits usually overlie glacial till but may also lie directly on bedrock. Lacustrine clays are generally of moderate to high plasticity and are often laminated.

Lacustrine clays are not usually as strong as glacial tills, typically ranging from very soft to stiff consistency, have higher moisture content and are more compressible. Lacustrine silts and fine sands are often of very loose to loose compactness. Lacustrine deposits can also be stiffer or more compact; particularly where they are interbedded with tills due to re-advances of the ice sheets. Compared to tills, lacustrine deposits generally provide lower bearing capacity and allowable loading is likely to be governed by the settlement tolerance of the proposed structure.

### Glacial Outwash

Outwash materials are typically laid down by flowing water from glacial melt water and precipitation within the basin as the glacier retreats. As such, these deposits are coarser, consisting primarily of sand and gravel, and contain a lesser fraction of fine-grained sediment. Outwash deposits can be extensive or interbedded as layers or lenses within tills.

These coarse sediments generally possess excellent frictional characteristics and provide good bearing support for foundations when confined. Settlement of foundations supported on these relatively “clean” granular deposits can be expected to occur rapidly upon application of load, essentially during construction for dead loads, and is a function of the in-situ compactness of the deposit.

### 4.1.3 Bedrock

Beneath the recent sediments and/or glacial deposits, the underlying bedrock consists of the Devonian age Cleveland, Chagrin and Huron Shales of the Ohio Formation. Old preglacial valleys are present offshore of downtown Cleveland and to the east within the study area. In these old buried valleys, the shale is generally more than 100 feet (30 meters) below the lakebed and unlikely to significantly affect foundation selection. However, the offshore bedrock surface rises in elevation towards the west. This trend is in evidence onshore where shale cliffs line the shore in the western part of Cleveland. Offshore of the westernmost part of Cleveland and continuing westward to the Cuyahoga County line, shale is documented in the study area (3 to 5 miles/5 to 8 kilometers out) as little as 40 feet (12 meters) below the lakebed and could be shallower in places.

The upper part of the Ohio Formation, the Cleveland Shale and Chagrin Shale, is the only bedrock strata likely to be encountered by any potential wind turbine foundation. The strike of these members in Cuyahoga County generally trends northeast to southwest. Beds and laminations are typically planar and dip to the southeast less than five degrees below horizontal.

The Cleveland Shale generally ranges from 20 to 60 feet (6 to 18 meters) in thickness. It is typically dark gray to black, thin bedded and weathers to a brown, laminated, fissile material. The Cleveland Shale contains pyrite concretions and scattered siltstone and sandstone interbeds that are typically less than one inch (25 millimeters) thick. Joints in the Cleveland Shale are occasionally clay coated. The contact between the Cleveland and Chagrin Shales is characterized by a ½- to 1-inch (12 to 25 millimeter) thick pyritized fossil bed together with changes in color and material.

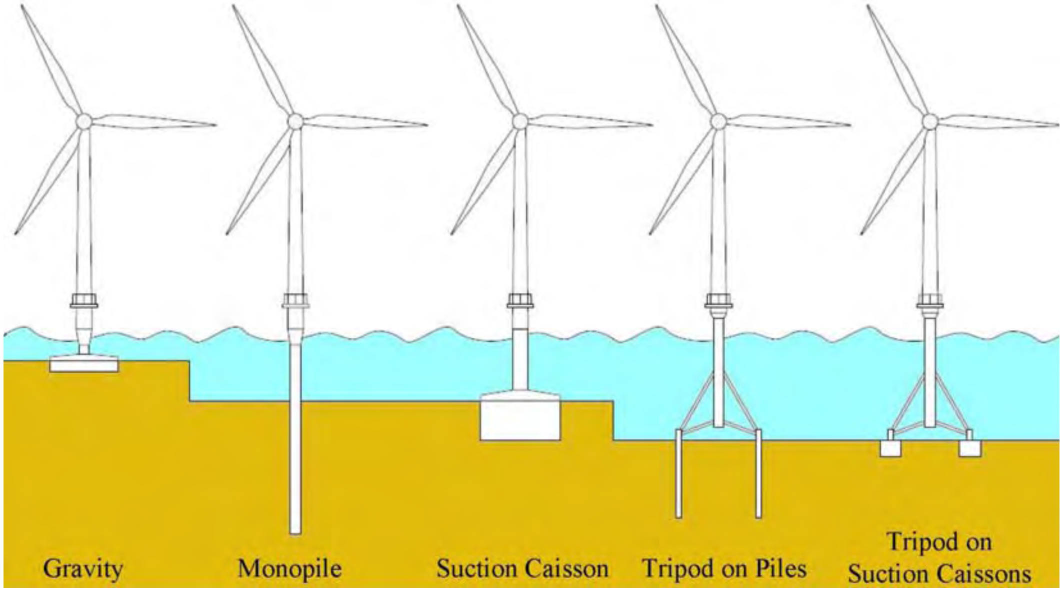
The Chagrin Shale is more than 400 feet (120 meters) thick and, when unweathered, consists of blue-gray clay shale in medium to thick beds. It is generally less brittle and fissile than the Cleveland Shale. The Chagrin weathers to yellowish-gray, very soft, clayey shale when exposed. Concretions and sandstone/siltstone interbeds are scattered randomly throughout the formation. Joints in the Chagrin Shale are often clay coated.

The unconfined compressive strength of intact cores of the shale typically ranges from 3,000 to 12,000 pounds per square inch (20 to 85 megapascals). However, weathered specimens may have compressive strength as low as a few hundred pounds per square inch (2 to 5 megapascals).

## 4.2 Foundation Types

The most common foundation types currently used for support of offshore wind turbines are monopile and gravity base foundations. Over the past several years, the Civil Engineering Research Group at Oxford University has performed considerable research relative to the design and installation of suction caissons for support of offshore wind turbines. In 2002, a full-scale prototype suction caisson was installed at the Aalborg University offshore test facility in Frederikshavn, Denmark to support an offshore wind turbine.

Piles, gravity base and suction caisson foundations may also be used to support multi-legged or lattice structures in deeper water applications (greater than about 65 to 80 feet/18 to 24 meters) where monopiles or gravity/suction based monopods are typically inadequate. However, the slender structural members comprising the tower support frame are susceptible to damage from ice loads. These foundation types are illustrated schematically in the following figure.



*[Modified from 25]*

Research and development is also ongoing for floating/moored structures for support of single and multiple turbines in very deep water applications, greater than about 120 feet (35 meters) up to hundreds or even thousands of feet.

The Lake Erie waters three to five miles (five to eight kilometers) off the Cuyahoga County shoreline are generally no deeper than 55 feet (17 meters). For offshore wind turbines sited in this area, the commonly used monopile and gravity foundations as well as the currently developing suction caisson foundations are potentially applicable. More detailed descriptions of these foundation types, their applicability and some advantages and disadvantages of each are presented in the following paragraphs.

### 4.2.1 Monopile

Most existing offshore wind turbines are supported on monopiles. The monopile foundation is a relatively simple design consisting of a large diameter (typically 10 to 16 feet/3 to 5 meters) steel pile. The piles are commonly transported on barges but can also be capped and floated to the installation site. The monopile is advanced into the lakebed by drilling, driving or a combination of both. The required penetration depth varies depending on the design loads, water depth and subsurface conditions but is typically in the range of 3.5 to 4.5 times the pile diameter in stiff clay and 7 to 8 times the diameter in softer soil.

Monopiles are generally suitable for use in waters up to 65 to 80 feet (20 to 25 meters) deep; however, the offshore wind industry is pushing these limits to support larger turbines in deeper waters than previously thought possible. In 2003, monopiles as large as nearly 17 feet (5.1 meters) in diameter and weighing more than 300 tons were used in water up to 85 feet (26 meters) deep to support seven GE Wind 3.6 MW turbines at Arklow Bank, Ireland. Some of the piles were driven more than 100 feet (30 meters) into the seabed.

*Monopile Installation at Arklow Bank, Ireland [30]*

Thirty Vestas V90 3.0 MW turbines are supported on monopiles at the Barrow Offshore Wind Farm in the East Irish Sea. The piles at Barrow are 15.6 feet (4.8 meters) in diameter, up to 200 feet (60 meters) long, weigh nearly 500 tons and, in 2006, were installed in water up to 75 feet (23 meters) deep. Nine of the piles encountered refusal before reaching their design penetration depth. The soil and weak sedimentary rock within the piles was drilled out and the holes advanced below the bottoms of the piles allowing them to subsequently be driven to final depth. The drilling was accomplished with a BAUER BFD 5500 Flydrill; a drilling system especially developed by the German company BAUER Maschinen GmbH for installation of offshore monopiles in difficult conditions. During drilling operations, the more than 80-ton Flydrill unit is supported directly on the partially driven pile. The drilling bucket is extended to the seabed within the pile by means of a telescoping kelly bar.

*BAUER Flydrill [31]*

The first offshore wind turbines (in an unsheltered environment) in the United Kingdom were erected near Blyth, Northumberland in 2000 and are supported on monopiles. The water depth at the site ranges from approximately 20 to 30 feet (6 to 9 meters). The monopiles supporting the two Vestas V66 1.75 MW turbines at Blyth are approximately 11.5 feet (3.5 meters) in diameter and penetrate 40 and 50 feet (12 and 15 meters) into the seabed. These piles were not driven, but rather the holes predrilled into sandstone. The piles were subsequently lowered into the slightly oversized holes and grouted in place.

At the Horns Rev (Denmark) Wind Farm, 80 Vestas 2 MW wind turbines are supported on monopiles approximately 13 feet (4 meters) in diameter. Located in waters between 20 and 45 feet (6 and 14 meters) deep, the monopiles for this wind farm were driven approximately 80 feet (24 meters) into sandy seabed. These monopile foundations weigh 180 to 230 tons each.

*Monopile Driving at Horns Rev [32]*

Monopiles are an attractive option in that they are relatively simple to fabricate, require little or no preparation of the lakebed and can be installed quickly. Conversely, specialized, heavy-duty equipment is required to install monopiles. Deep soft soil deposits may require excessive penetration depths and monopiles are not well suited to soils containing boulders. Finally, monopiles would be difficult to remove, should it ever be required for future decommissioning activities. It is more likely that they would be cut off at or slightly below the lakebed since complete extraction would be practically impossible due to the overwhelming resisting forces.

In the Great Lakes region, Tower Tech Systems, Inc. currently has the capability to fabricate monopiles at their Manitowoc, Wisconsin facility. From their location on the Manitowoc River, Tower Tech has access to Lake Michigan and, thus, all of the Great Lakes and, via the St. Lawrence, the Atlantic Ocean for shipping their products.

### 4.2.2 Gravity

Gravity foundations for offshore wind turbines generally consist of a large reinforced concrete base with a relatively slender stem extending above the water surface. The bases typically range from 40 to 60 feet (12 to 18 meters) in diameter or base width. For cold weather applications, a cone is typically incorporated in the design of the stem to reduce ice loads. As the name suggests, gravity foundations resist overturning due to their weight together with soil support on the downwind (compression) side of the foundation. Gravity foundations have been used predominantly in shallow water applications, typically less than 35 feet (10 meters). At greater water depths, monopiles generally become more economically attractive.

Two examples of gravity foundation supported wind farms are those at Middelgrunden and Nysted, Denmark. Gravity foundations support 20 Bonus 2 MW turbines at Middelgrunden. The foundations are between 55 and 60 feet (16.5 and 18.5 meters) in diameter, range in total height from 26 to 37 feet (8 to 12 meters) and weigh nearly 2,000 tons each. Water depths at the Middelgrunden site vary from approximately 13 to 26 feet (4 to 8 meters).

*Middelgrunden Gravity Foundation Construction in Dry Dock*
*Copenhagen, Denmark [35]*

At Nysted, gravity foundations support 72 Bonus 2.3 MW turbines in 20 to more than 30 feet (6 to 9 meters) of water. The design of these foundations differed from those at Middelgrunden. Rather than a solid circular concrete base, the Nysted foundations were designed and constructed with open cell hexagonal bases and filled with ballast after positioning on the seafloor. The up to approximately 56-foot (17-meter) wide Nysted foundations weighed more than 1,400 tons before ballasting and approximately 2,000 tons after ballasting the base and hollow shaft with olivine, rock and sand. The bases are founded on stiff clay till generally 25 to 40 feet (7.5 to 12 meters) below the water surface.

*Gravity Foundations Under Construction and In Transit*
*Nysted, Denmark Wind Farm [36, 37, 38]*

The industry is pushing the limits and using gravity foundations in deeper waters as well. In 2007, work began on the Thornton Bank Offshore Wind Farm near Zeebrugge, Belgium. The first phase of the project includes six REpower 5 MW turbines (with plans for a total of 60 turbines) that are to be supported on gravity foundations in water depths ranging from approximately 40 to 90 feet (12 to 27 meters).

*Gravity Foundations Under Construction*
*Thornton Bank (Belgium) [39]*

As can be seen in the preceding photograph, the design of these foundations differs from both the Middelgrunden and Nysted gravity foundations. These innovative, prestressed concrete foundation elements consist of a cylindrical shaft atop a conical shell that, after placement on the prepared seabed, are filled with ballast to resist overturning. The concrete structures have a base diameter of nearly 80 feet (24 meters), weigh nearly 3,000 tons empty and, depending on the quantity and type of ballast, will have total weights as great as 7,700 tons.

Gravity base foundations can be founded on a wide range of materials but; due to bearing capacity and settlement considerations, are best suited for use where soil conditions are relatively uniform. They can also be placed on soil deposits containing boulders where the use of monopiles might be impractical or impossible. Gravity foundations have the further advantage of being constructed onshore using conventional means. Since they are founded only a few feet below the sea/lakebed level, gravity bases can also be completely removed upon decommissioning of the wind turbine.

Although having the advantage of onshore construction, gravity foundations require specialized, heavy lifting equipment for transport to the installation site.  Another disadvantage of gravity bases is the significant sea/lakebed preparations necessary prior to placement.  These include, but are not limited to, dredging of soft sediments and careful placement and leveling of a gravel pad upon which to place the foundation.  These operations are generally expensive and become more so as water depth increases.  Gravity base foundations are also more sensitive to scour from ocean currents than other foundation types; however, scour may be of less concern in the Lake Erie setting.

### 4.2.3 Suction

Suction based foundations for supporting offshore wind turbines have been adapted from concepts previously used in the offshore oil and gas industry for anchoring floating platforms.  The geometry of suction caissons resembles that of most gravity foundations, consisting generally of a large diameter base (up to 50 feet/15meters or larger) supporting a smaller diameter column upon which the turbine tower is mounted. However, the suction caisson base consists of a steel cylinder, open at the bottom, and resembles an upside-down bucket.  Once installed, the suction caisson functions similar to a gravity foundation, relying on the weight of the soil enclosed in the bucket and suction for stability.

The unusual installation method of the suction caisson sets it apart from other foundation types.  The rim of the bucket, or skirt, cuts into the sea/lakebed a short distance under its own weight and achieves a seal.  The water trapped in the bucket is then pumped out through the top producing differential pressure (suction) and advancing the bucket deeper into the sea/lakebed.  In cohesive soils, the suction advances the caisson to its final depth by overcoming the bearing capacity beneath the rim and adhesion/skin friction on the inner and outer surfaces of the bucket.  In more permeable sand soils, water flows upward into the caisson due to the suction.  The upward flow reduces the effective stress, nearly causing the granular soil to boil.  This phenomenon greatly reduces the bearing capacity beneath the rim and the frictional resistance on the inside of the bucket facilitating penetration into the sand.  Installation can be problematic in layered soils, particularly where clay overlies sand, since the clay layer prevents upward water flow through the sand.  Also, if the unbalanced pressure is too great across a relatively thin clay layer, it could rupture or heave within the suction caisson.

A prototype suction caisson was installed in 2002 at the Aalborg University offshore test facility in Frederikshavn, Denmark to support a Vestas V90 3MW wind turbine.  The prototype was approximately 40 feet (12 meters) in diameter with an approximately 20-foot (6-meter) skirt or bucket and weighed approximately 150 tons.  The installation period at this near-shore location was approximately twelve hours with the actual soil penetration accomplished in six hours. Research indicates this foundation type to be feasible, given favorable subsurface conditions, in water depths up to 130 feet (40 meters).

*Prototype Suction Caisson – Frederikshavn, Denmark [43]*

Development of the suction caisson concept for supporting offshore wind turbines has been slowed by an incident during installation of a second prototype in Wilhelmshaven, Germany in the spring of 2005. This second prototype was more than 50 feet (15 meters) in diameter with a 50-foot (15-meter) skirt and weighed nearly 450 tons. It was intended to support a 4.5 MW Enercon E-112 turbine. The skirt failed during installation most likely due to collision with a crane barge that compromised the structural integrity of the skirt.

Like gravity foundations, suction caissons are well suited for uniform soil conditions where differential settlements will be small, particularly sands and softer clays. Because they are light compared to gravity foundations, suction caissons do not require specialized heavy lifting equipment and can be floated to the installation site. Neither do they require specialized driving equipment like monopiles. Perhaps the greatest advantage of suction caissons is the simplified installation method. Once positioned on the sea/lakebed, installation is essentially accomplished with a pump of suitable capacity to withdraw the water trapped within the bucket. Suction caissons can also be completely removed at the end of their design life relatively easily by reversing the installation process and pumping water back into caisson forcing it out of the sea/lakebed.

Since suction caissons are relatively new to the offshore wind industry, they have yet to establish a successful track record and thus far have been proven useful over a limited range of conditions. Like gravity foundations, they are also susceptible to scour in marine environments.

## 5.0 SUMMARY

The information from generalized geologic references together with the available site-specific data indicates that a wide range of lakebed conditions can be anticipated off the Cuyahoga County shore. While these varying conditions might make one foundation type preferable to another in a particular location, they do not preclude the siting of wind turbines anywhere within the study area. Except for a surficial layer of soft recent sediment, the area west of downtown Cleveland, where glacial till over relatively shallow bedrock is anticipated, is likely best suited for foundation support. East of downtown Cleveland, the study area lies over an ancient buried river valley where bedrock is 100 feet (30 meters) or more below the lakebed. The old valley is filled with interbedded glacial related deposits of till, outwash and lacustrine sand, silt and clay of varying consistency and compactness. The eastern portion of the study area does, however, have the advantage of water a few feet (1 or 2 meters) shallower than the western portion.

Given the broad range of subsurface conditions that could possibly be encountered at the eventually selected turbine sites, none of the three foundation alternatives presented stands out as an obvious choice over the others based on soil conditions alone. However, with water depths generally 40 feet (12 meters) or deeper 3 to 5 miles (5 to 8 kilometers) offshore, monopiles are an attractive option for a wide range of potential soil/bedrock conditions. In addition, facilities for the fabrication and supply of monopile foundations currently exist within the Great Lakes Basin (Tower Tech Systems, Inc. on the Manitowoc River/Lake Michigan in Manitowoc, Wisconsin).

Monopiles would be well suited for use in stiff glacial till or in areas offshore of the western part of the County where they might be socketed into shale bedrock. Monopiles might also be preferred in this area to penetrate through deposits of soft or semifluid recent lake sediments that would require more significant lakebed preparation for a gravity foundation alternative. Some risk of obstruction by large glacial erratic boulders exists for the monopile option; however, this risk could be substantially mitigated by exploratory drilling at each monopile location. Offshore of the central and eastern parts of the County, piles longer than typically required could be necessary should deep deposits of soft lacustrine clay be encountered in the old buried bedrock valley.

Gravity foundations appear to be feasible for nearly all the potentially anticipated lakebed conditions. However, wind, wave and ice loads combined with water depths of typically 40 feet (12 meters) or greater will likely result in the need for very large, heavy gravity bases. If placed on thick deposits of soft clay, gravity base foundations could undergo significant post construction settlement. Gravity foundations also have the disadvantage of requiring significant lakebed preparation efforts prior to installation. This issue could be of particular concern for turbines located in the offshore area west of Cleveland where soft sediments up to 6.5 feet (2 meters) thick are reported. Furthermore, very large, specialized equipment is required for transport and installation of gravity bases. Such equipment would either need to be custom fabricated locally or existing equipment likely disassembled for mobilization into the Great Lakes Basin at great expense and effort.

Suction caissons are also a viable, albeit developing, alternative for support of offshore wind turbines. Successful installation has thus far, however, only been proven in sands and soft clays so their application may be limited. Achieving adequate penetration with suction caissons may be difficult or impossible if located in areas of hard till deposits or if boulders are encountered. Given the complex geologic history of the site, layered soil profiles also are not out of the question within the depths that might be penetrated by suction caisson foundations. This could also be problematic for installation of suction foundations, particularly where sand underlies clay.

All three of the foundation alternatives presented are feasible for at least some portion of the range of expected conditions 3 to 5 miles (5 to 8 kilometers) off the Cuyahoga County shore. When other factors unrelated to subsurface conditions, such as fabrication, transport and installation methods/equipment, are considered; monopiles appear to be the preferred foundation alternative for the pilot project. However, the final selection should be made once site specific investigations have been performed. The additional exploratory work should include geophysical surveys of the selected turbine sites and, ultimately, soil boring and sampling within the footprint of each turbine foundation. Representative samples should be tested for index properties (particle size, Atterberg Limits, moisture content), shear strength and consolidation properties. Depending on the locations selected and anticipated conditions; consideration might also be given to performing cone penetrometer testing and/or vane shear tests as part of the field exploration.

## 6.0 LIMITATIONS

This desktop geotechnical report has been prepared for the exclusive use of JW Great Lakes Wind LLC for the Great Lakes Wind Energy Center Feasibility Study Project. The report may not contain sufficient information for other parties or other uses. The contents of this report are for feasibility level preliminary planning only and are not intended for use in final design or construction. Additional geotechnical studies, reports, and services will be needed if the project proceeds to design or construction.

## 7.0 REFERENCES

1. Holcombe, T.L., et al., *Lake-Floor Geomorphology of Lake Erie*, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Geophysical Data Center, World Data Center A for Marine Geology and Geophysics Research Publication RP-3, January 2005.

2. Holcombe, T. L., et al., *Revised Lake Erie Postglacial Lake Level History Based On New Detailed Bathymetry*, Journal of Great Lakes Research, v. 29 issue 4, , p. 681-704, 2003.

3. Brose, D. S., The Royal Ontario Museum and Cleveland Museum of Natural History, Encyclopedia of Cleveland History, Geology & Natural Resources, http://ech.case.edu/ech-cgi/article.pl?id=GNR, Last Modified: 02 Mar 1998 11:21:26 AM.

4. Carter, C.H., Benson, D.J., and Guy, D.E., Jr., *Man-Made Structures and Geomorphic Changes Since 1876 Along The Ohio Shore of Lake Erie*, in Craig, R.G., and Craft, D.E., editors, Applied Geomorphology: Boston, Allen and Unwin, p. 148-164, 1982.

5. Coogan, A.H., *Ohio Surface Rocks and Sediments*, Modified from Chapter 3 of Fossils of Ohio, Division of Geological Survey, Bulletin 70, 21 p., 1996.

6. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, Coordinated Great Lakes physical data. U.S. Army Corps of Engineers, Detroit, Michigan, 12 pp, 1977.

7. Department of the Army – U.S. Army Corps of Engineers, *Known and Potential Environmental Effects of Oil and Gas Drilling Activity in the Great Lakes*, Final Report, p. 222, 2005.

8. Department of the Army – U.S. Army Corps of Engineers, Engineering Manual No. 1110-2-1810, *Engineering and Design, Coastal Geology*, 1995.

9. Farrand, W. R., *Glacial Lakes Around Michigan*. Geological Survey Division, Michigan Department of Environmental Quality, Bulletin 4, 1988.

10. Frank, G W., *Salt Intrusion in Northeastern Ohio*, The Ohio Journal of Science. v63 n2. pp 55-59, 1963.

11. Greater Cleveland Growth Association, *Appendix B, Soil Report, The Lake Erie Jet port Project*, Cleveland Ohio, 40 p., 1971.

12. Menzies, J., *The Quaternary Sedimentology and Stratigraphy of Small, Ice-Proximal, Subaqueous Groundingline Moraines in the Central Niagara Peninsula, Southern Ontario*; Géographie Physique et Quaternaire, v.79, no.1, p.75-86, 2001.

13. Munro-Stasiuk, M.J., Fisher, T.G., and Nitzsche, C.R., *The origin of the western Lake Erie Grooves, Ohio: implications for reconstructing the subglacial hydrology of the Great Lakes Sector of the Laurentide Ice Sheet.* Quaternary Science Reviews, v. 24, p. 2392-2409, 2005.

14. Sanford, B.V., Silurian- Devonian of Southwestern Ontario, Figure 8: Structure Section B-B', 1975.

15. Ford, J.P., *Glacial and Surficial Geology of Cuyahoga County, Ohio*, Ohio Department of Natural Resources, Division of Geological Survey, Report of Investigations No. 134, 1987.

16. *The Ohio Coastal Atlas*, Ohio Department of Natural Resources, Office of Coastal Management, Printed 2007.

17. Carter, C.H., Williams, S.J., Fuller, J.A. and Meisburger, E.P., Report No. MR 82-15, *Regional Geology of the Southern Lake Erie (Ohio) Bottom: A Seismic Reflection and Vibracore Study*, Department of the Army, Coastal Engineering Research Center, December 1982.

18. Crowell, K., *Ground Water Resources of Cuyahoga County*, Ohio Department of Natural Resources, Division of Water, Ground Water Resources Section, 1979.

19. Pincus, H.J., *Engineering Geology of the Ohio Shore Line of Lake Erie*, Ohio Department of Natural Resources, Division of Shore Erosion, Technical Report No. 7, Sheet E, 1960.

20. Dames & Moore (under contract to Howard, Needles, Tammen and Bergendoff), *Lake Bottom Geotechnical and Geophysical Studies, Reports No. 5-1 & 5-2, For the First Phase Airport Feasibility Study for the Lake Erie Regional Transportation Authority*, May 1974.

21. Grass, J., *Ice-scour and ice ridges of Lake Erie, Ontario, Canada.* Proceedings of the Ice Scour and Arctic Marine Pipelines Workshop, 13th International Symposium on Okhotsk Sea and Sea Ice, Mombetsu, Hokkaido, Japan, 1-4 February 1998. C-CORE, St. John's, Nfld, 1998.

22. Pryor, S., Shahinian M., and Stout, M., *Offshore Wind Energy Development in the Great Lakes: A Preliminary Briefing Paper for the Michigan Renewable Energy Program*, University of Michigan School of Natural Resources & Environment, April 2005

23. Houlsby, G.T. and Byrne, B.W., *Suction Caisson Foundations for Offshore Wind Turbines and Anemometer Masts*, Journal of Wind Engineering Volume 24 No 4, pp 249-255, 2000.

24. Watson, G., *Final Report on OWEN Workshop on Structure and Foundations Design of Offshore Wind Installations*, Engineering and Physical Sciences Research Council - Offshore Wind Energy Network, April 2000.

25. Byrne, B.W. and Houlsby, G.T., *Assessing Novel Foundation Options for Offshore Wind Turbines*, World Maritime Technology Conference, London, UK, March 2006.

26. Det Norske Veritas, *Recommended Practice DNV-RP-E303, Geotechnical Design and Installation of Suction Anchors in Clay*, October 2005.

27. Westgate, Z.J. and DeJong, J.T., *Geotechnical Considerations for Offshore Wind Turbines*, August 2005

28. Houlsby, G.T., Byrne, B.W., Martin, C. and Fish, P., *Suction Caisson Foundations for Offshore Wind Turbines*, Journal of Wind Engineering Volume 26 No. 3, pp 144-155, 2002.

29. Zaaijer, M.B., *Comparison of Monopile, Tripod, Suction Bucket and Gravity Base Design for a 6 MW Turbine*, Offshore Wind Energy in Mediterranean and Other European Seas (OWEMES Conference), Naples, Italy, April 2003.

30. www.mammoetvanoord.com, June 2008

31. de Vries, Eize, *A solid foundation: Technological Developments from the DEWEK Conference*, Renewable Energy World Magazine, Volume 10 Issue 1, January/February 2007.
http://www.renewableenergyworld.com/rea/news/reworld/story?id=51565

32. IMIA Working Group 45, Ciamberlano, F., Chairman, *Engineering Insurance of Offshore Wind Turbines*, The International Association of Engineering Insurers 39th IMIA Annual Conference, September 2006.

33. Ibsen, L.B. and Liingaard, M., *Prototype Bucket Foundation for Wind Turbines - Natural Frequency Estimation*, Aalborg University Department of Civil Engineering Technical Report No. 9, December 2006.

34. M.B. Zaaijer and A.R. Henderson, *Review of Current Activities in Offshore Wind Energy*, 2004

35. *The Middelgrunden Offshore Wind Farm – A Popular Initiative*, www.middelgrunden.dk, June 2008.

36. *COWI Offshore Wind*, Marketing Brochure, www.cowi.com, June 2008.

37. *COWI Nysted Offshore Wind Farm at Rødsand, Denmark*, www.cowi.com, June 2008.

38. Volund, P., Larsen, S.T. and Gjerding, J.B., *Foundations for 23-29 m Depth of Borkum Riffgrund in 2006.*

39. Photo for Thornton Bank from: www.c-power.be/index.html, June 2008.

40. Pearson, D., *Decommissioning Wind Turbines In The UK Offshore Zone*, Enron Wind.

41. COWI Thornton Bank Offshore Wind Farm – Phase 1, Belgium, www.cowi.com accessed June 2008.

42. Nielsen, S.A., *Case Study: Implementation of the Bucket Foundation Concept*, European Offshore Wind Conference and Exhibition, December 2007.

43. www.hornsrev.dk, Newsletter on the Horns Rev Project, November 2002.

44. Det Norske Veritas, *DNV-OS-J101: Design of Offshore Wind Turbine Structures*, June 2004.

45. Hintgen, J.S., Masters Thesis, *Offshore Wind Farms in the Western Great Lakes: An Interdisciplinary Analysis of Their Potential*, University of Wisconsin-Madison, 2003.

46. Byrne, B.W. and Houlsby, G.T., *Foundations for Offshore Wind Turbines*. Phil. Trans. Roy. Soc. A 361, Dec., pp 2909-2930, 2003.

47. Guy, D. E., Jr., *Estimated rates of sand transport for the Ohio shore of Lake Erie*: Ohio Geological Survey file data, 2 sheets, 1994.