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HANDBOOK

CRANE HARDSTANDS FOR INSTALLATION OF WIND TURBINES

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stowa@stowa.nl www.stowa.nl
TEL 033 460 32 00
Stationsplein 89 3818 LE Amersfoort
POSTBUS 2180 3800 CD AMERSFOORT

Publicaties van de STOWA kunt u bestellen op www.stowa.nl

COLOFON

EDITION Stichting Toegepast Onderzoek Waterbeheer
Postbus 2180
3800 CD Amersfoort
The Netherlands

AUTHORS M.P. Rooduijn
D.E. den Arend
J. Boukes
A.R. Jacobs
W. Ormel

SUPERVISORY COMMITTEE
At the time of this publication's release, the composition of the supervisory committee was as follows:
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A BRIEF INTRODUCTION

STOWA is the knowledge center of the regional water managers (mostly Dutch Water Authorities) in the Netherlands. We develop, collect, distribute and implement applied knowledge that water managers need to adequately carry out their mandate. This knowledge spans the fields of applied technology, the natural sciences, administrative law and the social sciences. STOWA works in highly demand-driven way. We carefully identify the knowledge requirements of water authorities and respond to these by approaching the appropriate knowledge providers. The initiative in this process lies mainly with the users of the required knowledge, but sometimes it can come from knowledge institutes or business and industry as well. This two-way flow promotes advances and innovation. Working in a demand-driven way also means that we ourselves are constantly alert to the 'knowledge requirements of the future'. We aim to put issues on the agenda even before others have considered them, to prepare for the future. STOWA unburdens water managers. We take on the jobs of tendering and supervising joint knowledge projects. We ensure that water managers stay linked to these projects and also 'own' them. This way we can be sure that the right knowledge needs are being met. The projects are supervised by committees, which also include regional water managers as members. The major lines of research are identified per work field and are established by special program committees. In these committees, too, regional water managers are members. STOWA not only links those who need knowledge with those who can provide it, it also connects regional water managers amongst themselves. The collaboration of water managers within STOWA ensures that they remain jointly responsible for the programming, that they set a joint course, that multiple water authorities are involved in one and the same research effort and that the results quickly benefit all water authorities. STOWA's fundamental principles are set out in our mission: Defining the knowledge needs in the field of water management and developing, collecting, making available, sharing, strengthening and implementing the required knowledge or arranging for this together with regional water managers.

FOREWORD

The size and height of wind turbines on land have grown considerably during the past decades. The cranes needed to install (and to maintain) these turbines have therefore also undergone huge increases in size and weight, resulting in increased crane loads.

Hardstands for these increasingly heavy cranes demand careful, safe and economical design. At the same time, many location-specific factors play a role in hardstand design, such as crane type, the loads to be lifted, the environment and characteristics of the supporting soil, which in the western regions of the Netherlands is often weak. The correct handling of potential risks involved in the lifting operation is another area that demands particular concern.

Against this backdrop, the industry initiated an effort to develop a design guideline for crane hardstands used for installing wind turbines. Back in the days of SBRCURnet, a plan of action was developed and funding obtained. Then development of the guideline began. When in late 2017, SBRCURnet closed its doors, Stowa stepped in to support continuation of the process.

While initially the intention was to develop a design guideline, it gradually became apparent that development of a specific guideline would be an exceedingly complex task. This is because there are many location-specific factors that make customized design necessary for each individual site. Moreover, designers often don't know until a very late stage which crane or crane type will be utilized and what loads will in fact need to be designed for. Preparation of a concrete customized design before knowing what crane will actually be used – including the corresponding ground pressures and wind loads – will often lead to the need for a re-design at a later stage. The present publication therefore should be read more as 'a handbook for design', than as a specific design guideline. The hope is that experience gained using this handbook in the coming years will feed into development of an actual design guideline in the future.

This publication is intended for experts involved on the client side, designers, geotechnical engineers/designers, insurers, inspectors, equipment suppliers and other contractors and subcontractors. It will also be useful for permit- and license-issuing authorities, such as water authorities and municipalities, for support in assessing applications. In developing this handbook, somewhat of a balance was sought between the responsibility of the entities involved, on one hand, and demands from the market on the other.

Aspects specific to the crane hardstand itself are central, given that this is the location that receives the heaviest loads, and therefore also has the most stringent design and execution requirements. Site access and construction roads to crane hardstands are not considered here.

Ir. Joost Buntsma
Director STOWA

SUMMARY

Worldwide the demand for wind turbines that produce increasing amounts of power at lower and lower cost has led to development of tall turbines with heavy components. To install these turbines, tall and heavy cranes have been developed, which themselves produce extremely heavy loads on the crane working platform, or ‘hardstand’. This scale increase in the wind turbine industry has led to a strong demand for clarity and guidelines for the design of heavy-duty crane hardstands for wind turbine installation.

Crane hardstands require careful, safe and economical design. At the same time, many location-specific factors play a role in hardstand design, such as crane type, the loads to be lifted, the environment and the characteristics of the supporting soil, which in the western regions of the Netherlands is often weak. The correct handling of potential risks involved in the lifting operation is another area that demands particular concern.

Due to the many location-specific factors and uncertainty about the type of cranes that will ultimately be utilized, the decision was made to formulate a handbook focused on design with which experience can be gained in the coming years. The longer-term objective is to develop a more specific guideline in the future, based on that experience.

This handbook was written, in principle, for use in the Dutch situation, with the corresponding laws and regulations.

The handbook is intended for use in the design, the execution, and the operation and maintenance of crane hardstands for relatively heavy lifting cranes and foundation rigs with comparable loads. The loads on a crane hardstand are static or quasi-static, but dynamic loads are also possible due to the own-weight of materials, wind loads and forces arising during the lifting operation.

Crane loads up to and including the 750-ton class are assumed, with the corresponding turbine heights and weights. Above the 750-ton class, larger sizes, weights and ground pressures will apply. For these cases, highly specialized, custom solutions will be required.

With the exception of short passages regarding crane transport between turbine locations, site access and construction roads are not considered here.

This publication is intended for experts involved on the client side, designers, geotechnical engineers/designers, insurers, inspectors, equipment suppliers and other contractors and subcontractors. It will also be useful to permit- and license-issuing authorities, such as water authorities and municipalities, to support their assessments of applications.

The publication starts by describing important factors and starting points regarding the type of wind turbine to be installed. Then, recommendations are made for selecting the right crane, as the crane that will be used determines the ground pressures that ultimately arise on a crane hardstand.

This handbook does not discuss the stability of the crane and crane parts themselves, but it does consider the stability of the foundation of the crane hardstand. In determining the crane loads and testing the soil bearing capacity, consideration is given to the differing safety philosophies that apply to each of these aspects.

When testing foundation stability, the allowable soil bearing capacity and the loads arising from the crane play an important role. The strength and deformation capacity of the soil determine the load capacity and deformation of the crane foundation. An overview is provided of the conduct of risk-based soil investigation according to the principles of the Geotechnical Risk Management (GeoRM) methodology.

The design of a crane hardstand is prepared based not only on specifications provided by the turbine vendor, but also information obtained about the subsoil and requirements imposed by the environment. In addition to a discussion of various design aspects, such as alternative design options or solutions, the modeling method used and the products to be delivered, recommendations are made that seek to produce an efficient design process and durable design.

Finally, factors and considerations regarding execution, operation and maintenance of the crane hardstand are discussed. This includes the monitoring that must be performed to supervise risky processes (deformations, vibrations and noise) during installation of the hardstand and during the lifting operation. In addition, quality assurance and testing of the completed structures are discussed. In this regard, attention is also given to temporary hardstands and interplays with, among other things, cable installation, the foundation of the wind turbine, site access and construction roads, and transport of the wind turbine itself.

THE STOWA IN BRIEF

The Foundation for Applied Water Research (in short, STOWA) is a research platform for Dutch water controllers. STOWA participants are all ground and surface water managers in rural and urban areas, managers of domestic wastewater treatment installations and dam inspectors.

The water controllers avail themselves of STOWA's facilities for the realisation of all kinds of applied technological, scientific, administrative legal and social scientific research activities that may be of communal importance. Research programmes are developed based on requirement reports generated by the institute's participants. Research suggestions proposed by third parties such as knowledge institutes and consultants, are more than welcome. After having received such suggestions STOWA then consults its participants in order to verify the need for such proposed research.

STOWA does not conduct any research itself, instead it commissions specialised bodies to do the required research. All the studies are supervised by supervisory boards composed of staff from the various participating organisations and, where necessary, experts are brought in.

The money required for research, development, information and other services is raised by the various participating parties. At the moment, this amounts to an annual budget of some 6,5 million euro.

For telephone contact number is: +31 (0)33 - 460 32 00.
The postal address is: STOWA, P.O. Box 2180, 3800 CD Amersfoort.
E-mail: stowa@stowa.nl.
Website: www.stowa.nl.

CRANE HARDSTANDS FOR INSTALLATION OF WIND TURBINES

CONTENTS

1

INTRODUCTION

1.1 INTRODUCTION

Worldwide the demand for wind turbines that produce increasing amounts of power at lower and lower cost has led to the development of tall turbines with heavy components. To install these turbines, tall and heavy cranes have been developed, which themselves produce extremely heavy loads on the crane hardstand.

While at the start of the 1980s, wind turbines were some 15 m in height, by the mid-1990s they had already reached heights of 50 m. Today, wind turbines can average 100 m in height. Current forecasts suggest that the wind turbines of the future will have an average hub height of 150 to 200 m.

Due to this increase in scale, transport of the masts from the production location to the building site has become a major logistical challenge. Because a mast, due to its weight and diameter, cannot be transported in one piece, it is transported in as large components as possible and put together on site.

Due to the aforementioned scale increase, strong demand has emerged from within the wind turbine market in the Netherlands for clarity and guidelines for the design of the heavy-duty crane hardstands that are used to install modern wind turbines.

The transport and building (up) of wind turbines places high demands on the design and execution of the crane hardstand. To ensure a safe and reliable hardstand, knowledge about the subsoil, or underground properties, is of essential importance.

There are indications from this publication's target group that numbers of incidents are on the rise. Attempts are being made to preempt these by using rather conservative starting points for the design. Ambiguity in specifications and requirements also leads to the use of conservative starting points for the design.

Furthermore, there is a need for a better balance between the responsibilities of the stakeholders, on one hand, and demands from the market on the other. Contractors, engineering firms, investors and crane hire companies are seeking a productive balance between many aspects, particularly the amount of power that can be generated, specifications, requirements, interfaces, responsibilities, costs, safety, reliability and feasibility.

Due to the many location-specific factors involved and uncertainty about which cranes will ultimately be utilized, the decision was made to draw up a handbook focused on the design of the crane hardstand, the idea being that experience gained with this handbook in the coming years can then be applied to develop a more specific guideline in the future.

1.2 AIM

This publication combines knowledge and experience about wind turbines, cranes, soil conditions, design, execution, and operation and maintenance, for the following aims:

- Increased safety and reliability
- Clear specifications and requirements
- Guidelines for both design and execution
- Greater understanding and control of (geotechnical) risks through implementation of risk-based soil investigation
- Greater understanding of the interfaces between stakeholders and greater support
- Increased efficiency and workflow speed
- Cost reduction

1.3 TARGET GROUP

The target group consists of those parties that are directly or indirectly involved in the design and/or execution of crane hardstands for installing wind turbines. The parties that are directly involved typically include a wind farm commissioning agent or client, designers, geotechnical engineers/designers, insurers, inspectors, suppliers of geosynthetics and equipment and other contractors and subcontractors. But this handbook will also be useful for parties that are indirectly involved, such as those responsible for evaluating safety aspects (government) and other stakeholders in the environments of a wind turbine project (those who own land, buildings and other structures near the project).

These stakeholders will not all have the same degree of interest and concern for all of the different topics covered in this handbook. This handbook will be a particularly important document for actors on the client side, designers, geotechnical engineers and crane hirers.

1.4 SCOPE OF APPLICATION

This handbook was written, in principle, for use in the Dutch situation, with the corresponding laws and regulations.

It is intended for use in the design, execution, and operation and maintenance of crane hardstands for relatively heavy lifting cranes and foundation rigs with comparable loads. The organization and framework of this handbook is presented in figure 1-2 and figure 1-2.

With the exception of short passages regarding crane transport between turbine locations, site access and construction roads are not considered here.

The loads on a crane hardstand are static or quasi-static, but dynamic loads are also possible due to the own-weight of materials, wind loads and forces arising during the lifting operation.

This handbook assumes the use of telescopic cranes with crane loads up to and including the 1,200-ton class and lattice boom cranes in the 750-ton class, with corresponding turbine heights and weights in conformance with the table 3-1 and Appendix A.

Above these classes, larger dimensions, weights and ground pressures will apply. For these cases, highly specialized, custom solutions will be required.

1.5 GUIDE FOR READERS

Chapter 2 addresses the factors and starting points that must be considered in relation to the type of wind turbine being installed. The type of wind turbine sets specific requirements for the construction site and its surroundings. These directly determine a variety of aspects and the starting points that need to be used in the design, execution, and operation and maintenance of the crane hardstand.

Chapter 3 provides recommendations for selecting the right crane. The crane determines the ground pressures that will ultimately arise on a crane hardstand. Key areas of concern for selecting the right crane are the dimensions and weights of the wind turbine components, as well as transport, set-up and assembly, maintenance and disassembly of the crane.

Chapter 4 presents guidelines for the use of risk-based soil investigation according to the Geotechnical Risk Management (GeoRM) methodology. Practically speaking, risk-based soil investigation means that the amount and level of detail of the soil investigation performed are adapted to the specific geotechnical risks in play at the crane hardstand site.

Chapter 5 concerns the design of a crane hardstand. Figure 1-2 presents the design as one of the activities in the construction process. The design of a crane hardstand is prepared based on the specifications given by the turbine vendor, the information obtained about the subsoil and requirements imposed by the environment.

In addition to various design aspects, such as alternative design options or solutions, the modeling method used and the products to be delivered, recommendations are made that seek to produce an efficient design process and a durable design.

Chapter 6 addresses factors and considerations regarding execution, operation and maintenance of a crane hardstand. Monitoring for the purpose of supervising risky processes (deformations, vibrations and noise) during installation of the hardstand and during the lifting operation are discussed as well. Quality assurance and testing of the completed structures are also explored. This chapter also addresses temporary hardstands and interplays with, among other things, cable installation, the foundation of the wind turbine, site access and construction roads, and transport of the wind turbine itself.

FIGURE 1-1 **FLOW CHART OF THE PRESENT HANDBOOK ON CRANE HARDSTANDS FOR INSTALLING WIND TURBINES**

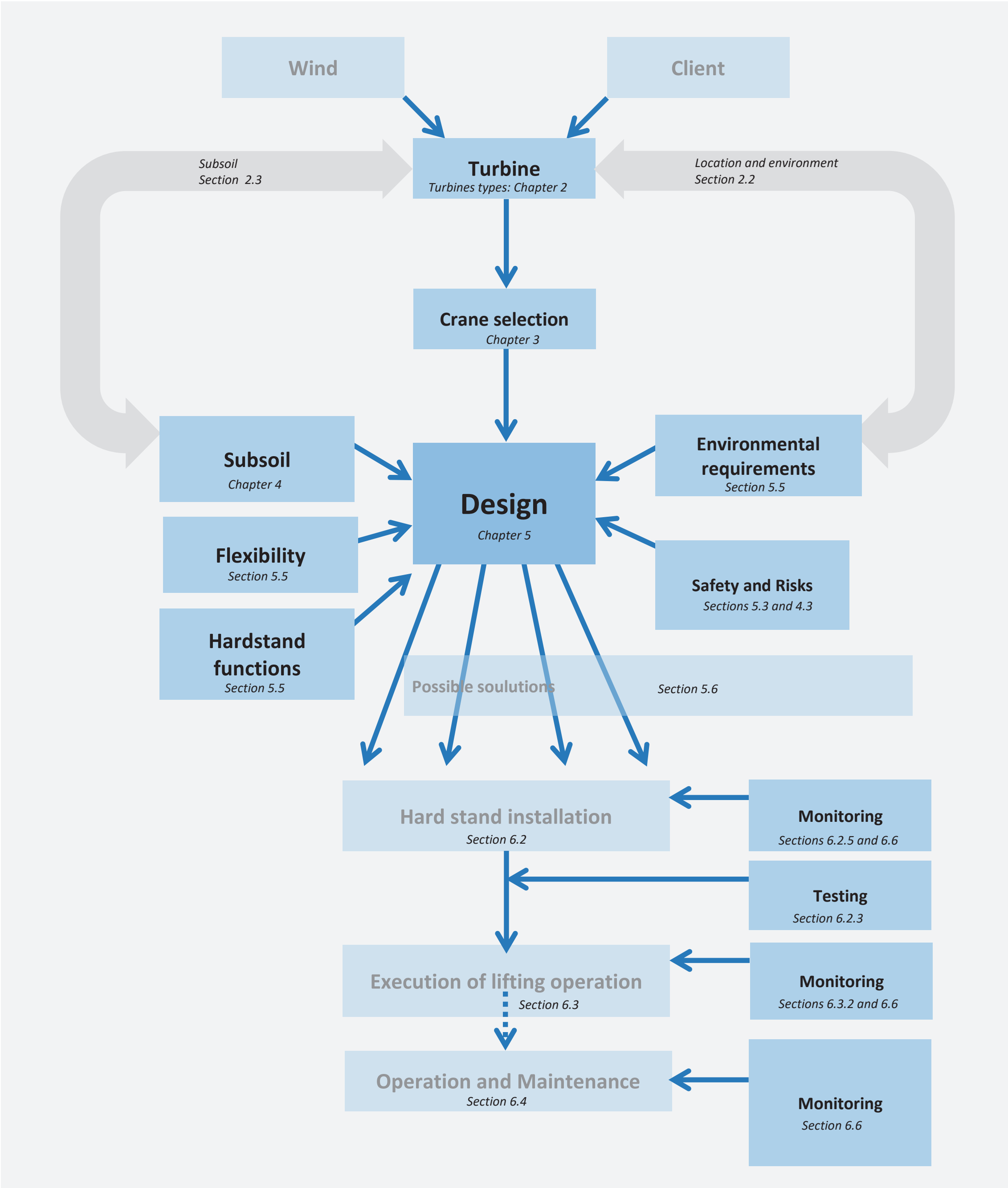
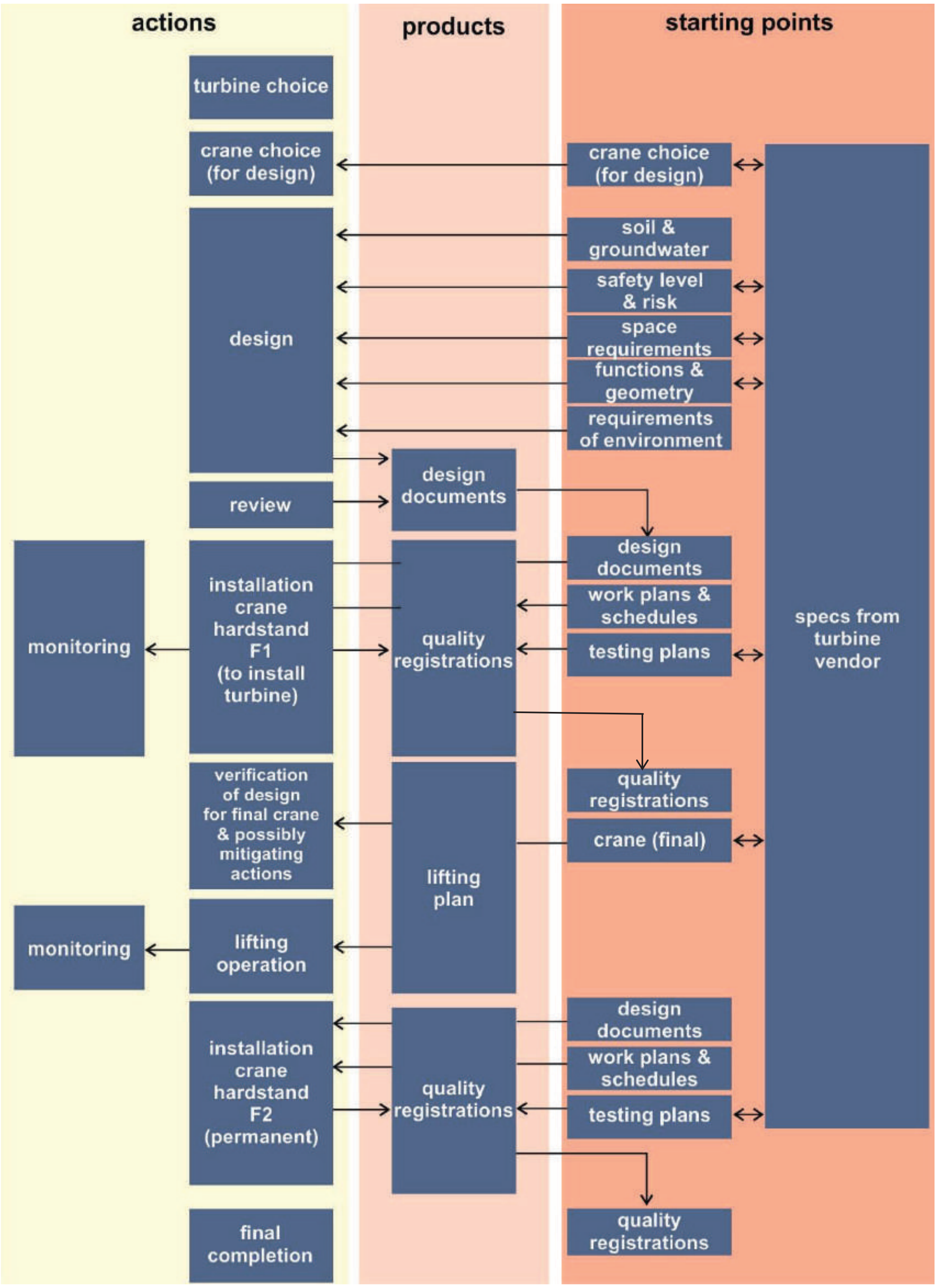


FIGURE 1-2 ACTIONS, PRODUCTS AND STARTING POINTS FOR CRANE HARDSTANDS FOR INSTALLING WIND TURBINES



2

TURBINE TYPES

2.1 INTRODUCTION

Wind turbines are made of heavy components such as the tower, nacelle and rotor (with inclusion of rotor blades as an option). To be able to build the turbine, all these components must be lifted to the required heights.

The weights of these components differ for the various types of turbines available in the market, but for every wind turbine the lifting of these components is the key factor in the design of the crane hardstands. These components influence the location of the crane hardstand in relation to the turbine foundation and the bearing capacity that will be needed. Furthermore, the building method chosen or available for installing the wind turbine will influence the design and execution of the crane hardstand.

Wind turbines are built by several parties contracted by a client. The client chooses different forms of contracts and tendering procedures, and the different tasks involved are typically divided into different lots in which flexibility is key. The parties contracted for these lots then often divide the work again into different components to be carried out by subcontractors. This subdivision into work packages results in numerous interfaces between the components, and a corresponding need for adequate alignment between them.

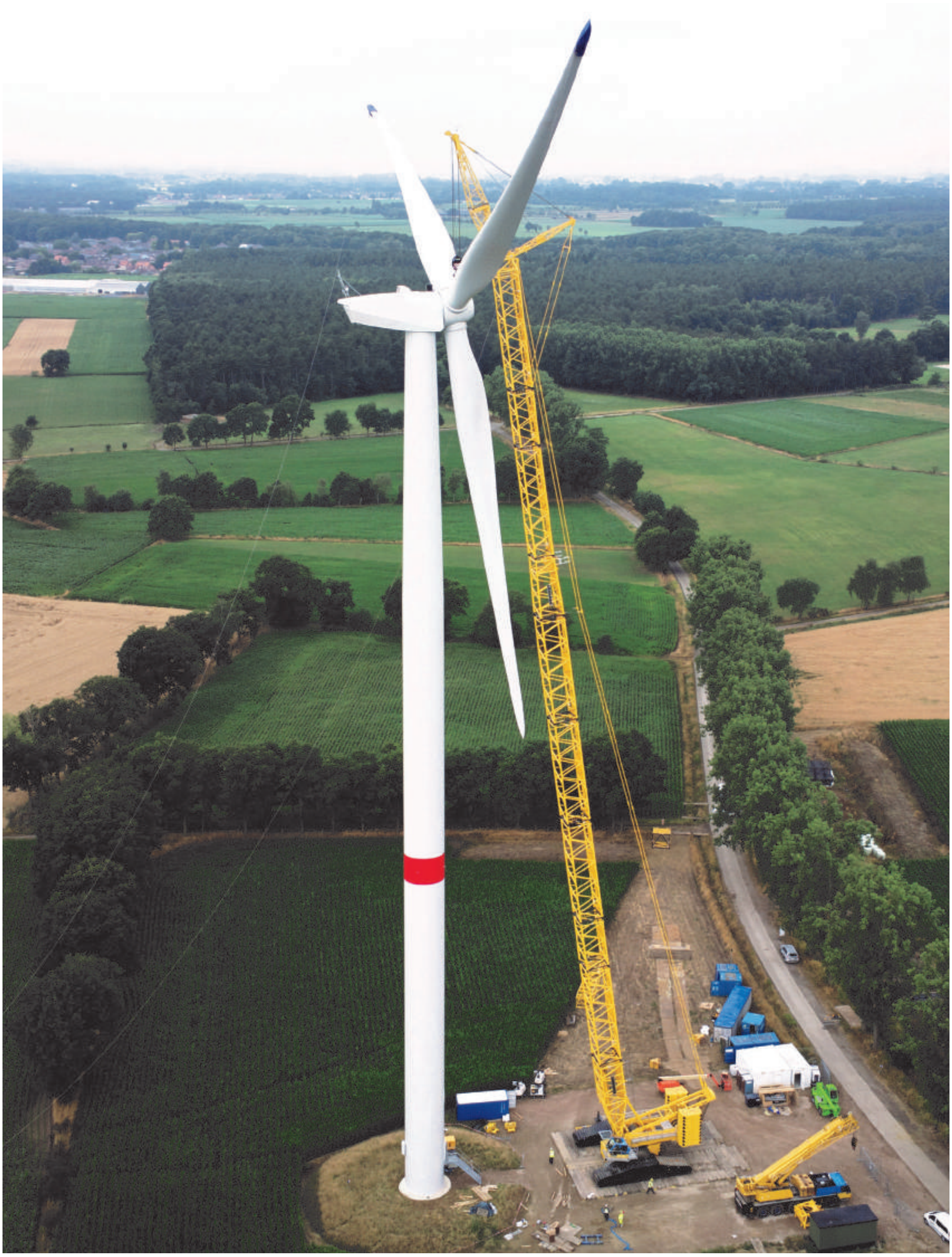
Development of wind farms takes place in different types of environments, each posing its own challenges in relation to subsoil characteristics and structures nearby. As a result, those developing wind turbine locations in the future will be confronted with increasingly complex business cases for larger and more efficient wind turbines (larger in both power output and height), which will more and more be built in areas with limited civil infrastructure.

The sections below address these aspects in further detail.

2.2 LOCATION AND ENVIRONMENT

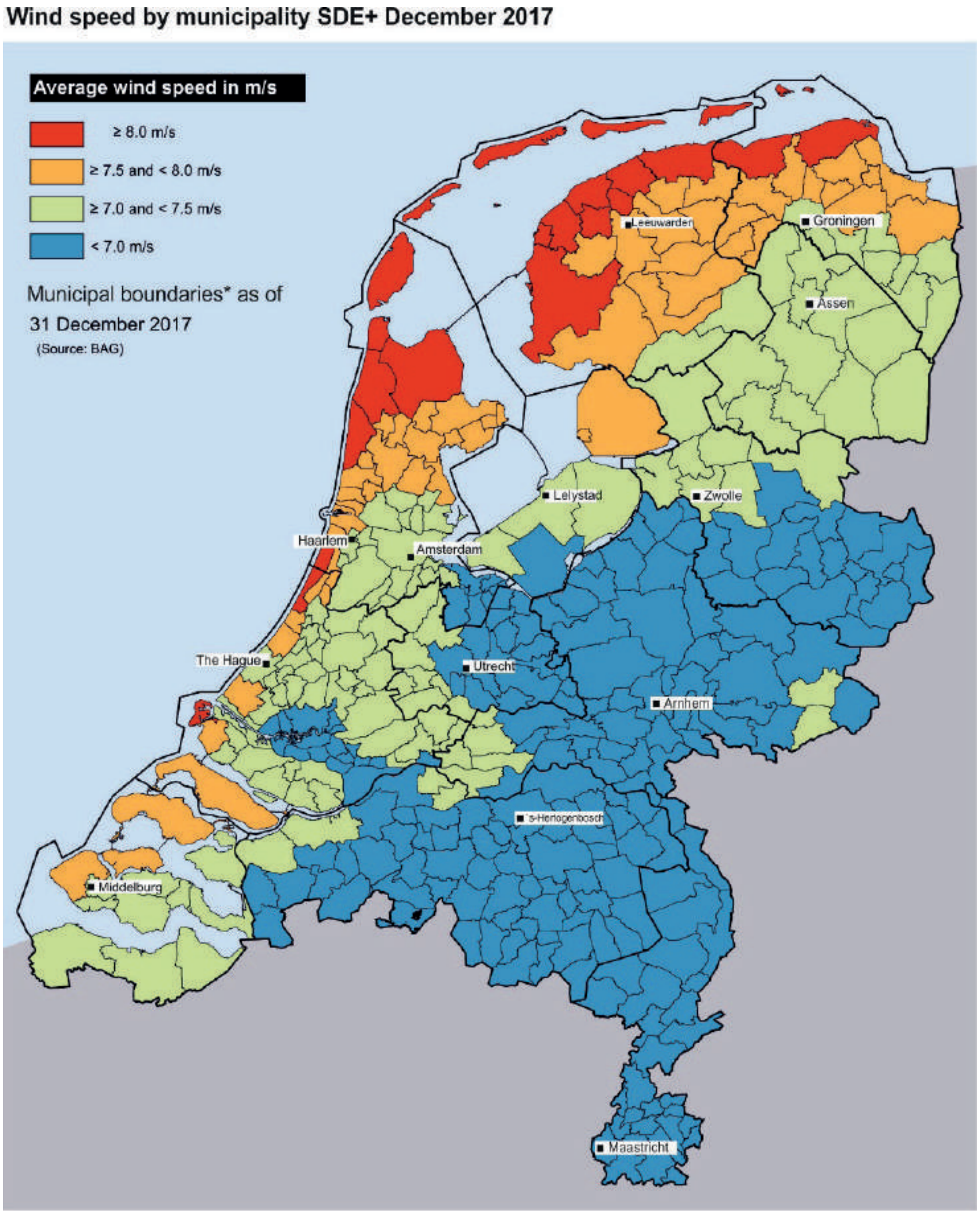
2.2.1 OPTIMUM LOCATION AND TURBINE HEIGHT

From the perspective of energy production, the location of a wind turbine is primarily determined by the most ideal hub height. In general, larger turbines (with larger rotor diameters) produce more electricity, but the forces acting on the turbine are also greater. Due to these greater forces, more drastic and expensive measures are needed to guarantee the desired service life [40]. For that reason, larger turbines are generally suited to locations with little wind, and smaller turbines are suited to locations with a lot of wind.



To standardize this site suitability, four wind turbines classes are provided in IEC 61400-1 [36]: I, II, III and IV. Each is suited to different average wind speeds, respectively, 10, 8.5, 7.5 and 6 m/s. Looking at the wind speed map in figure 2-1, an idea can be gained of which turbine type will be suitable for any given location in the Netherlands (map created by the Royal Netherlands Meteorological Institute (KNMI), Statistics Netherlands and the Netherlands Enterprise Agency). Thus, turbines in class III and IV can be ruled out for locations along the coast, because they will be unable to handle the loads. The other way around is possible: turbines in class I could be placed onshore, but because these turbines are more expensive and often cannot be produced for the higher hub heights, it is more economical to choose another type.

FIGURE 2-1 **WIND SPEED MAP OF THE NETHERLANDS**



Notes: 1. Due to the large differences in wind speeds, the municipality of Rotterdam is divided into smaller districts. 2. Average wind speeds (m/s) are measured at 100 m height over the 2004-2013 period per municipality.
Source: KNMI, CBS and RVO.nl

2.2.2 REQUIREMENTS IMPOSED BY THE ENVIRONMENT

Technology and economic considerations are not always the lead concerns, as can also be seen in table 2-1, which presents an overview of the wind turbines installed in the Netherlands since January 2015. We see, for example, that relatively small turbines have been placed in Limburg and Gelderland in recent years, while larger turbines would have been more logical considering the wind speeds in these provinces.

TABLE 2-1 OVERVIEW OF WIND TURBINES CONSTRUCTED IN THE NETHERLANDS SINCE 2015*

	Average hub height (m)	Average rotor diameter (m)	Average yield (kW)	Number
Groningen	88	94	2918	30
Friesland	63	71	1796	23
Drenthe	92	117	3300	1
North Holland	61	62	1349	36
Flevoland	115	116	4827	77
Overijssel	94	85	2783	6
South Holland	87	92	2881	27
Utrecht	Unknown	Unknown	Unknown	0
Gelderland	99	91	2517	12
Zeeland	89	110	930	15
North Brabant	95	104	2769	29
Limburg	98	92	2300	1
Offshore	88	126	3777	193
Total	90	109	3339	450

* The table is not an exhaustive summary; it is intended to provide an impression only.

The environments in which wind farms are being developed are becoming more complex, and stakeholders in these environment are becoming increasingly vocal in their demands and conditions. Due to all these imposed requirements, the location selected for a wind turbine may not always be optimum from an economical and/or technical perspective.

This section discusses in brief the various above-ground interfaces that make up the framework in which the height (diameter) and position of a wind turbine are determined. For more information on this topic, refer to the risk zoning handbook for wind turbines published by the Netherlands Enterprise Agency (in Dutch) [35].

NOISE AND SHADOW FLICKER

The noise produced by a rotating wind turbine and shadow flicker may be sources of nuisance for residents and businesses near the turbine. To minimize this potential nuisance, wind turbines are placed at the most optimum location possible without significant compromises to their energy yields.

AIR TRAFFIC

Air traffic and flight routes influence turbine location and height because air traffic may not be hindered by wind turbines. Even where turbines do not directly influence air routes, flickering warning lights must always be installed on turbines with a tip height greater than 150 m. These lights can be perceived as a nuisance by people in the environment.

RADAR

In the Netherlands various radar systems are installed which – to communicate – require a free emission path between them or between radar and receiver. In many places, this emission path is found at the same height as the vertical range of the rotor blades of a wind turbine.

FLORA AND FAUNA

Regarding flora and fauna, definitive limits can be defined for turbine positions and heights, taking into consideration mainly flying animals whose flight zone is within the vertical range of the rotor blades.

LINE INFRASTRUCTURE

Existing infrastructure, such as automobile roads and highways, railways, waterways, dikes and levees, high-voltage lines, water management works, cables and pipelines, both below ground and above ground, impose various limitations on the placement of turbines and the corresponding civil works. Moreover, these line infrastructures often have high-risk zones in which a turbine may not be built, or where components of a defect turbine must not be able to encroach; for example, if a wind turbine were to fall over. These zones are imposed to guarantee the safety of users and the surrounding environment.

2.2.3 KEY CONCERNS REGARDING CIVIL WORKS

The section above described the factors that determine where a wind turbine can be placed. This location is often chosen based on limitations and conditions imposed by the environment and will not by definition be technically the best position for the turbine.

Similarly, the required civil infrastructure, which in fact includes the crane hardstand, is not a lead consideration in decisions on turbine placement. Nonetheless, the challenges imposed by the environment cannot be avoided and must therefore be solved within the civil domain. Examples of these challenges are, among other things, poor subsoil characteristics, a less than ideal water balance, underground cables and pipelines, and building of bridges over waterways.

Because these challenges can make civil works costly, it is advisable to take a close look at the requirements and minimum specifications for these works and discuss and coordinate how they are to be handled among the parties concerned.

The sections below address the main considerations and requirements that generally arise in such discussions. Each topic is examined in greater detail in the relevant chapter of this handbook.

AREA AND SPACE REQUIREMENTS

The required dimensions of the crane hardstand depend on the dimensions of the crane (outrigger spacing) planned to be used to install the wind turbine, as well as the purposes the hardstand is to serve during the execution phase and service life of the turbine. For taller wind turbines, heavier cranes are used with a larger footprint. Furthermore, to set up the different types of crane different types of equipment are needed, and this also imposes differing requirements on the working surfaces required.

Methods of delivery, too, such as ‘just in time’ delivery’ or ‘storage on site’, alongside how the space devoted to the crane hardstand will be used and the needs of other site users, impose particular demands on the working surface and the surface area required for the hardstand.

SLOPE

Slope can be a necessary or least costly solution for drainage of the crane hardstand. Water authorities and farmers can set requirements for slope related to compensation water and prevention of damages to crops.

The slope requirements for the hardstand will also depend on the crane type. For example, a crawler crane cannot operate on a sloped hardstand unless extra measures are taken, such as mats.

Stability and safety
Stability and safety of a crane hardstand must be guaranteed throughout the execution phase and the service life of the turbine. Compliance with the needed reliability level is assured in the design documents, in work plans/schedules and in testing/verification documentation.

For a sufficient and complete test of stability and safety, in addition to adequate knowledge of load cases, adequate information about soil layering and characteristics of the soil profile is essential.

An important and uncertain factor regarding the load on the crane, and therefore the load on the supporting ground, is the contribution of the wind load. The wind load is a key factor in crane stability as well. The wind speeds at which the lifting operation can still safely be performed differ for the different types of crane. Taking into consideration the season and wind speeds at the site may well lead to the decision to use a different type of crane to minimize the risk of extreme delays in the installation works.

SETTLEMENT AND TILTING

During the lifting operation, limits and maximum differences are set for settlements, to ensure that the crane can operate safely. A very slight settlement difference on the hardstand surface will have much larger consequences at the top of the crane.

PLACEMENT AND HEIGHTS

The placement of the crane hardstand is related to the location of the turbine foundation and the working radius of the crane to be employed. There is a minimum and maximum distance from the center of the crane from which the placement of the crane hardstand will follow.
The crane used to install the turbine depends, among other things, on the height difference that has to be bridged. The installation heights of the crane hardstand and the turbine foundation will influence the crane to be used.

DESIGN

Chapter 5 discusses problems and solutions in more detail. In designing and executing the crane hardstand the cost of these solutions will need to be compared with the various alternatives available to optimize the hardstand. In this process, the abovementioned considerations must be considered.
A so-called ‘trade-off matrix’ or TOM, can be used to choose the most economical, but above all safe option, for all parties involved in all phases of a project.

2.3 SOIL CHARACTERISTICS

The subsoil will not necessarily be of good quality in many places in the Netherlands. The western regions of the country in particular are known to have weak, compressible, low bearing capacity soil layers. Because these layers are found at different depths, no standard solution can be given for a single most economically effective design for a crane hardstand. Geotechnical and geohydrological investigation will be required to obtain the necessary localized data about subsoil characteristics.

2.4 LOADS

Table 2-2 presents a global overview of the weights and installation heights involved in building a wind turbine. The weights in table 2-2 are for the nacelle and rotor hub. The lower tower components may be heavier, but because these are installed at a lower height than the nacelle and rotor hub, they are not the determinative factor in the load cases used for the crane hardstand.

Table 3-1, in section 3.5, presents the lifting loads for the most common cranes in more detail.

TABLE 2-2 WEIGHTS AND HEIGHTS INVOLVED IN INSTALLING A WIND TURBINE*

	Lifting loads for nacelle and rotor hub	
	Min. hub height	**Max. hub height**
Hub height (m)	60	165
Min. weight (ton)	45	105
Max. weight (ton)	70	110

* This table is not an exhaustive summary, and is intended to provide an impression only.

2.5 APPROACHING THE MARKET

As soon as the placement locations of the wind turbines are known, the client can approach market parties to bid for the installation works. Several forms of contract are available with which the client can approach the market, but the work will always be awarded to a contractor that cannot execute the entire job alone. Multiple contractors will therefore always be involved, and they will have to take steps to align the interfaces between their various contributions.

In the tendering phase, the interfaces are not yet known to the various parties, so a maximum amount of flexibility is sought in the tender request and resolution. Though the contract parties seek to maintain that flexibility for as long as possible, for an optimum and economical design and execution process, that flexibility will at some point have to be narrowed.

Nonetheless, in today's project planning processes there is typically insufficient time to narrow down that flexibility adequately and based on the right arguments. Alongside the contractual risks (due to contract changes) arising from any narrowing down of flexibility, lack of time is a reason why options tend to be narrowed down only partially or not at all.

2.6 THE FUTURE

2.6.1 WIND TURBINES

Wind turbines have grown rapidly in both size and in the power of the generator over the past three decades. Figures 2-2 and 2-3 below depict this development over the past 25 years These figures show the growth in average hub heights, rotor diameters and power installed in the Netherlands over the years. As far as the technology is concerned, these trendlines could well continue.

FIGURE 2-2 DEVELOPMENT OF WIND TURBINE SIZE, 1982-2017

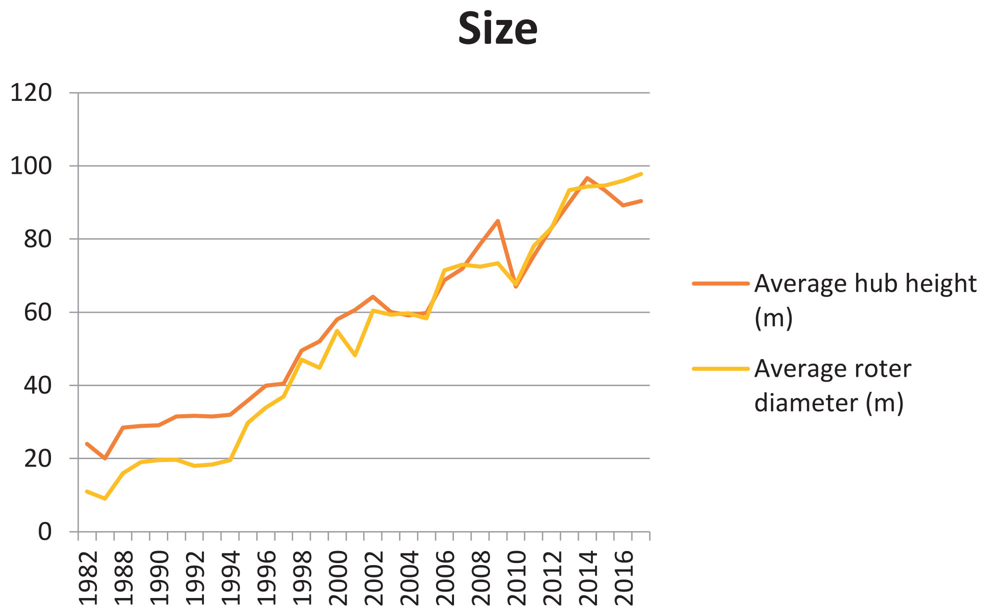
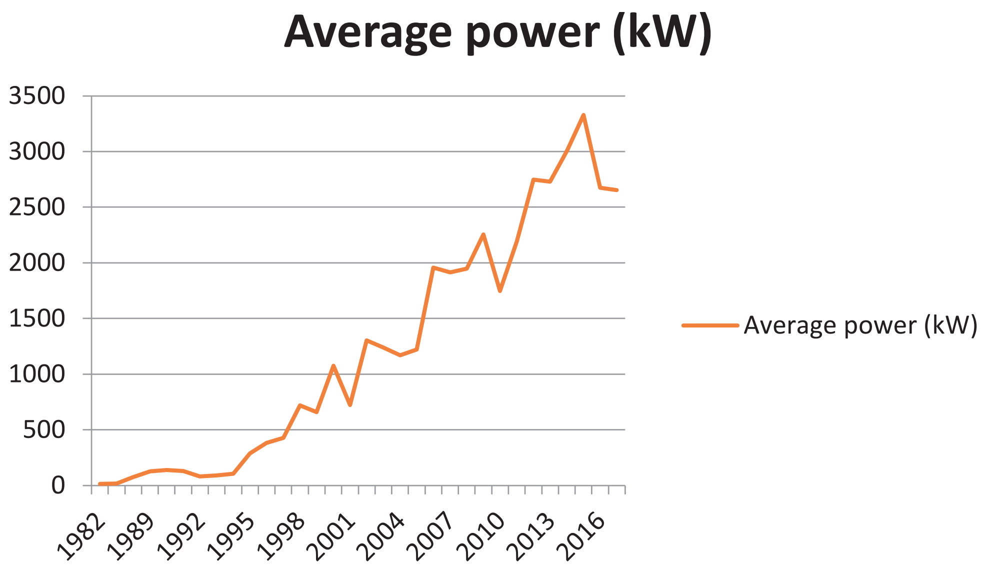


FIGURE 2-3 DEVELOPMENT OF WIND TURBINE POWER, 1982-2017



2.6.2 TECHNOLOGICAL POTENTIAL FOR THE FUTURE

Table 2-3 presents some of the turbines available in 2017, providing a snapshot of the trend in the market towards increasingly large turbines. In practice, the goal pursued is to always use as large a turbine as possible within the political and technical constraints.

TABLE 2-3 WIND TURBINES AVAILABLE IN 2017*

Brand	Type	Power (MW)	Hub heights (m) and IEC class	Rotor diameter (m)
Siemens	SWT-3.4-101	3.4	74.5-94 (IEC I)	101
Vestas	V117	4.0/4.2	84 m (IEC II), 91.5 m (IEC I)	117
Nordex	N131	3.9	84-134 (IEC III)	131

* The table is not an exhaustive summary, and is intended to provide an impression only. For instance, onshore turbines are also available with a rotor diameter of 140 m and a hub height of 160 m (an example is the Senvion 3.6M140).

2.6.3 POTENTIALS

With increases in the numbers of wind farm projects and the growing heights of the turbines, resistance to wind farm projects has also grown among a variety of stakeholders. This means that locations where wind turbines can be built will become increasingly limited in the future, and possibly, fewer turbines will be allowed to be built in the most desirable locations. Pressure to reduce costs will therefore increase, bringing even higher pressure to optimize the design and execution of the crane hardstand. Achieving this will require a focus on 'must haves' and 'nice to haves', alongside possibilities (and impossibilities) for quicker builds.

3

CRANE CHOICE, LOADS AND SPECS

3.1 INTRODUCTION

The ground pressures that arise on a crane hardstand are strongly dependent on the type of crane that is selected. The selection of a suitable crane is driven largely by the dimensions and weights of the wind turbine components to be installed, but other factors have to be considered as well.

This chapter begins by examining the different types of cranes and auxiliary attachments and systems used with them. Based on that information, the sections that follow discuss points that must be considered when choosing, hiring and assembling the cranes.

Based on a variety of load cases, the chapter finally explores in greater detail the ground pressures that arise under the crane. The resulting numbers are indicative and intended only to raise awareness of the magnitudes involved. From the large spread in the values given, it will be clear that no specific and binding recommendation can be provided based on the given load cases. Every project situation will therefore always demand individual attention, in close consultation with the crane hirer.

3.2 CRANE CATEGORIES AND CONFIGURATIONS

3.2.1 CRANE TYPES

In Europe, mobile cranes are commonly used to install wind turbines. In a few cases, tower cranes or so-called ‘climbing cranes’ might be used. Tower cranes, unlike mobile cranes, are equipped with a slewing ring at the very top of the crane. For that reason, these may also be called ‘top-slewers’.

Use of tower cranes requires a custom-built concrete foundation to anchor the machine, often with the additional option of connecting the crane tower to the tower of the wind turbine at one or multiple points.

Climbing cranes are machines that can be mounted onto the tower of a wind turbine and, together with the assembly of each new tower segment, climb higher towards the top. To date, climbing cranes have only been used to a very limited extent, as they require very specific adaptations to the turbine tower.

Because mobile cranes are used virtually without exception for the installation of wind turbines in the Netherlands, tower cranes are not further discussed in this handbook.

PHOTO 3-1 **LIEBHERR 1000 EC-B 125 LITRONIC TOWER CRANE**

The following mobile cranes can be distinguished:
- Mobile cranes with a telescopic boom, also called telescopic cranes
- Mobile cranes with a lattice boom, also called lattice boom cranes

There are three types of undercarriages for the telescopic and lattice boom cranes:
- Undercarriage on wheels. A crane with an undercarriage on wheels always has outriggers to enable the machine to be set up in a stable and level fashion in the operational mode.
- Undercarriage on crawler tracks. Cranes with crawler tracks do not generally have outriggers; the crawler tracks therefore determine the tipping lines of the crane. Most crawler cranes are lattice boom cranes. Crawler cranes with telescopic booms are very rarely used in the Netherlands as the main crane for installing a wind turbine. These cranes do regularly serve as auxiliary cranes to assist in assembly of the main crane.
- Undercarriage with four outriggers only (the pedestal crane).

PHOTO 3-2 **DEMAG PC 3800-1 PEDESTAL CRANE**

Cranes with crawler tracks have the advantage of independent movement when they are fully assembled. In most cases, crawler cranes can even travel with a load on the hook. However, due to the sharply increased risk of instability and the likelihood of damage to the crane hardstand, travel of the crane (with and without a load) is avoided if at all possible.

Cranes with outriggers cannot be moved in the operating mode. They can, however, level themselves. For that reason, these cranes have less need for an absolutely horizontal hardstand.

PHOTO 3-3 **LIEBHERR LG1750, A LATTICE BOOM CRANE WITH AN UNDERCARRIAGE ON WHEELS**

In addition to the aforementioned mobile cranes, there are a few other types of cranes in the market that can be used for installing wind turbines:

- 'Narrow track' crawler cranes (usually configured with a lattice boom). These crawler cranes have a very narrow track base, which allows the crane to be moved in assembled state over the construction roads between different turbine locations. Because of the narrow track base, these cranes have outriggers for use in the operating mode.
- The GTK1100. A single manufacturer developed this unique crane type, which is equipped with a vertical telescopic boom on which an uppercarriage is mounted with a standard telescopic boom.

Both of these cranes are very rarely utilized on construction sites in the Netherlands. They are therefore not discussed further in this handbook.

Though telescopic cranes can have an undercarriage on crawler tracks, most have undercarriages on wheels with outriggers. Therefore, for ease of reading, the term 'telescopic crane' is used hereinafter to refer to the latter type.

3.2.2 CRANE CAPACITIES

The capacity of a crane is indicated by the maximum lifting weight, expressed in 'tons'. Lattice boom cranes are available in capacity classes comparable to those of telescopic cranes, but also in classes far exceeding these. In today's market, telescopic cranes are available in classes from 30 to 1,200 tons. The lattice boom cranes now available in the market range from approx. 30 to 3,000 tons.

The capabilities of telescopic and lattice boom cranes cannot be compared based on their maximum tonnage. With an identical capacity classification both types can lift an equal maximum tonnage on their minimum working radius. However, at larger distances from the crane, the maximum loads that can be lifted are very different.

That means the capabilities of a '500-ton' telescopic crane can by no means be compared with those of a '500-ton' lattice boom crane. It can be said that a lattice boom crane has a greater capacity on average than a similarly classified telescopic crane.

3.2.3 AUXILIARY SYSTEMS

The following auxiliary systems are discussed:
- Jib
- Superlift attachment
- Mechanical outriggers
- Guying system

JIB

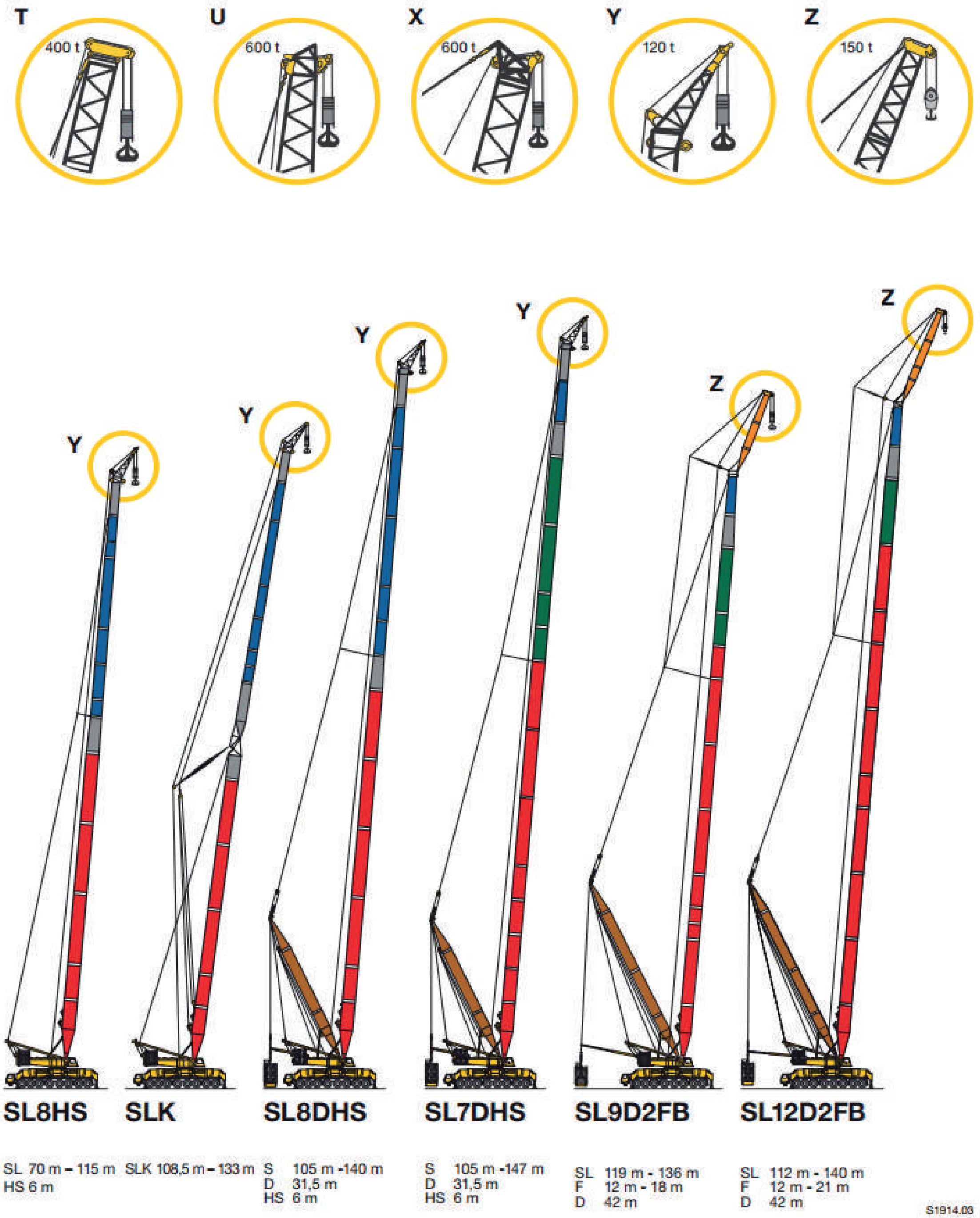
On most cranes, the telescopic booms can be extended using an attachment arm, also called the 'fly jib'. With very few exceptions, fly jibs can be recognized by their lattice structure. The jib can be rigidly mounted (sometimes at an angle) at the top of the main boom, in which case it is formally known as a 'fixed fly jib', sometimes called a 'boom extension' in practice.

For the larger telescopic cranes (starting from about 350 tons) the fly jib can also be mounted in an articulated, or hinged, manner on the main boom. This configuration often requires extra assemblage components, such as A frames and winch equipment. The articulated jib is formally called a 'luffing fly jib'.

PHOTO 3-4 TWO LIEBHERR LTM1500-8.1 CONFIGURED WITH LUFFING JIB

Lattice boom cranes can also be configured with a 'luffing jib' or 'boom extension'. Many lattice boom cranes can additionally be equipped with a 'wind kit'. This is made up of an extra jib, some 6 to 14 m in length, which can be mounted at a fixed angle at the top of the boom extension (figure 3-1). This creates a small kink at the top, which enables nacelles to be brought into position with enough clearance.

FIGURE 3.1 THE WIND KITS (COMPONENTS Y AND Z) OF THE LIEBHERR LG1750



SUPERLIFT ATTACHMENT

Lattice boom cranes in the 300-ton class and higher can be configured with a so-called 'superlift attachment' (also called 'additional counterweight'). In this case, an extra boom is mounted to the crane, also called the 'derrick boom', which is angled backwards (the orange boom in figure 3-1). By connecting this boom to the corresponding extra ballast (the 'superlift ballast' or 'derrick ballast'), a large increase in capacity is achieved.

The superlift ballast is usually stacked on a support frame, called 'the tray'. Only if the crane is adequately in balance (that is, with sufficient load on the hook) can the tray be lifted free from the ground, in order to make the slewing of the crane possible. When a lifted load is set down, the superlift tray also has to be put back on the ground at the same time. Less common (and also less readily available in the market) is use of a so-called 'ballast wagon'. The superlift tray is, in this case, equipped with a steerable set of wheels which enables the crane to slew without the abovementioned equilibrium state.

PHOTO 3-5 **THE SUPERLIFT TRAY OF A LIEBHERR LR 1600/2**

On lattice boom cranes in classes up to 750 tons, the superlift tray is found up to 22 m behind the center of the crane (the slewing ring). The total weight of the superlift ballast on the tray can be as much as 400 tons. Obviously, the crane hardstand will have to be larger and more heavy duty if the crane to be used is configured with a superlift attachment.

MECHANICAL OUTRIGGERS

Another relevant auxiliary system that can be mounted on crawler cranes is the 'mechanical outriggers'. When erecting the boom of a lattice boom crane, the following applies:

- For short boom configurations, the boom can be erected without auxiliary equipment. The normal amount of ballast on the crane creates adequate stability.
- For medium length boom configurations, the standard ballast is insufficient to ensure stability: auxiliary equipment will be needed to erect the boom. In that case, for most crawler cranes mechanical outriggers will be attached to the crawler tracks. The longer moment arm this creates allows for the boom to be erected.
- For very long boom configurations, the superlift attachment must always be assembled. The superlift ballast then ensures sufficient stability. It is very possible that the superlift

attachment will not be used in the subsequent lifting works. The tray is then detached and left in place, so that if weather conditions deteriorate it can be quickly re-attached to lower the boom.

PHOTO 3-6 THE MECHANICAL OUTRIGGERS OF A LIEBHERR LR 1600/2

In many cases, a superlift attachment can be used to raise medium length booms as well. However, this requires numerous extra freights for delivery of all the needed components and the superlift ballast, and the time required to set up the crane is substantially increased as well.

GUYING SYSTEM

This auxiliary system is available only on telescopic cranes with a capacity of approx. 300 tons and greater. It is also known as 'superlift' (unfortunately, being confusing).

The guying system ensures tensioning, consequently reinforcing the main boom, with the result being increased crane capacity. The guying system consists of two backwards facing arms mounted on the main boom. The arms can be mounted parallel to each other, or configured at an angle (the 'V position'). In the V position, the main boom is not only reinforced in the forward bending direction, but also stabilized sideways.

In installing wind turbines, a long main boom is often used so that loads can be brought to great heights. When a longer main boom is used, sideways forces, such as wind, play a greater role. This is why the guying system is always in the V position for wind turbine erection.

PHOTO 3-7 **TWO DEMAG AC500S WITH A LUFFING JIB AND GUYING SYSTEM IN V POSITION**

3.2.4 CRANE SELECTION AND FLEXIBILITY

In the highest capacity classes only lattice boom cranes are available. However, if the lifting works fall within the capabilities of telescopic cranes, then a number of considerations will play a role in selecting the type of crane to be used. For instance, the supply and assembly of a telescopic crane generally requires less time and auxiliary equipment (assist cranes and trucks) than a lattice boom crane. Mobilization and demobilization costs are therefore lower and flexibility (ease of moving the crane) is greater. However, the crane hire cost per day is usually lower for a lattice boom crane than for a telescopic crane with comparable capacity. The duration of a project will therefore play a role in the decision, in addition to the lifting capacity.

The choice of a suitable crane type and its configuration will also be influenced by the following:
- The space available for crane assembly
- The size of the wind farm, as well as the number of wind turbines to be installed
- Crane availability (supply and demand). Experience shows that demand for cranes in the wind industry increases markedly in the second half of each calendar year.

Often, a combination of telescopic cranes and lattice boom cranes is used for installing wind turbines. Where the crane types are combined, the telescopic crane is used to install the first tower sections, after which a lattice boom crane takes its place. In big wind farm projects, a large number and variety of different crane types can often be found, with the telescopic cranes preceding the lattice boom cranes on the job.

The time that must be allowed between placing the order for a crane and the point of its mobilization has fallen rapidly in recent years, from multiple months to just a few weeks in some cases. However, the shorter the ‘notice time’ given, the more limited the availability of suitable cranes will be. If in such a case, the crane hardstand is made in such a way that it is suitable for one particular type of crane, problems can arise in the construction schedule.

The solution can be found in placing the crane order earlier, or by making the crane hardstand flexible, so that a number of different types of cranes can be utilized.

The crane types and auxiliary systems described in this chapter are those most frequently used in installing wind turbines in the Netherlands at the time of this writing. Particular challenges are posed in transporting these cranes to and from the work site, in crane assembly and disassembly and, of course, when a crane is in operating mode. Following from these, requirements are given regarding access roads to the construction site, the space required to assemble the crane and specifications for the crane hardstand itself.

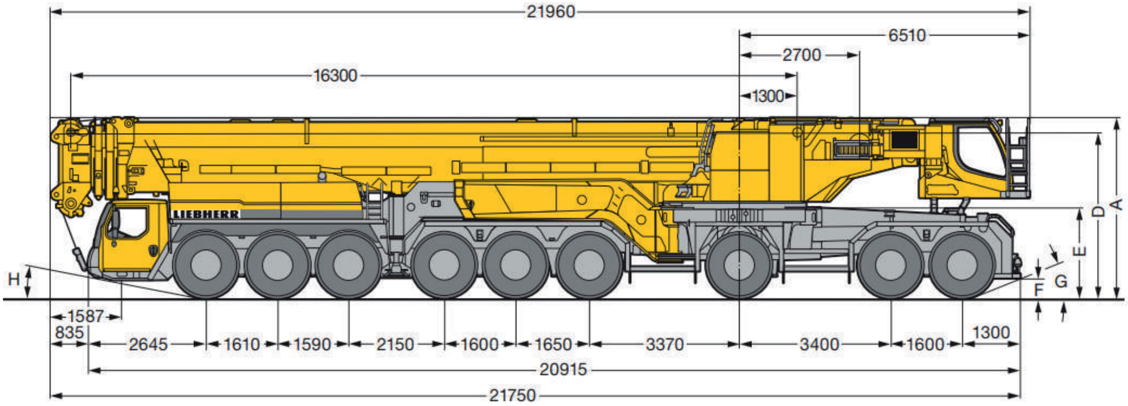
Consideration of these challenges and requirements will enable a determination to be made, for each individual situation, of whether it is feasible to construct the crane hardstand for maximum versatility. If this turns out not to be the case, then the parties involved must be aware that the crane order will have to be placed early on, to guarantee that the right type of crane will be available.

3.3 TRANSPORT

3.3.1 TO AND FROM THE JOB SITE

The largest self-propelled cranes at this point in time have nine axles (18 wheels). The total weight of the crane in transport mode is 100 tons; the maximum axle load is 12 tons, and the crane is approx. 22 m in length. All the components that go with the crane are transported via freight truck combinations, each of which also has a maximum total weight of 100 tons and axle loads of up to 12 tons.

FIGURE 3-2 **SIDE VIEW OF THE LIEBHERR LTM1750-9.1, ON NINE AXLES**



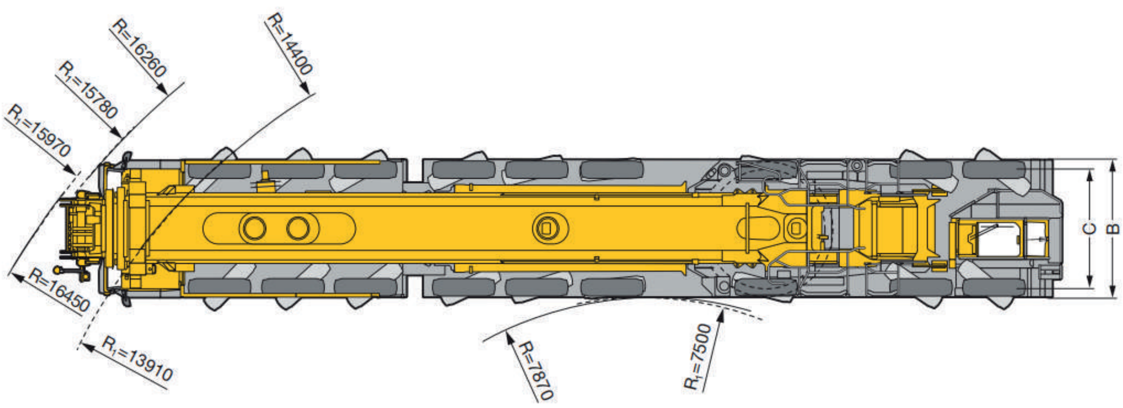
For mobile cranes heavier than 60 tons and freight truck combinations heavier than 50 tons, a request for a transport permit has to be made to the Netherlands Vehicle Authority (RDW) to travel on public roads. Long-term transport permits can be granted for many main roads for weights up 100 tons. For heavier vehicles, or if the roads to be traveled are not included in the long-term permit, incidental permits can be requested. In the Netherlands, the processing time for such requests is two to three weeks.

The last part of the transport route to a wind turbine site is usually over private roads owned, for example, by a water authority or port authority. Transport permits do not apply to these roads. It is up to the client of the crane hire company to acquire permission to transverse these roads and thus also to ensure that the road is suitable for the transport.

Cranes without wheels are transported to the job site entirely by freight trucks. The heaviest combinations in such cases also weigh 100 tons, with axle loads of up to 12 tons and lengths of some 22 m.

Self-propelled cranes are 3 m wide, so construction roads should preferably be at least 4 m wide. Curves need to be constructed wider, to allow for cranes' larger turning radius. Of particular concern in wind farm construction in the Netherlands, sufficient distance must be maintained from embankment slopes (including those of ditches) at all times. The minimum distance is determined using a stability calculation in consultation with a geotechnical engineer.

FIGURE 3-3 **TURNING RADIUS OF THE LIEBHERR LTM1750-9.1 (B = 3 M)**



It must be noted that the transport of large cranes to and from a job site represents a major logistical challenge. The number of freight loads required will be large. As an indication: a crawler crane in the 600-ton class equipped with a long main boom plus a wind kit takes approx. 30 freight loads to deliver. If a superlift attachment is also needed, this number increases to 40-50 freights. Then there is the added problem that the components which leave the previous job site first need to arrive at the next job site last.

A huge number of freight trucks will enter and exit the job site in a period of just a few days. Room to maneuver can sometimes be very limited on such sites. Incoming or outgoing freight trucks will sometimes have to back into or out of an area. To avoid unsafe situations, the following measures are recommended:

- Create turning areas for freight trucks.
- Create spaces where vehicles can pass each other. This applies to locations where the construction site is at a large distance (> 500 m) from public roads.
- Appoint a logistical coordinator (or 'truck pusher') to direct the truck traffic. This person works from a strategic position on the job site, for example, at the entrance to the site from the public road.

The aforementioned requirements for temporary roads do not take into account the dimensions and weights of the wind turbine components that will have to be delivered. For these, exceptionally long truck-trailer combinations are often used (e.g., to transport the turbine blades), and maximum vehicle weights may exceed 100 tons (e.g., for transport of nacelles). The same applies to mobilization of foundation rigs to the job site, as truck weights of up to 150 tons are no exception.

3.3.2 TRANSPORT BETWEEN TURBINE LOCATIONS

Under strict conditions, cranes on wheels can be driven in a fully or partially assembled state. In that case, the total weight of these machines can be up to 300 to 400 tons. Axle loads of more than 30 tons are routinely observed and in certain cases, peaks of nearly 50 tons arise. The crane's instruction manual describes all of the possible transport configurations and the minimum conditions required for them.

PHOTO 3-8 TRANSPORT OF A LIEBHERR LTM1750-9.1 BETWEEN TWO TURBINE LOCATIONS IN PARTIALLY ASSEMBLED STATE

Lattice boom cranes on crawler tracks and pedestal cranes are generally entirely disassembled and then transported on freight trucks. Transport permits will generally have been applied for upon the initial delivery of these cranes to the wind farm location. Because transport between turbine locations often occurs over short distances and off public roads, no permits are needed for this. The freight trucks used are therefore generally more heavily loaded than when the crane parts were first delivered.

There are other options for moving partially or fully assembled cranes, for example, a crawler crane can travel by itself, and a crane can be moved using hydraulic modular trailers. However, these solutions are applied only in exceptional cases and are therefore not further discussed in this handbook.

3.4 SET-UP AND ASSEMBLY

In organizing the crane assembly site, a distinction is made between the platform on which the crane itself will be set up (the 'hardstand') and the space needed for assembling the boom-jib combination of the crane (the 'boom assembly area').

3.4.1 THE CRANE HARDSTAND

GENERAL

The space needed for the crane in operating mode is called the 'hardstand'. The hardstand must at all times be level, have sufficient bearing capacity and be easily accessible.

Mobile cranes with outriggers must always be set up completely horizontal (level). The outriggers can, if needed, accommodate any irregularities on the hardstand. However, large differences in levels (> 10 cm) should be avoided, as the stroke of the outrigger cylinders is often limited.

Most crawler cranes have very strict requirements regarding the slope of the hardstand; this may be no more than +/- 0.3˚, in accordance with the instruction manual of the specific machine. This corresponds to approx. 0.52%.

In assessing the levelness of the crane, settlement of the hardstand also has to be taken into account.

Use of a crane with a superlift attachment imposes extra requirements on the hardstand. More space is needed around the crane, and the subsoil must be tested (possibly at multiple spots) to ensure that it can support the pressure load arising from the superlift ballast. The crane hirer must provide the exact weight of the superlift ballast and indicate where on the ground it must be placed during boom erection and (possibly) during operation.

ELEVATED PLATFORM

Particularly for the larger crawler cranes, the hardstand is commonly built up in multiple layers (for example, a sand layer covered with Ekki mats). A very elevated hardstand can present additional challenges in setting up the crane. The undercarriage, or 'body', of a crawler crane is usually delivered on a semi low-loader truck and preferably unloaded directly onto the definitive set-up platform. The undercarriage 'unloads itself' from the trailer, by extending four auxiliary hydraulic outriggers that are mounted on the frame.

If the platform is elevated, it can be impossible for the transport combination to drive up it. Construction of an (adequately surfaced) access ramp is then necessary. A maximum incline of 4˚ (approx. 7%) should be adhered to as a rule of thumb for such ramps.

It is strongly advised not to fully assemble the crane first and only then position it on the platform. This creates major safety risks, not only as a consequence of crane tilting, but also due to the extremely high peak pressures that can arise due to height differences under the crawler tracks.

3.4.2 THE BOOM ASSEMBLY AREA

GENERAL

The boom assembly area is often given inadequate attention in the design of the working areas. The area for setting up the boom and/or fly jib must be entirely free of obstacles. Obstacles can be permanent objects, like houses or trees, or they can be temporary. For example, mounds of shifted soil can form a hindrance on the site.

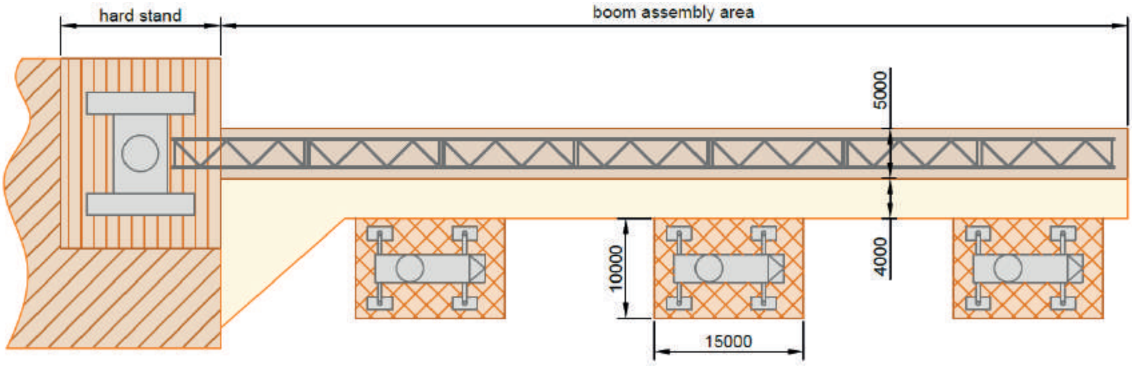
THE DIMENSIONS OF THE BOOM ASSEMBLY AREA

The length of the boom assembly area is determined by the chosen type of crane and crane configuration. For a lattice boom crane, the following rule of thumb can be used to estimate the required assembly area length: the total field length required to assemble the boom and any fly jib is approximately equivalent to the hub height of the wind turbine plus 10 m to 15 m. Additionally, the boom pivot point is approx. 1.5 to 2.0 m in front of the center of the slewing ring of the crane.

For telescopic cranes the boom assembly area length is more difficult to estimate based on the hub height of the turbine. The fly jib type and its length can be known only after the maximum extension length of the telescopic boom is determined. The length of the boom assembly area then amounts to the total length of the fly jib plus approx. 15 m (the length of the retracted telescopic boom), calculated from the center of the slewing ring.

The main booms of crawler cranes in the 400- to 750-ton classes are 3.0 to 3.5 m wide. In order to be able to work on both sides of the boom, a total width of 5.0 m is required. Adjacent to this, a 4.0 m wide access road needs to be constructed to allow for delivery of the crane components. This road is also used for maneuvering with auxiliary equipment, such as telehandlers. The auxiliary cranes must be positioned parallel to the boom assembly area and need a hardstand of roughly 10.0 m x 15.0 m in size. The crane hire company must provide the client lift drawings stipulating the length of the boom assembly area and positions of the auxiliary cranes (figure 3-4).

FIGURE 3-4 EXAMPLE SPECIFICATIONS FOR A BOOM ASSEMBLY AREA



The 5.0 m wide stretch has to be level, dry and easy for personnel working on the site to walk on. Often the job site will be on farmland, in which case ground improvement is required. Levelling the ground surface and then laying out a path of steel plates can be a solution in these cases. A necessary condition however is that the steel plates be placed on adequately drained, dry ground. This reduces the risk of the plates slipping out of under the drive wheels of, for example, a telehandler. Therefore, on wet (clay) soils a layer of sand must always be applied, or a system to ensure sufficient drainage must be provided (see also section 5.5.3).

Particular attention must be given to the positions of the boom supports, which need to be placed under the main boom during crane assembly. Pressure on such supports can be in the range of approx. 65 to 100 tons for cranes in the 600-ton and 750-ton classes. It is therefore important to use load spreading measures. Most crane hire companies can provide these, often in the form of hardwood (Ekki) mats. It is advised that the delivery of auxiliary equipment be discussed early on, in the preparatory phase of the works.

The 4.0 m stretch must be easily and safely navigable for the auxiliary cranes and for the freight trucks delivering the crane components. For the construction of these auxiliary roads, the same specifications should be adhered to as for the other site roads.

The space next to the access road to the wind turbine site is often used for boom assembly. This is a logical choice. However, it must be ensured that the site remains accessible to emergency service vehicles in case of calamities during the assembly activities.

ORIENTATION OF THE BOOM ASSEMBLY AREA

Next to the fact that immovable obstacles may constrain the orientation of the boom assembly area, the limitations of the crane also have to be allowed for.

For crawler cranes, the boom must be assembled perpendicular or parallel to the orientation of the crawler tracks. If outriggers must be used to erect the boom, the orientation is always perpendicular to the crawler tracks. A crawler crane can be moved after the boom is erected. This provides some flexibility in the orientation of the boom assembly area. However, in that case, consideration also has to be given to the need to check ground pressures arising at two crane locations. There is also a risk of damage to the hardstand due to crawler track movements.

PHOTO 3-9 **BOOM ASSEMBLY AREA**

For cranes with an undercarriage with outriggers, the more favored orientation for assembly of the boom or fly jib is perpendicular to the undercarriage or over the rear of the undercarriage. Assembly over the driver's cab should be avoided. For some crane types, it is acceptable to deviate from these preferred orientations. However, if this is being considered, the crane hire company should be consulted.

ADDITIONAL REQUIREMENTS FOR THE BOOM ASSEMBLY AREA

Because for most lattice boom cranes, the boom has to be assembled horizontally, the boom assembly area should preferably be level terrain. If this turns out to be impossible, then a sloping terrain could be compensated for by the use of raised boom supports. This does add to the complexity of the assembly and disassembly operation, and therefore more time will be needed for the job. Furthermore, additional auxiliary equipment will then usually be required, such as aerial work platforms.

PHOTO 3-10 **A RAISED BOOM SUPPORT FOR USE ON STEEPLY SLOPING TERRAIN**

It is important for the boom assembly area to remain clear during the assembly and disassembly phases and during the lifting operation, to allow for lowering the boom during any sudden spell of bad weather. For this reason, the boom supports must remain in place, even during the lifting operation.

3.4.3 AUXILIARY CRANES

Telescopic cranes (sometimes with a crawler undercarriage) are most commonly used as auxiliary cranes. For assembly of a lattice boom crane, hardstands for the auxiliary cranes need to be provided immediately adjacent to and/or behind the main crane and also at multiple spots parallel to the boom assembly area. Auxiliary cranes are not always needed for assembly of a telescopic crane. In a main boom configuration without extra auxiliary systems, a telescopic crane can fully erect itself, with no other equipment required.

The crane hire company must provide lift drawings that show the placement of any auxiliary cranes required, including the corresponding dimensions and ground pressures arising.

Wind turbine components are often delivered to the job site and put in storage before the installation works begin. Telescopic cranes are often used to unload these components. To unload turbine blades, two telescopic cranes are commonly used (‘tandem lift’). The crane hire company, in consultation with the client, must determine ahead of time where these cranes should be placed.

Finally, it should be mentioned that at the job site, in addition to sufficient space for the auxiliary cranes and storage of components, there needs to be space for tool containers, any other equipment that is needed and canteen facilities. In deciding the locations of these, it is again important to be mindful of the possible need to lower the boom and the placement of the superlift tray .

3.5 CRANE LOADS AND SPECIFICATIONS

3.5.1 GENERAL

This section summarizes indicative values for ground pressures underneath cranes arising during:

- Erection of the boom
- Operating mode
- Movement of the crane between turbine locations

The calculations employ data available at the time of this writing for the following, commonly used crane types:

- The LTM1500-8.1, a 500-ton telescopic crane
- The LTM1750-9.1, a 750-ton telescopic crane
- The LR1600/2, a 600-ton lattice boom crane on a crawler track undercarriage
- The LR1750/2, a 750-ton lattice boom crane on a crawler track undercarriage
- The LG1750, a 750-ton lattice boom crane on an undercarriage with wheels

All five are Liebherr brand machines. Liebherr provides computation software to determine outrigger and crawler pressures. That program, called ‘Liccon’, offers extensive simulation functionalities and was used in obtaining the ground pressures summarized here.

Table 3-1 lists the load cases considered.

TABLE 3-1 **LOAD CASES**

Nr.	Crane type	Crane configuration	Nacelle weight (tons)	Hub height (m)
1	LTM 1500-8.1	TY3SN	70	60
2	LTM 1750-9.1	TYV2EN	80	80
3	LTM 11200-9.1	T3YV2VEN	80	105
4	LR 1600/2	SL3F	80	105
5	LG 1750	SL8HS	80	105
6	LR 1600/2	HSL4DF	80	120
7	LG 1750	SL8HDS	80	120
8	LR 1600/2	SL13DFB	80	140
9	LG 1750	SL7DHS	80	140
10	LR 1750/2	HSL7DHS	80	140
11	LR1750/2	SX3D4F2B	105	165
12	LG 1750	SX3D4F2B	110	165
13	LG 1750	SL12D2FB	140	130

Notes:

1. See also Appendix A.
2. It should be emphasized that the table does not prescribe the exact cranes needed for the respective load cases. Multiple crane manufacturers can supply cranes with capabilities comparable to the crane types listed here.

3.5.2 PRESSURE LOADS ARISING DURING CRANE ASSEMBLY

During boom erection, very high pressures can arise beneath the outriggers or crawler tracks; in a variety of cases, these may be even higher than in the operating mode. When raising the boom of a crawler crane perpendicular to the crawler tracks, almost the entire weight of the machine will be distributed over one crawler track (situation without superlift ballast). When raising the boom in the lengthwise direction of the crawler tracks, extremely large peak pressures arise under the front rollers of both tracks.

The table in Appendix A presents the ground pressures arising during erection of the boom. The pressures exerted by cranes with outriggers are expressed in mass and force (tons and kN) and by crawler cranes in mass and force per square meter (ton/m^2 and kN/m^2).

In reading the table in Appendix A, the following should be kept in mind:

- For crawler cranes it is assumed that the boom is raised lengthwise to the crawlers. In some cases, ground pressures can be reduced by increasing the superlift ballast. Moreover, raising the boom perpendicular to the crawlers results in lower ground pressures.
- It is recommended to assume that the wind load is not discounted in the outrigger and crawler track pressures. See also the general comments in section 3.5.3.

PHOTO 3-11 **ERECTING THE BOOM OF A DEMAG CC 3800-1**

For lattice boom cranes up to the 750-ton class, many of the auxiliary cranes used are telescopic cranes in classes ranging from 90 to 200 tons. The heavier types are used to lift the uppercarriage of the crane and/or the crawlers. To lift the boom and fly jib parts, however, a lighter auxiliary crane usually suffices. Nonetheless, the decision is sometime made to use a large auxiliary crane, as it can also be employed for other assembly activities.

TABLE 3-2 **GROUND PRESSURES OF AUXILIARY CRANES OBTAINED USING THE 'LICCON' SOFTWARE**

Crane type	Crane configuration	Total weight of the crane excl. load (tons)	Load case	Max outrigger force (kN) and Outrigger pressure [kN/m²]
LTM1090-4.1	36.2 m main boom 21 ton ballast outrigger base 8.5 x 7.0 m	66.0	Lifting of a boom component G = 13 tons at 14 m radius	490 kN mat: LxB= approx. 2.5 x 1.3 m= 151 kN/m²
LTM1200-5.1	26.7 m main boom 72.0 ton ballast outrigger base 8.9 x 8.3 m	140,0	Lifting of an uppercarriage G = 66 tons at 9 m radius	1010 kN mat: LxB= approx. 3.3 x 2.0 m= 153 kN/m2

Notes on Table 3-2:

1. The crane types referred to here are examples; various other types of cranes can be employed.
2. The given values are intended purely as an indication. The possible auxiliary crane positions and the radii corresponding to them largely determine the outrigger forces and pressures that will arise.

3.5.3 PRESSURE LOADS ARISING FROM A CRANE IN OPERATION

The table in Appendix A presents ground pressures arising from cranes in the operating mode.

In reading the table in Appendix A, the following should be kept in mind:

- The given pressures apply to the heaviest load case: when the uppercarriage of the crane is diagonally slewed. That is to say, the moment of the crane is largely absorbed by one outrigger or by the tip of a crawler track.
- On a fully luffed main boom with no load on the hook, the counterweight of a crane generates a strong backwards-acting moment. In some cases, the ground pressures arising in this situation are larger than in the operating mode when the maximum load is being lifted. In its preparations, the crane hirer must therefore consider not only the lifting situation but also the 'empty hook' situation.

GENERAL COMMENTS

- Liebherr indicates that the values generated by its Liccon software include a load factor of 5%. This covers small dynamic effects due to crane movements. It must be emphasized, however, that this factor excludes any effects arising due to wind. Not all crane manufacturers are transparent about whether load factors are included in their support software. It is therefore advisable to always assume that these are characteristic values (excluding load factors). For safety issues pertaining to wind loads during turbine installation and transport, see [29] and section 6.3.2.
- The outrigger forces or crawler track pressures that arise are provided by the crane hire company on the lift drawing, often in tabular form. In many cases, the lifting engineer will not know the exact slewing range and direction of the crane. For this reason, engineers often elect to indicate the peak pressures that arise when the crane slews 360˚ with a load. This yields four values, which, however, do not represent any one particular load situation and therefore cannot be adopted one-to-one in an eventual ground pressure calculation. Consultation on this between the crane hire company and client will therefore be of essential importance.

TAILING OPERATIONS

An auxiliary crane is often required to safely turn a load from a horizontal to a vertical position ('tailing'). In a tailing operation a distinction is made between the main crane and the tail crane. The auxiliary cranes used in crane assembly are also frequently used as tail cranes. Indicative ground pressures for these machines are given in section 3.5.2.

PHOTO 3-12 **TAILING OPERATIONS FOR A TOWER SECTION**

EFFECTS DUE TO WIND

The lengths of main booms have grown more or less apace with the increasing hub heights of wind turbines. The horizontal forces that arise during the lifting operation, mainly as a product of wind, have therefore become an increasingly important issue in boom design.

Assumptions for mobile cranes designed in compliance with NEN-EN 13000 [52] are a load area of 1.0 m^2 per 1.0 ton lifting load and a wind resistance coefficient of the load of 1.2 . Based on these values, standard permissible wind speeds are given. The permissible wind speed is provided in the operating manual of the crane and differs per crane and per configuration.

However, if the area of the load to be lifted is greater than 1.2 m^2/ton (low weight/large sail area), the crane hirer must reduce the permissible wind speed. Based on the wind load area, the load weight and the wind resistance coefficient of the load, a new permissible wind speed has to be determined using the calculation method provided in the operating manual. From this it follows that lifting a load with a large sail area – such as a fully assembled rotor star – may only be performed at very low wind speeds.

Despite this allowance for the effects of the wind, the booms of modern cranes will exhibit a degree lateral deflection, owing to their manufacture from high-yield strength steel. Due to this initial deflection, a moment arm arises that can further reinforce boom deflection, the so-called second-order effect. This phenomenon occurs particularly in cranes with booms longer than 100 m.

The total bending moment on the boom increases the pressures beneath the crane's outriggers or crawler tracks. This effect is not yet accounted for in the crane support software; which therefore produces only static values. Manufacturers are expected to expand their software in the future so that the effects of wind can be included in simulations. The actual effects on the ground beneath should then become clearer, which will allow for more precise starting points for design of the crane hardstand.

It is important to mention that this effect occurs in the operating mode of the crane when there is a maximum load on the hook. Because in many situations, the maximum pressures will be those exhibited during the boom erection operation, the aforementioned effects will not always necessarily be a determinative factor in the design of the crane hardstand.

Until the manufacturers have adapted their software, for combinations of a crane with a boom longer than 100 m and heavy loads with large sail areas (for example, a fully assembled rotor star), crane hirers are recommended to consult with the manufacture on the effects of wind on the vertical loading beneath the outriggers and crawler tracks.

For more information about wind loads on mobile cranes, see the FEM guideline [29] and Liebherr training manual on wind effects [70].

3.5.4 PRESSURE LOADS OCCURRING DURING CRANE TRAVEL

As noted earlier, crawler cranes and pedestal cranes are almost always fully dismantled to move them between turbine locations. Cranes with an undercarriage on wheels can drive themselves. In many cases, it is permitted to leave part of the attached auxiliary systems and/or crane ballast assembled or on the crane during such movements.

The table below presents a few examples of cranes and configurations that allow for movement in a partially assembled state, in accordance with the instruction manual, and the axle loads arising in such movements.

TABLE 3-3 AXLE LOADS DURING CRANE MOVEMENTS

Crane type	Crane configuration	Total weight of the crane	Maximum axle load
LTM1750-9.1	Main boom with guying system 66.5 m luffing jib 84-ton ballast	approx. 260 tons	Axles 1-6: 32 tons Axles 7-9: 23 tons
LTM11200-9.1	Main boom 7 parts with guying system and 6.0 + 6.5 m boom extension 52-ton ballast	approx. 280 tons	Axles 1-4: 31 tons Axles 5-9: 31 tons
LG1750	21 m main boom 145-ton ballast	approx. 370 tons	Axles 1-4: 49 tons Axles 5-8: 43 tons

In these three cases the following applies:

- The maximum average slope allowed is 1% (0.6˚), with peaks of up 5.2% (3.0˚) permissible
- Driving speeds must be minimal (approx. 1-2 km/hour)
- Maximum 3 second wind speed of 9 m/s
- Depending on the configuration, outriggers must be half or fully extended, with outrigger cylinders extended to approx. 5-10 cm above the ground

Before starting a project, clarity needs to have been obtained about the capacity of the construction roads between the turbine locations. If these are unsuited for the heavier axle loads, the crane will need to be fully disassembled and reassembled again in order to move it. This obviously has a significant influence on the time required for crane assembly and disassembly per location.

3.5.5 LOAD SPREADING

The responsibility of the crane hire company ends, in principle, upon delivery of the mats for use under the crane. For cranes with outriggers, these are always steel mats that go with the crane being used. Telescopic cranes in the Netherlands generally have mats that reduce the ground pressures arising to approx. 100-200 kN/m^2. A crane mat will always bend somewhat under a load. The ground surface must therefore have a degree of elasticity to enable the outrigger pressure to be effectively distributed over the entire mat surface.

Crawler cranes generally do not come with standard mats. In practice, these machines (up to the 750-ton class) are usually placed on a platform of hardwood mats. These mats are often Azobe (Ekki) and have a thickness of 20 cm, a width of 1 m and are 5-6 m in length. The mats are placed perpendicular to the drive direction of the crawler crane, in two rows, beneath the center of each crawler track. If there are doubts about the suitability of the supporting ground, the decision may sometimes be made to use a double layer of mats.

The effective width over which a wooden mat spreads the pressures arising under the crawler tracks is highly dependent on the characteristics of the supporting ground. The crane hirer will therefore preferably provide the civil expert with the track pressures arising and specifications for the mats to be used.

It is important to realize that the addition of heavy mats for extra load spreading also results in an extra load on the hardstand due to the weight of these mats.

3.6 MAINTENANCE AND DISASSEMBLY

For maintenance activities, the same general requirements apply to the crane hardstand as described earlier. However, for maintenance, the weights to be lifted will usually be lighter, and the cranes used tend to be on-site for a shorter period of time than upon the initial installation. For this reason, there is a greater probability that telescopic cranes will be used.

Often after completion of the initial turbine installation phase, the boom assembly area will no longer be kept clear, and in some cases the crane hardstand will be reduced in size as well. When lifting activities have to be carried out, temporary measures may therefore be needed to assemble a crane and perform the works safely. This handbook can also be applied to the design of such temporary crane hardstands.

After its operational service life, every wind turbine is disassembled. Flexible implementation of the crane hardstand in the new-build phase increases the likelihood that it will also be suitable for use by the cranes available when the turbine has to be removed. See also section 3.2.4.

3.7 SUMMARY

The factors that must be considered regarding crane selection, loads and specifications for the design of a crane hardstand for installing wind turbines are summarized below.

- The choice of a crane is determined by:
  - The duration of a project
  - The space available for crane assembly
  - The number of wind turbines to be installed
  - The availability of cranes

  If a crane hardstand is designed in such a way that it is suitable for multiple types of cranes, the chance of delays due to the possibly limited availability of a certain type of crane is smaller.
- Transport roads to and from the site must at least be suitable for vehicles up to 100 tons (mobile cranes and freight combinations) and for axle loads up to 12 tons. If the construction roads between turbine locations are made in such a way as to be suitable for heavier weights and axle loads, cranes can be moved between them in a partially assembled state. This reduces crane assembly and disassembly times. During such movements, depending on the configuration chosen, machine weights can reach up to 300-400 tons with axle loads of up to some 50 tons.
- It is advisable to make allowances for turning areas and spaces where vehicles can pass each other, as well as to appoint a logistical coordinator (or 'truck pusher') to direct truck traffic.
- The crane hardstand must be level and have high bearing capacity. Allowance has to be made for the placement and weight of a superlift tray, if required. Space is also needed for auxiliary cranes to operate directly adjacent to and behind the main crane.
- The boom assembly area must be level and clear of obstacles. Arrangements have to be made for the delivery of crane components, placement of auxiliary cranes and ongoing accessibility of the construction site to emergency services.
- For crawler cranes, the boom must be assembled either perpendicular or parallel to the crawler track orientation. For cranes with an outrigger undercarriage, the strongly favored orientation for assembly of the boom or fly jib is perpendicular to the undercarriage or over the rear of the undercarriage. For some crane types, deviations from these standards may be possible; on these consult the crane hire company.
- At the site, there must be sufficient space around the hardstand, if required, for storage of components and the cranes needed to unload these components, alongside tool containers, auxiliary equipment and canteen facilities.
- There must be an ability to lower the boom of the crane at all times. During the lifting operation the boom assembly area must remain clear of obstacles; the boom supports must be left in position, and the same applies to any superlift ballast used.
- The outrigger force and crawler pressure figures supplied by the crane hire company do not include partial load factors, nor do they take dynamic effects into account.
- In determining the maximum ground pressures, the crane hirer must consider the operating mode (with and without a load in the hook), in addition to the boom erection operation.
- The effective width over which the loads under the crane mats is spread is dependent on the elasticity of the ground.

The table in Appendix A gives values for ground pressures arising in various situations. That is, when erecting the boom and in the operating mode (when lifting the nacelle). It must be emphasized that these values are indicative and can vary widely from project to project. Adherence to the assembly and lift drawings that must be provided by the crane hirer is therefore paramount. These show not only the positions of the main crane and auxiliary cranes, but also confirm the ground pressures arising beneath the outriggers and/or crawler tracks.

3.8 FUTURE DEVELOPMENTS

In the coming years, wind turbines will continue to grow in hub heights and rotor diameters. Crane development will continue as well. However, a turning point is approaching when the size of the crane and the associated costs outweigh the return of the wind turbine. New developments are therefore on the horizon.

WIDENED MAIN BOOM

A development that has already materialized is a local widening of the main boom, which enables it to handle sideways loads better. Manufacturers Demag and Liebherr already offer this upgrade on various types of cranes, under the names ‘Boom Booster’ and ‘Power Boom’.

PHOTO 3-13 THE FIRST CRANE WITH A LOCALLY WIDENED BOOM, THE DEMAG CC8800-1 WITH BOOM BOOSTER

CRAWLER CRANE WITH OUTRIGGERS

Up to now, crane manufacturers have been able to achieve boom extensions within the NEN-EN 13000 [52] crane design specification norm, without increasing the size of the base that gives the cranes their stability. Here, similarly, the end is in sight. Current predictions expect new generations of crawler cranes with very long booms to be equipped with four heavy outriggers. This variant of the standard crawler crane is not entirely new, as these kinds of machines were already built in the past. Because of the increasing boom lengths, however, we will be seeing this modification reappear.

PHOTO 3-14 A NEW CRAWLER CRANE WITH OUTRIGGERS AT THE LIEBHERR TEST SITE

OUT OF SERVICE STABILITY

Another future development is an addition to NEN-EN 13000 [52] regarding stability norms for cranes. This concerns the stability of a crane while it is out of service; that is, with the crane set up for the operating mode with a raised boom, but no lifting being performed. The combination of an empty hook (no downwards force) and a very long, wind-sensitive boom, can in strong winds, produce a critical situation with regard to crane stability. For this reason, the stability norms will be expanded with a part that addresses the ‘out of service’ situation.

4

GEOTECHNICAL AND GEOHYDROLOGICAL INVESTIGATION

4.1 INTRODUCTION

Crane hardstands must, by definition, provide adequate safety and stability. Crane safety and stability is derived foremost from a high bearing capacity of the hardstand and a sufficiently strong and rigid subgrade. Soil deformations, such as settlement that occur due to a loaded crane in service, must be confined to within set limits.

As part of the design process, the soil stability (strength) and degree of deformation must be calculated and tested and checked against the set limits and prevailing standards and guidelines. If the soil is by nature not sufficiently strong and stiff, it must be improved or loads transferred to deeper, stronger sand layers. The properties and geometry of the crane hardstand can also be improved, for example, using a mixed aggregate, possibly in combination with a geotextile for reinforcement.

Soil strength and deformation are calculated and tested using characteristic average values for the properties of the given soil layers. These values are determined based on soil investigation (geotechnical analyses). Also, measurements are carried out of the groundwater table height and hydraulic head of the soil layers (geohydrological analyses).

In part because the geotechnical and geohydrological properties of the subsoil are measured very locally (point measurements), they are characterized by a relatively high degree of uncertainty. The extent of this uncertainty depends on the amount of information that is available about the soil profile, characteristics and behavior. The amount of variation and the precision of the data on soil properties, groundwater table height and hydraulic head determine the reliability of soil behavior predictions and with it, the geotechnical risks.

Geotechnical risks can be effectively managed by applying the Geotechnical Risk Management (GeoRM) methodology. GeoRM offers a structured way to deal with the uncertainties that arise from the different geotechnical risks. The GeoRM approach requires the soil investigation to be performed using a risk-based methodology. The risk-based process inherent in the GeoRM approach to soil investigation is also consistent with the widely known and often-used RISMAN methodology. Appendix B describes the principles of risk-based soil investigation in more detail.

In practical terms, risk-based soil investigation means that the amount and level of detail of the soil investigation carried out is tailored to the particular geotechnical risks found at a crane hardstand site. The soil investigation to be implemented is therefore determined on an as-needed basis for each project phase and/or level of detail. Sections 4.4 through 4.6 discuss how the required type and amount of soil investigation is determined for the design of a crane hardstand.

Nonetheless, no generic recommendation can be given for the type, amount and level of detail of soil investigation needed for a crane hardstand. Local factors and conditions specific to each individual project site will always need to be considered.

The results of the soil investigation needed in a particular project phase should generally be available in that same project phase. This means the investigation must have already been done before the first step of the corresponding phase has been completed. The time required to perform the soil investigation therefore needs to be allowed for; this must include not only the time required for the field analyses, but certainly also the laboratory component!

Note that in some cases, time and cost reductions can be achieved by combining the soil investigation needed for multiple project phases and carrying them out, if possible, together at an early stage. Because the amount of soil investigation required is determined by the risks involved, this strategy can be particularly effective for projects where a comprehensive overview of the risks is needed early on.

The principles presented in this chapter are based on CUR/Geo-Impuls Report 247 (in Dutch), which discusses risk-based soil investigation from planning to implementation [17].

4.2 STANDARDS AND GUIDELINES

NEN-EN 1997-2 [47] and [48] contain standards for implementation of soil investigation. In addition, much information and a number of implementation guidelines for soil investigation can be found in CUR162 [12], CUR Report 2003-7 [14] and in the CUR/CROW guidelines for geotechnical laboratory analysis [21]. There is also the British standard, BS 5930 [7], and an ICE publication [28] containing guidelines for setting up soil investigation. For an overview of the relevant standards and guidelines, see Appendix C.

4.3 RISK ASSESSMENT

To carry out soil investigation in a targeted and efficient way, it must be known what types of risks and uncertainties one is seeking to minimize with the soil investigation.

For a crane hardstand, a number of highly generic risks exist, regardless of the project location. These risks will therefore have to be considered in the soil investigation done for every crane hardstand. The tables below summarize these risks and link them to the corresponding relevant types of soil investigation.

TABLE 4-1 GEOTECHNICAL RISKS AND THEIR POTENTIAL CONSEQUENCES FOR A CRANE HARDSTAND

Geotechnical risk	Consequence
Inadequate soil bearing capacity	Subsoil failure, inadequate edge stability, falling over of crane, loss of soil strength, schedule and cost overruns
Too much (differential) settlement of the subsoil	Unacceptable tilting of the crane, inability to correct the tilting
High groundwater table	Soil instability and unacceptable deformation
Inadequate compaction of soil improvement	Inadequate density, strength and stiffness of the granular layer. This can, in turn, lead to differential settlement and loss of bearing capacity
Environmental influences; deformation of surrounding structures	Damage to surrounding buildings, cables/pipelines and flood defenses; reputational damage
Disruptions due to vibrations and noise	Damages in surrounding environment, legal actions, delays, reputational damage

TABLE 4-2 RELATIONSHIP BETWEEN GEOTECHNICAL RISKS AND SOIL INVESTIGATION FOR A CRANE HARDSTAND

Geotechnical risk	Underlying cause	Soil investigation
Inadequate soil bearing capacity	Soil profile is different than expected	Cone Penetrometer Test (CPT) combined with water pressure measurement (piezocone), borings with disturbed and undisturbed sampling
	Layer thickness is larger than expected	CPTs, borings with disturbed and undisturbed sampling, further classification
	Incorrect assumptions of soil type	CPTs with piezocone, borings with disturbed and undisturbed sampling
	Density and strength are lower than expected	CPTs, borings with disturbed and undisturbed sampling, further classification, triaxial tests, direct simple sheer (DSS) tests (peat)
	Wrong choice for soil improvement	CPTs, borings with disturbed and undisturbed sampling, further classification, triaxial tests, direct simple sheer (DSS) tests (peat), compression test
Too much (differential) settlement of the subsoil	Soil profile is different than expected	CPTs with piezocone, borings with disturbed and undisturbed sampling
	Layer thickness is larger than expected	CPTs, borings with disturbed and undisturbed sampling, further classification
	Density and stiffness are lower than expected	CPTs, borings with disturbed and undisturbed sampling, further classification, compression test
	Groundwater table height and/or hydraulic head different than expected	CPTs with piezocone, installation of monitoring wells
	Wrong assumption of soil type	CPTs with piezocone, borings with disturbed and undisturbed sampling
High groundwater table	Relatively low soil bearing capacity and relatively low initial effective stress	CPTs with piezocone, monitoring wells, water pressure gauges
Inadequate compaction of soil improvement	Wrong compaction method chosen, too light or too heavy, too little consolidation. Sand not well compacted	(Manual) CPTs, nuclear density measurements, ring sampling and proctor test
Environmental influences; deformations of surrounding structures	Subsoil deforms too much due to incorrect stiffness parameter for the subsoil	CPTs, borings with triaxial tests and/or compression tests
Disturbances due to vibrations and noise due to installation of piled embankments or sheet piling	Vibrations (e.g., due to pile-driving) cause secondary settlements of loosely packed sand, or sand layers transmit vibrations to nearby buildings causing damage and nuisance	CPTs and borings

4.4 DETAIL LEVEL: VERY ROUGH (SKETCH AND INITIATION PHASE)

4.4.1 DESCRIPTION

The data that has to be gathered in the sketch and initiation phase must be sufficient to enable assumptions to be made regarding project feasibility and time and cost requirements (estimated).

In general, little specific information is known in this phase. For example, the exact location where the wind turbine is to be built and the exact placement of the crane hardstand may not be known, and the locations of site access and construction roads may not yet have been determined.

In the sketch and initiation phase, the main factors considered are the types of structures to be built and execution methods, as these are among the key factors determining feasibility. Information about the subsoil will figure into the determination of, for example, what a prudent location or route choice will be.

4.4.2 TYPE OF CALCULATIONS

Because little data is known in the sketch and initiation phase and there is still a wide freedom of choice, only exploratory calculations can be done at this stage, based on rules of thumb and correlations. These will include, for example, exploratory settlement and stability calculations based on soil parameters derived from CPTs, sometimes combined with values from experience in the area or Table 2.b of NEN 9997-1 [46].

4.4.3 TYPE OF SOIL INVESTIGATION

In the sketch and initiation phase, existing data from readily available sources will first be consulted. The soil investigation that needs to be implemented will be determined in large part by the extent that conclusions can be drawn from known data about the soil profile. Any such conclusions must be drawn by a geotechnical consultant.

After the existing data has been assessed, soil investigation can be considered. Additional soil investigation may be needed in this phase if crucial data are lacking for the entire project site or a key part of it.

In this phase, it is important, first of all, to consult historical sources to obtain all existing data that could be important in the decisions to be made. This historical research may include the following:

- Arial and satellite photos
- Digital Elevation Model for the Netherlands (AHN)
- TNO geological map sheets, see the national top layer mapping (geologic)
- The ‘DINOloket’ (a central portal for data and information on the Netherlands’ subsurface) for soil investigations conducted in the past
- Historical information (earlier building, old landscape maps, foundation drawings, nearby structures, etc.) from municipal archives, the national archive, etc.
- Groundwater levels based on water authority decisions
- If available, reports drafted for nearby works
- If available, monitoring data (e.g., on settlement and sand thickness) compiled for nearby works

Any supplementary soil investigation done in anticipation of the preliminary design phase must consist at least of the following:

- A site visit (to visually inspect the area and its direct surroundings)
- CPTs
- Borings
- Monitoring wells

HISTORICAL INFORMATION

Historical topographical maps and aerial photos can reveal a number of aspects, such as older drainage ditch patterns, which can still be of influence on the site, for example, as a cause of differential settlement. If the site was built-up in the past, it is important to obtain information about any former foundations. Foundation remnants may still be present at the site, or extraction of piles could have caused ruptures between deeper and more shallow groundwater flows.

Accurate mapping of any underground objects can be useful for settlement calculations and foundation design, as well as in determining, for example, the feasibility of vertical drain installation.

Many sources of historical information, such as old maps and aerial photos, can be found on the internet. In addition, there is always the option of searching through digital and paper archives (municipal archives, the national archive and so forth) for historical documents (construction and foundation drawings) and for information that can contribute more in-depth knowledge about the history of the site.

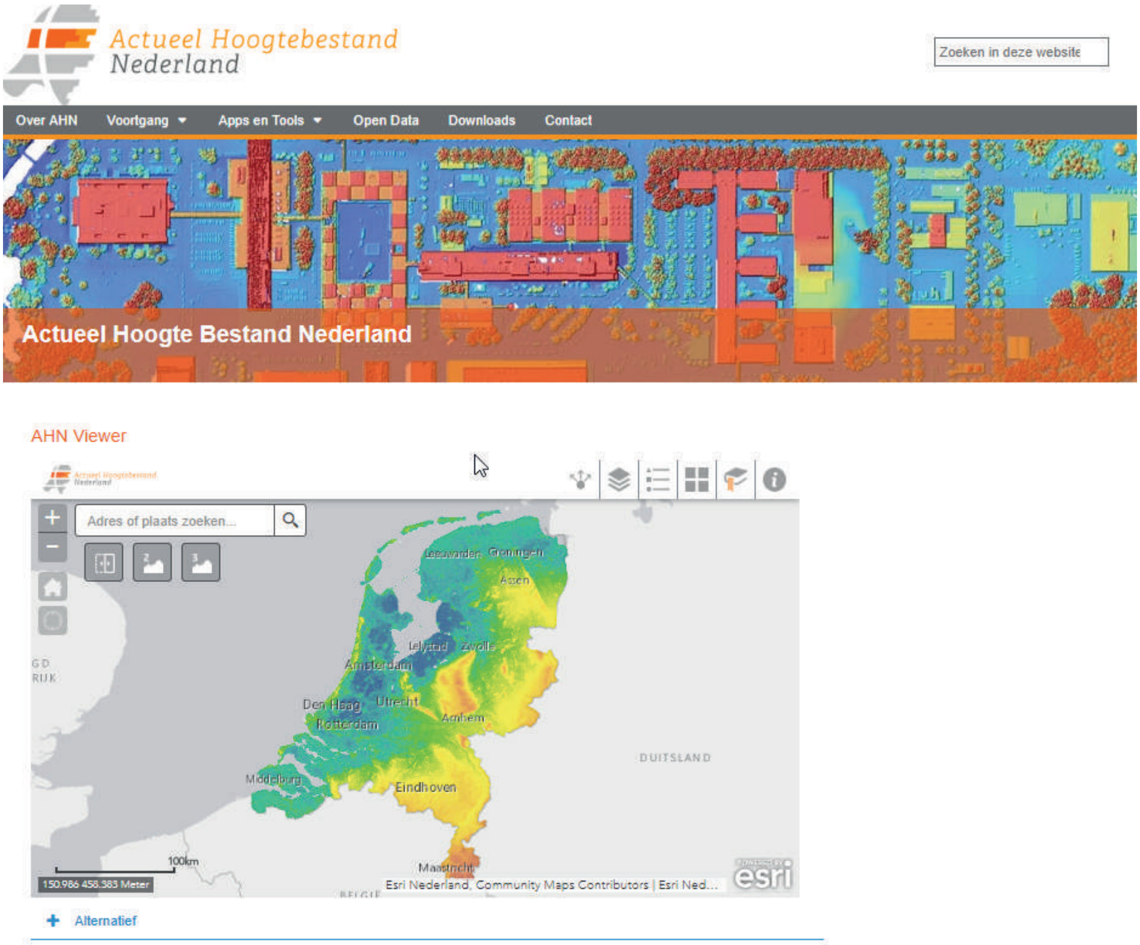
SITE VISIT

A visual inspection of the area where the work is planned can provide a wealth of information, if done by a geotechnical engineer or engineering geologist. The relief and properties of nearby ground surfaces can offer clues as to the heterogeneity of the subsoil and problems that might be expected (e.g., differential and residual settlement). Attention can also be given to (the condition of) adjacent areas, works of art and geological features visible on the ground surface (e.g., differences in vegetation, ditch patterns, etc.). For example, the water level in any water bodies will be indicative of the groundwater table height.

DIGITAL ELEVATION MODEL FOR THE NETHERLANDS (AHN)

Examination of AHN maps can sometimes reveal heterogeneity in subsurface conditions at the building site, see photo 4-1. The maps use colors to distinguish ground surface elevations. Old geological features in the landscape can sometimes be identified in a very straightforward way using differences in ground surface elevations.

PHOTO 4-1 DIGITAL ELEVATION MODEL FOR THE NETHERLANDS (AHN)

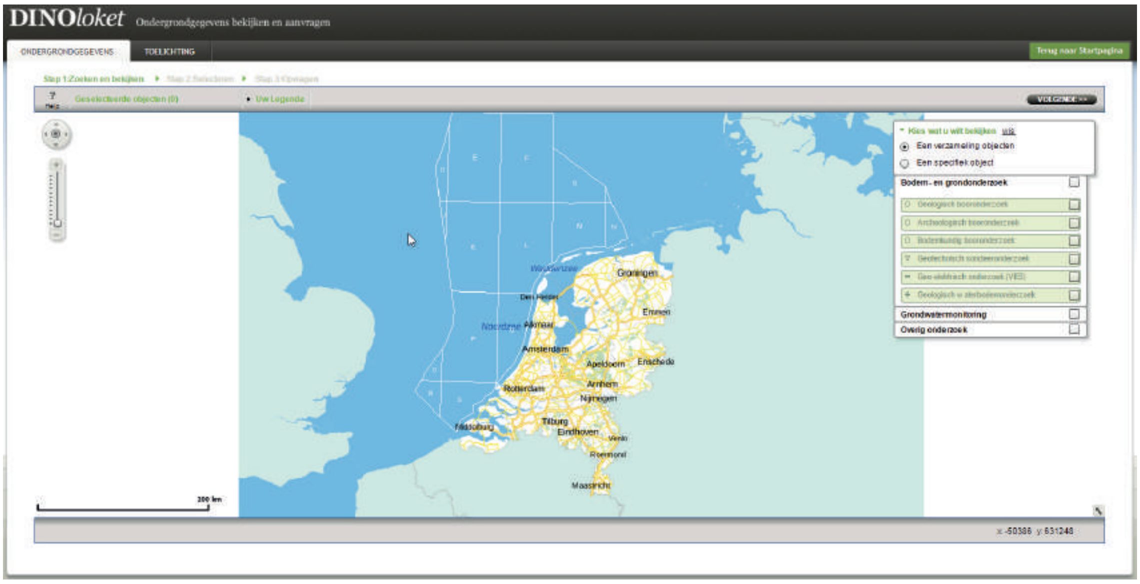


DINO PORTAL

The ‘DINOloket’ is a portal that provides access to subsurface data for the Netherlands. It is managed by GDN (part of TNO) in different databases (the DINO database and BRO database), see photo 4-2.

These repositories contain both data and information based on and derived from them. A lot of these data are supplied by businesses, government agencies and members of society. The oldest data originate from the 19th century, and new data are added regularly. The data are utilized, among other things, for activities related to safety, sustainability, mining, drinking water and construction projects.

PHOTO 4-2 **DINO PORTAL FOR VIEWING AND REQUESTING SUBSURFACE DATA**



4.4.4 AMOUNT OF SOIL INVESTIGATION

If the historical research suggests that additional soil investigation is required in this project phase, it can begin with several investigative CPTs approx. 25 m apart on the site. If a preferred location for the crane hardstand is already known, the CPTs should be done in that area.

To get an impression of the hydraulic head of the different soil layers, CPTs can be done with a piezocone, to measure water pressure as well as the usual cone resistance and friction. These measurements enable more precise classification.

To get a general impression of the phreatic groundwater level, a short monitoring well can be placed at the edge of the building site.

The depth to which the soil investigation should be performed follows from the historical research or the results of the initial CPTs. The maximum depth to be included in the investigations depends on the type of foundation to be used and its depth of influence.

Based on the results of the CPTs, the decision can already be made in this project phase to carry out a boring, perhaps with the corresponding laboratory analyses. This decision will depend on the amount of variation observed in the soil profile, based on the results of the CPTs, as well as the size and expected complexity of the project.

Whether borings are done now or in the next, preliminary design project phase, will depend, among other things, on whether additional information is needed to assess project feasibility. The amount of time available will also play a role in determining whether additional soil investigation can be carried out at this stage.

Boreholes are drilled directly adjacent to the CPTs considered indicative. The borings can then be used immediately for placement of monitoring wells.

4.5 DETAIL LEVEL: COARSE (PRELIMINARY DESIGN)

4.5.1 DESCRIPTION

By the preliminary design phase, the project location is chosen and the primary geotechnical specifications are known. The data gathered must be sufficient to enable a rough planning/scheduling of the work and a rough cost estimation. In this phase, the crane type to be used will have to be determined, with the corresponding crane loads, and a viable technical solution obtained for the crane hardstand.

4.5.2 TYPES OF CALCULATIONS

For the design of a viable technical solution, calculations are generally performed using standard geotechnical design tools. Depending on the type of project, these will include analytical calculations of strength, stability and deformation for various foundation alternatives.

In some cases, it might be necessary to perform calculations with PLAXIS finite element analysis (FEA) software. The soil parameters needed are dependent on the soil model used. The soil model is chosen by a geotechnical consultant/engineer based on the mechanism to be analyzed.

The type and amount of soil investigation done must be tailored to the type of calculations to be performed. The more advanced the calculations, the more specific the soil investigation will have to be in order to obtain reliable soil parameters. Table 4-3 presents the most common soil parameters for analytical and FEA settlement and stability calculations.

TABLE 4-3 REQUIRED PARAMETERS FOR ANALYTICAL AND FEA CALCULATIONS

Soil parameter	Type of calculation			
	Deformation/Settlement		Stability	
	Analytic	FEA	Analytic	FEA
Vol. Weight (γ and γ_{sat})	x	x	x	x
Cohesion (c')	-	x	x	x
Undrained shear strength (c_u or s_u)	-	-	x	-
Internal angle of friction (ϕ', ψ)	-	x	x	x
Coefficient of consolidation (c_v)	x	-	-	-
Permeability (k)	-	x	-	x
Compression constant (C_p, C_s - C_c, C_{α}, C_{sw} - a, b, c)$^{1)}$ and (λ, κ, μ)$^{2)}$	x	-	-	-
Stress history (σ_g, OCR, POP, K_0)	x	x	-	-
Modulus of elasticity (E, ν, E_{oed}, E_{50}, E_{ur}, G_0, $\gamma_{0,7}$)$^{3)}$	-	x	-	x

Notes: 1. Respectively, for the Koppejan, Bjerrum and a,b,c model. 2. PLAXIS FEA soft soil (SS) and soft soil creep (SSC) model, with or without superscript.* 3. Mohr-Coulomb (MC) model, hardening soil (HS) and HS small (HSS) model.

Characteristic values for the parameters are determined or estimated based on laboratory analysis and correlations with CPTs. NEN 9997-1 art. 2.4.5.2 describes the method for obtaining characteristic values for soil parameters or for their estimation. Testing methods are discussed in greater detail in section 4.5.3.

The calculations are performed on a number of representative cross sections for the requisite variants. Depending on the possible variants, and their influence on the surroundings, an exploratory assessment of vulnerable objects near the crane hardstand is carried out in the preliminary design phase.

Based on the results of the calculations, a decision is made regarding whether additional soil investigation will need to be done for the final design.

4.5.3 TYPES OF SOIL INVESTIGATION

In principle, all the necessary soil investigation must be implemented in the preliminary design phase. In this phase, the soil investigation should be of sufficient scope to comply with all applicable standards and requirements. Appendix C provides an overview of these.

In the preliminary design phase, results from the following types of soil investigation will generally need to be available:

FIELD SURVEYS

- All data from the previous phase or phases
- CPTs
- Borings
- Monitoring wells, as well as water pressure gauges in some cases

LABORATORY ANALYSIS

- Classification of soil types (volume weight wet/dry, water content, undrained shear strength, Atterberg limits) and borehole logs/descriptions
- Compression tests
- Triaxial tests

The laboratory analysis is performed on disturbed and undisturbed samples collected during borings. The compression and triaxial tests always require an undisturbed sample. Some of the classification tests can be performed on an undisturbed sample.

Important guidelines and points to consider when commissioning laboratory analyses are provided the CUR/CROW guidelines for geotechnical laboratory analysis (in Dutch) [21].

Table 4-4 presents the compression and strength parameters to be determined by laboratory tests for the settlement and stability calculations in table 4-3.

TABLE 4-4 PARAMETERS DERIVED FROM LABORATORY TESTS

Test	Parameter**
Compression test (compression)*	Pg, c_v; k; ν; C_p ;C_{s} ;; C_c , C_α ,C_{sw}; C_r; a; b; c; λ; κ; μ; $E_{oed,}$, E_{ur}
Triaxial test (strength)	ϕ' ;c'; E_{50}; ψ, c_u

Notes: * The overconsolidation rate (OCR) and pre-overburden pressure (POP) are also determined. Combined with the preconsolidation pressure P_g, these values describe the stress that a sample has sustained in the past. ** For PLAXIS FEA models only the parameters for the HS model are included. For the other models, such as the SSC and HSS, refer to the PLAXIS manual on material models.

Following on the results from this phase, a geotechnical consultant will carry out a revised geotechnical risk analysis. Risks corresponding to influences on the environment must also be considered in this phase. Any remaining or newly identified risks can then be investigated in more detail in a subsequent phase.

4.5.4 AMOUNT OF SOIL INVESTIGATION

It is difficult to provide general guidelines for numbers of CPTs and borings that need to be done, as these will depend on the expected variation in the soil profile and the presence of weak soil layers.

Information obtained in the sketch and initiation phase about variation in the soil profile is the starting point for determining the amount of soil investigation that needs to be done in the preliminary design phase.

The final decision regarding how much soil investigation to do is made by a geotechnical consultant using a risk-based approach, and will differ from project to project.

When setting up the analyses, it is important to consider whether any vulnerable objects, cables and pipelines might be in the area and need to be given special attention, as well as underground obstacles (such as undetonated explosives), old waterways and the like.

The survey depth will follow from the results of the historical research. Soil investigation should be carried out at least to the depth of influence of the foundation, with the depth of influence of both deformation and strength aspects considered.

Depending on the size and the shape of the crane hardstand, it is recommended that a number of CPTs be done along the perimeter as well as a number of CPTs in the middle of the hardstand area. Irrespective of the size of the platform, at least two CPTs must be carried out at a distance of at maximum 20 m from each other.

To get an impression of the hydraulic head of the different soil layers, at least one CPT with a piezocone is recommended, to measure water pressure in addition to the usual cone resistance and local friction. Having this measurement enables a more precise classification.

The phreatic groundwater level can be measured by placing 1 or 2 monitoring wells at 2-3 m depth along the perimeters of the building site. If the site for the crane hardstand still has to be prepared for development through preloading, depending on the height of the preloading, installation of several water pressure gauges is recommended. For preloading heights of 2 m or less and relatively strong subsoils, no water pressure gauges are necessary.

For crane hardstands on weak subsoils, sufficient borehole data must be obtained. Based on the results of the CPTs that have been done, at least one borehole should be carried out at the edge of the crane hardstand with disturbed and undisturbed sampling along with the corresponding laboratory analyses. The borings can be used immediately to place monitoring wells.

At least one, and preferably three or more, undisturbed samples must be tested for each distinguishable compressible layer to determine characteristic values for both compression and consolidation parameters, as well as strength parameters.

For weak layers that make a large contribution to the predicted stability and settlement (e.g., shallow thick peat layers), it is recommended that at least three samples be tested for strength and compression. More than three samples should preferably be tested, as this enables better estimation of the characteristic values compared to the safe values in Table 2.b of NEN99971 [46]. This fact is also acknowledged in CUR 2008-2 [15].

A borehole is preferably always drilled directly adjacent to a CPT that is considered indicative. The depth of the borehole follows from the results of the CPT analysis; it will generally extend 1 m into solid sand.

For sites developed on a sandy subsoil, short (manual) CPTs can be used to determine whether, for example, improvement of loosely packed sand layers is necessary. This type of investigation will be limited to the uppermost soil layers on the site.

If the crane hardstand is to have a piled foundation, a center-to-center spacing of 25 m should be adhered to for the CPTs. The depth of the CPTs must be at least 5 m under the expected pile tip level, in accordance with NEN 9997-1 [46].

4.6 DETAIL LEVEL: FINE (FINAL DESIGN)

4.6.1 DESCRIPTION

By the final design phase, all the basic choices will have been made for the design, and many for execution. What now follows is their further elaboration. This applies to design aspects as well as to execution methods and scheduling/planning aspects.

In this phase, the data collected must be sufficient to enable detailed designs to be prepared and a project execution plan formulated.

4.6.2 TYPES OF CALCULATIONS

In the final design phase, design and test calculations are performed for all components of the design. Like in the previous phase, here again, standard geotechnical design tools will be used. Depending on the project type, more advanced calculations might also be performed, such as, for example, finite element analyses, to enable more elaborate assessments of soil deformation and stability. Furthermore, in this phase extensive attention will be given to influences on the environment. Key in this regard are horizontal and vertical soil deformation, vibrations and noise.

4.6.3 TYPE AND AMOUNT OF SOIL INVESTIGATION

The soil investigation in the final design phase represents a further refinement of the soil investigation done prior to this point. As a rule, enough soil investigation will be available by this phase to draw up an execution plan.

It can be generally stated that in this phase, only specific problem areas should still be looked at. From earlier phases, the global geotechnical and geological picture of the subsoil should be sufficiently clear.

It is possible, however, for the risk analysis done in the previous phase to give rise to the need for additional study. Ultimately, the soil investigation for this phase has to be of sufficient scope that remedial measures can be established for all of the geotechnical risks identified.

Therefore, no minimum amount of soil investigation can be given for this phase, as it will depend entirely on the particular characteristics of the project.

5

DESIGN

5.1 INTRODUCTION

The design of the crane hardstand is the main focus of this handbook and is elaborated in section 5.2. A crane hardstand design must offer sufficient safety and comply with the prevailing standards. A distinction can be made between the safety of the crane itself, and the safety of the crane foundation. Separate standards are available for the testing of each of these different aspects. In determining the crane loads and testing the soil bearing capacity, consideration has to be given to the differing safety philosophies that apply to these different standards.

The starting points to be used in designing a crane hardstand follow from the specifications provided by the turbine vendor. The starting points below must be known or established:
- Type of wind turbine to be installed
- Type of crane needed to install the wind turbine[1]
- Loads on the crane hardstand
- Bearing pressures and corresponding contact surface areas
- Soil profile, soil parameters, groundwater level and hydraulic head
- Required safety level and risks
- Space requirements
- Functions and geometry of the crane hardstand
- Requirements imposed by the environment

The design of a crane hardstand is then prepared using the starting points given. In doing so, at least the following aspects have to be considered:
- Spatial integration into the environment
- Drainage
- Bearing capacity or load capacity (this generally determines the foundation type)
- Settlement
- Slope stability

The design of the crane hardstand depends, among other things, on the type of turbine to be installed and the crane needed to do the job. This often creates bottlenecks in the design process, because such choices have often not yet been definitively made at an early stage. For this, consensus has to be reached between the different parties involved (turbine vendors, crane hire companies and designers). Important in this regard is the need for consultation between the different parties involved and documentation of the starting points agreed. In particular, the crane loads and ground pressures beneath the crane tracks or outriggers are key starting points and must be identical across all the parties involved. Good alignment in this regard can prevent

1 It is recommended that a crane hardstand not be designed for only one type of crane. Rather, it should be suitable for several crane types. This is because a crane type can change during the design process, and for maintenance and/or disassembly other types of cranes will likely be required or available.

situations in which different parties use different starting points, which can lead to faulty design, the need to adapt the design later and/or underestimation of the geotechnical risks.

Because of the need for consensus on the starting points, it is important to begin designing the crane hardstand at an early stage. This is also important for spatial planning reasons, as permit applications and procedure times may need to be allowed for. But the same applies to the geotechnical design. Starting the geotechnical design at an early stage enables early identification of any geotechnical risks. These risks, such as impacts on the environment and any permits required, can have implications for decisions on which design solution is preferred. Examples are whether or not to use a foundation on piles, and whether to dig ditches to provide drainage for the crane hardstand.

The sections below present recommendations for the design of a crane hardstand. Where possible, a distinction is made between the different design phases (preliminary design or final design).

5.2 THE DESIGN PROCESS

The diagrams in figure 1-1 and figure 1-2 present the design process in context. It is important to recognize that, in most cases, the crane configuration to be used is not yet known when the design process begins. Only at a later stage, just before the construction works start, will the definitive crane choice often be known. Therefore, at the start of the design process assumptions are made regarding the crane, usually based on the following:

1. Specifications from the turbine manufacturer (often limited to a surface pressure that the hardstand must be able to withstand)
2. The expertise of the designer (the designer's expertise is a key factor in the quality of design and ease of installation of the hardstand)

Because the design process begins with assumed values, it is of utmost importance that a verification take place of whether the installed platform is in fact adequate for the specific crane configuration ultimately chosen. This verification establishes the platform's suitability for the chosen crane. Such verification has to be done well before the lifting operation begins. All too often this is not done, even now, or it is not done in time, resulting in damages or delays in the lifting operation.

It is in the interest of all parties involved (turbine vendors, crane hirer, civil contractor, client) that such a verification take place. The verification of the hardstand should preferably be done by the person who prepared the design, but the choice could also be made for an independent verification party.

Another point to consider in this process is the assumptions that were made before the design was prepared. Sometimes a lower design load is deliberately assumed, for reasons of economy. Doing so sets the stage for the need to use extra crane mats to spread the crane load over a wider surface area. Doing this, in fact, shifts part of the design responsibility to another party (often the crane hirer). It must be realized, however, that the crane hirer does not have the expertise needed to determine whether the mats provide enough load spreading. The load spreading that the mats can provide is dependent on stiffnesses and stiffness ratios of mats to the ground beneath. It is therefore strongly advised that the mat configuration be included from the very start in the design of the crane hardstand.

5.3 SAFETY LEVEL AND RELIABILITY CLASSES

The design of a crane hardstand must offer adequate safety and comply with the prevailing standards. As noted, a distinction can be made between the safety of the crane itself, and the safety of the crane foundation. Each of these aspects is addressed in a separate standard.

Along similar lines, with regard to standards a distinction can be made between crane stability and foundation stability. The safety of the crane is guaranteed in NENEN 13001-2 [53], while the safety and stability of the crane foundation are addressed in the civil design standards NEN 99971 [46], NEN-EN 1990 [50] and NEN-EN 1991-1 [51].

This handbook does not in fact concern the stability of the crane and crane components themselves, but rather the stability of the foundation of the crane hardstand. Of course, in testing foundation stability, the load capacity of the subgrade and the loads emanating from the crane do play an important role.

A key point to keep in mind when determining crane loads and testing load capacity is the need to apply the different safety philosophies of the lifting equipment/crane standards and the civil design standards. In essence, the partial load factors in the lifting equipment/crane standards are not valid for loads pursuant to civil applications.

The approach taken in this handbook is to view the crane loads on the hardstand, which are supplied by the crane hirer, as representative loads. The design load values for testing the stability of the foundation of the crane hardstand are then determined using the partial factors from the civil standards.

When designing a crane hardstand, a choice of safety level has to be made. The safety level is defined according to NEN-EN 1990 [50] in reliability classes: RC1, RC2 or RC3. The reliability class chosen determines which safety factors are to be used in the calculations for the design.

The reliability classes (RC) are directly linked to consequence classes (CC). By categorizing the crane hardstand in a reliability class, the consequences have to be explored if the crane hardstand should ultimately fail. This exercise must include the following aspects:

- The risk of loss of lives due to failure
- The risk of economic and social consequences for the environment in case of failure
- The failure of the crane hardstand causing the crane to tip over
- For hardstands for tall cranes (hook height up to 150 m) the size of the area that could be affected by failure of the hardstand is considerable. For every design and site, specific characteristics of the environment have to be considered: the failure of a crane hardstand in an agricultural area would have very different economic and social consequences than the failure of a crane in a busy port.
- In consultation with the client, consideration could be given to including economic damages to the wind farm if the hardstand should fail (delays in completion) in reliability class determination.

In practice, based on the aforementioned aspects, crane hardstands for wind turbines are often categorized in classes RC1 or RC2, depending on the environment in which the turbine is being built (RC1 for crane hardstands in rural areas, RC2 for crane hardstands in urban or industrial areas). If economic damages to the wind farm are included in the failure consequences, the crane hardstand will generally be categorized in the RC2 class. Crane hardstands that are constructed within the core area or protection zone of a primary flood defense are categorized in the RC3 class.

In conformance with NEN-EN 9997-1 [46], all geotechnical calculations must be tested according to design approach 3, with the application of partial load factors on representative loads or load effects and partial material factors on the characteristic material properties (soil parameters). The partial load factors and material factors for the design are found in Appendix A of NEN-EN 9997-1 [46].

It should be noted that material factors cannot always be derived per reliability class RC1, RC2 or RC3 for all geotechnical mechanisms. Only for the geotechnical mechanism 'general stability' can material factors be chosen for the three reliability classes. For a shallow foundation, the material factors are independent of the safety class.

5.4 LOADS AND LOAD COMBINATIONS

Turbine vendors often set requirements for the crane hardstand in the form of a maximum allowable bearing pressure; for example, 250 kN/m^2. However, it is strongly advised not to prepare the design of a crane hardstand based on such a requirement.

This is because it is the bearing forces that arise (under the outriggers or tracks) in combination with the corresponding contact surface area that is of real importance. The design has to be prepared based on a specific crane and lifting situation. Chapter 3 discussed the commonly used crane types, including indicative values for their loads as well as outrigger and crawler dimensions.

Note: The bearing pressures and corresponding contact surface areas on the crane hardstand can be determined only if the following data are known:
- *Type of crane, including ballast and any superlift ballast employed*
- *Weight of the components to be lifted*
- *Lifting plan for erecting the boom and lifting in the turbine elements*

These data are often not yet known at the early stages of hardstand design (sometimes they may not even be known when the final design of the hardstand is being prepared). In those cases, the outrigger forces or bearing pressures and corresponding contact surface areas have to be estimated based on a representative crane and lifting situation, so that a hardstand design can nonetheless be prepared. If this is done, it is absolutely essential that, prior to the start of the lifting operation, the expected outrigger forces or bearing pressures and corresponding contact surface areas are computed based on the lifting plan with the specific crane that is being utilized.
This means that the design of the crane hardstand has to be tested based on these actual expected outrigger forces or bearing pressures with the corresponding contact surface areas. If it turns out to be necessary, the design of the crane hardstand must be adapted or additional measures devised.

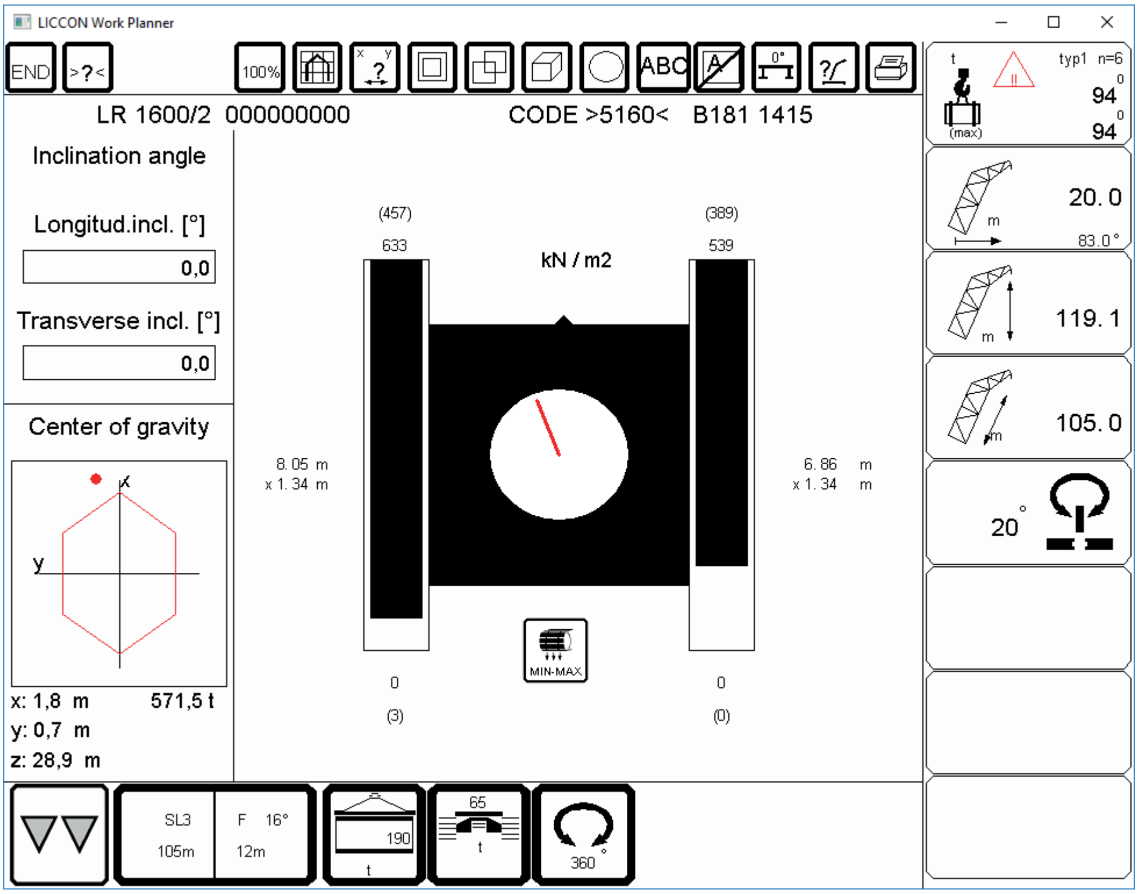
The starting point for determining the loads on the crane hardstand is a load diagram, drawn up for a specific crane and specific lifting situation. This is often prepared and supplied by the crane hire company. Based on this input, the necessary design load values can be obtained for testing the load capacity of the hardstand. Figure 5.1 summarizes the steps required to do this, and these are explained step by step in the sections below. Where necessary, a distinction is made between outrigger cranes and crawler cranes.

FIGURE 5-1 DIAGRAM FOR DETERMINING LOADS AT THE FOUNDATION LEVEL OF A CRANE HARDSTAND

5.4.1 STEP 1: INPUT CRANE LOADS

Figure 5-2 provides an example of the type of load diagram from software to determine the loads exerted by a crane on the ground beneath.

FIGURE 5-2 EXAMPLE OF A LOAD DIAGRAM FOR A 600-TON LR 1600/2 CRAWLER CRANE



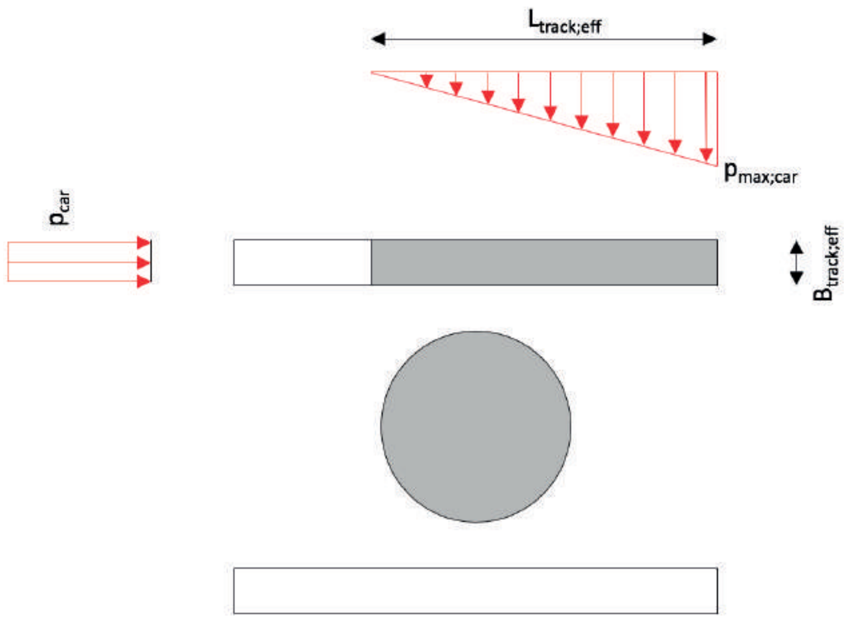
Key points in determining the crane loads on the foundation are presented below.

- Governing situations are used in calculating the outrigger forces or bearing pressures and corresponding contact areas. The following situations can be governing:
  - Erecting the main boom
  - Lifting a governing component (this can be the heaviest component, or the component for which the greatest radius has to be traversed)
  - Storm conditions: without lifting a component but with the boom raised
- Ensure that the correct combinations of loads and lifting orientations are used. If a load first has to be picked up from behind the crane and then put down around the front, then all the relevant orientations must be considered.
- For crawler cranes, keep in mind that the effective track length and width is often not the same as the total track length and width, because the entire length and width will not necessarily be in contact with the ground.
- In determining the outrigger forces or bearing pressures and corresponding contact surface areas, the software currently used by crane hire companies makes no allowances for the effects of wind loads. Because the cranes used to install wind turbines generally have an extremely long boom, the wind loads on the crane and on the component to be lifted can be substantial. The wind load can increase outrigger forces or bearing pressures by

tens of percentage points (for more on this, see section 3.5.3). The wind load also produces a horizontal load that is transferred via the crane to the ground beneath (see section 5.4.3). Until manufacturers have adapted their crane software, it is recommended that crane hirers consult the manufacturer on the effects of wind on vertical loading for the combination of a crane with a boom longer than 100 m and an extremely heavy and wind-sensitive load (for example, a fully assembled rotor star).

For outrigger cranes, an indicative vertical load on an outrigger plate will be supplied. For crawler cranes, a pressure diagram is given (with either a trapezoidal or triangular distribution), including a maximum bearing pressure from the crawler tracks on the ground beneath with the corresponding contact surface area (see figure 5-3 for a schematic diagram).

FIGURE 5-3 SCHEMATIC DIAGRAM OF LOAD FROM CRAWLER CRANE (FOR 1 CRAWLER TRACK)

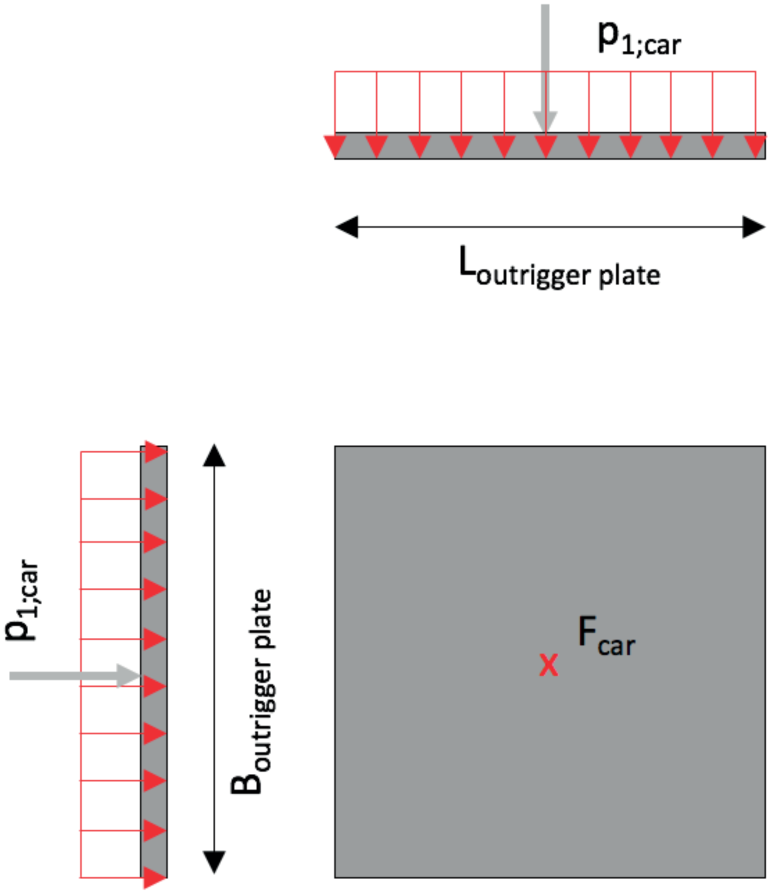


5.4.2 STEP 2: DETERMINE THE EFFECTIVE CONTACT SURFACE AREA

To determine the effective contact surface area between the machine and the crane hardstand a distinction is made between outrigger cranes and crawler cranes.

For outrigger cranes, the dimensions of the steel outrigger plates has to be known. Assuming that the outriggers are positioned centrally on these outrigger plates, the effective surface area is equivalent to the surface area of the outrigger plate. Figure 5-4 presents a schematic diagram of the load distribution over an outrigger plate.

FIGURE 5-4 SCHEMATIC DIAGRAM OF THE DISTRIBUTION OF A LOAD OVER AN OUTRIGGER PLATE FOR AN OUTRIGGER CRANE



For loads from crawler cranes, the effective surface area has to be considered. This relates to the fact that the load distribution under the tracks is not constant, but changes with lifting movements. Figure 5-5 provides an example of the bearing pressure beneath crawler tracks.

FIGURE 5-5 EXAMPLE OF BEARING PRESSURE BENEATH THE CRAWLER TRACKS OF A CRAWLER CRANE

Position	Left track		Right track	
1	A 455.2 kN/m²	C 135.9 kN/m²	B 455.2 kN/m²	D 135.9 kN/m²
2	A 465.1 kN/m²	C 239.0 kN/m²	B 352.1 kN/m²	D 126.0 kN/m²
3	A 375.4 kN/m²	C 375.4 kN/m²	B 215.7 kN/m²	D 215.7 kN/m²

The effective load surface area is calculated in conformance with section 6.5.2.2 (b) of NEN 9997-1 [46].

$$b' = B - 2 \cdot e_B \quad (5.3)$$

$$l' = L - 2 \cdot e_L \quad (5.4)$$

where:

B = the length of the short side of the contact surface area [m]

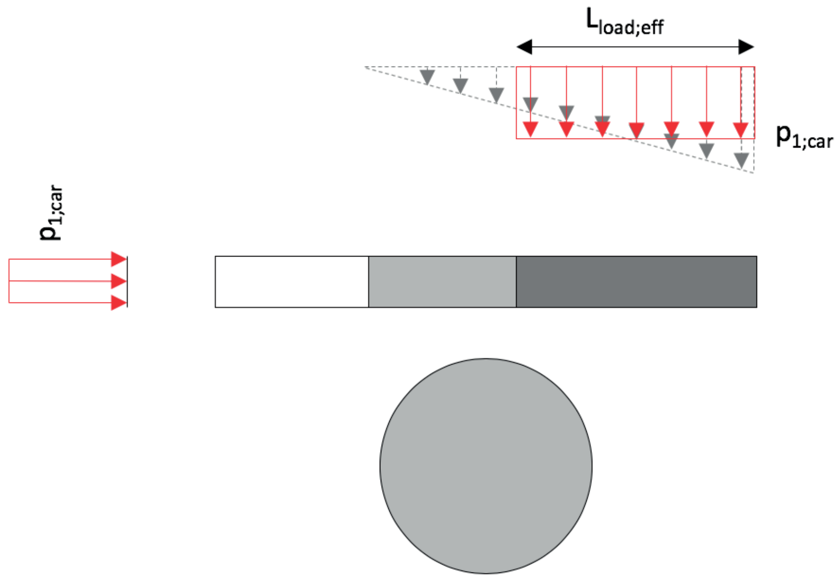
e_B = the eccentricity in the widthwise direction relative to the center point of the contact surface area [m]

L = the length of the long side of the contact surface [m]

e_L = the eccentricity in the lengthwise direction relative to the center point of the contact surface [m]

Figure 5-6 presents a schematic diagram of the conversion from a triangular load to a uniformly distributed load.

FIGURE 5-6 SCHEMATIC DIAGRAM OF CONVERSION FROM A TRIANGULAR LOAD TO A UNIFORMLY DISTRIBUTED LOAD (FOR ONE CRAWLER TRACK)



In cases where the bearing pressure beneath the outrigger plate or crawler track is greater than allowed for the bearing capacity of the ground, the bearing pressure can be reduced using supplementary load spreading mats or plates. The size and configuration of these mats then determines the bearing capacity analysis to be performed.

In incorporating the load spreading effect of the mats or plates, the following three aspects must be taken into account:

1. The extra load resulting from the weight of the mats has to be added to the loads from the crane.
2. Eccentric placement of the crawler tracks or outrigger plates on the mats: Because of this eccentricity the loads are not spread over the entire surface area of the mats, which must then be taken into consideration.

3. The surface area over which the mats can actually distribute the load has to be determined based on the difference in stiffness between the mats and the ground below. In many cases, it will be overly optimistic to calculate with a load distribution over the entire mat surface area, especially when relatively long mats are used on a stiff underground.

Figure 5-7 and figure 5-8 present schematic diagrams of how the load is further spread using mats.

FIGURE 5-7 SCHEMATIC DIAGRAM OF LOAD SPREADING BY MATS FOR AN OUTRIGGER CRANE

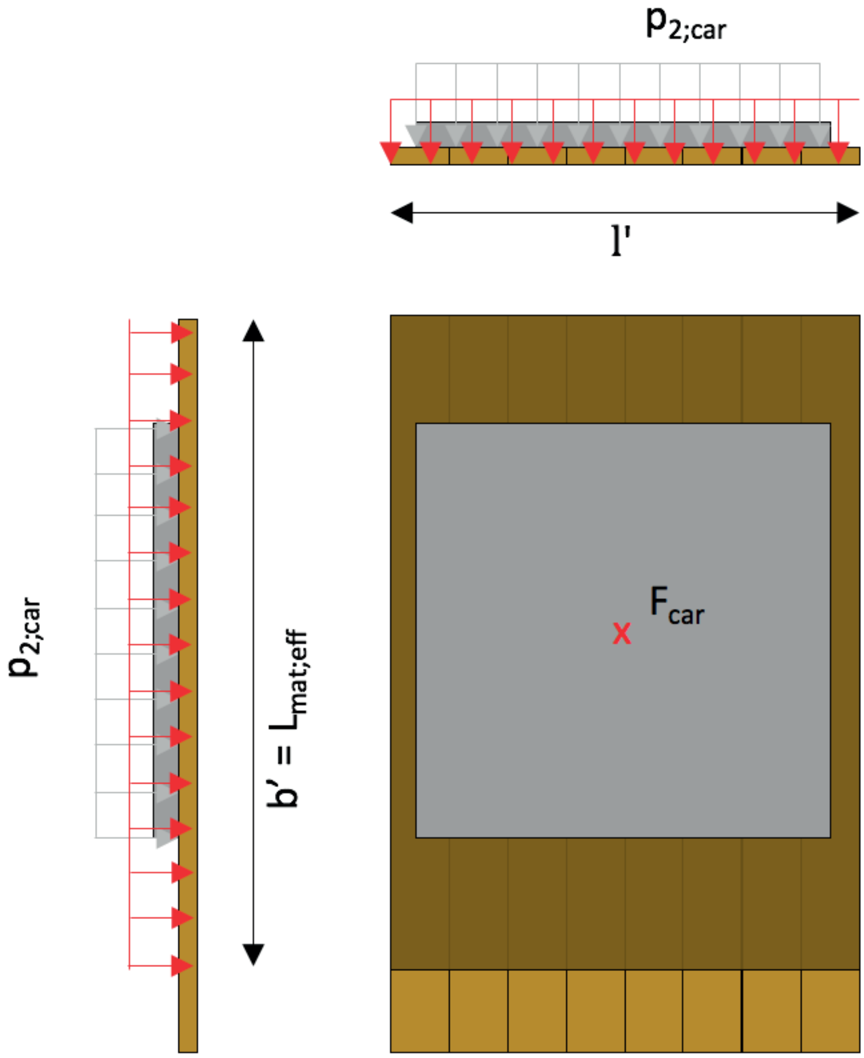
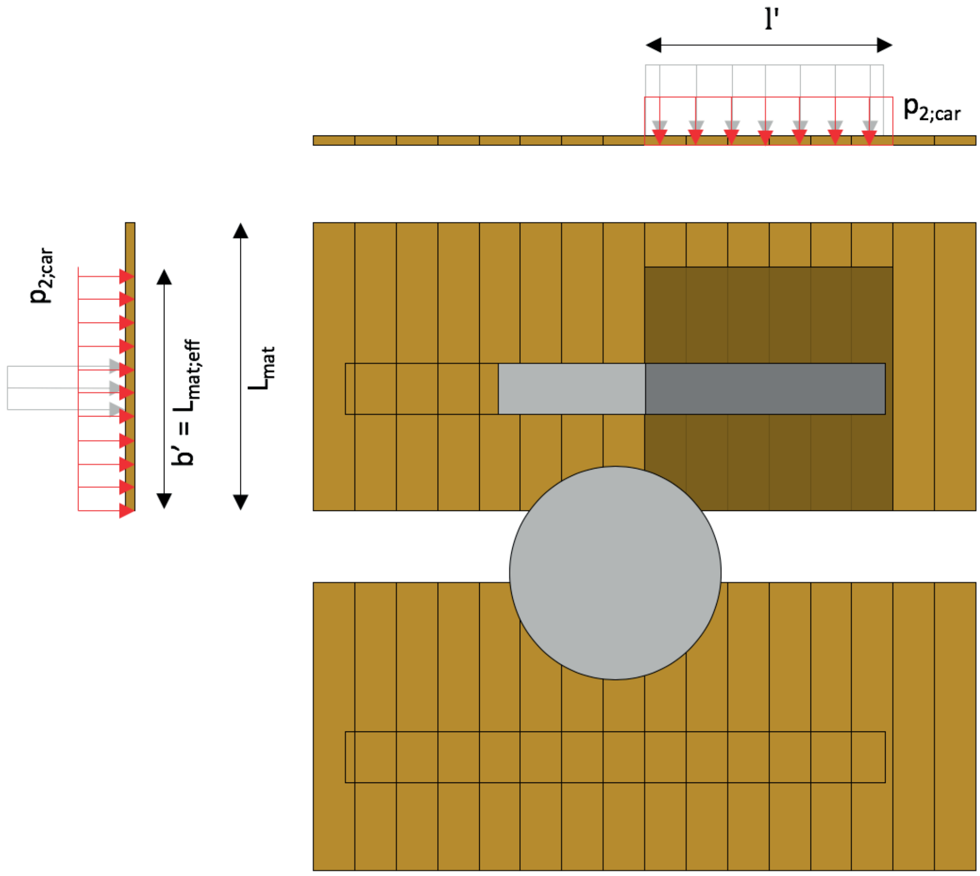


FIGURE 5-8 SCHEMATIC DIAGRAM OF LOAD SPREADING BY MATS FOR A CRAWLER CRANE (1 CRAWLER TRACK)



Sections 4.4 and 4.5 of the CUR/CROW publication "Accessibility of Building Sites: Geotechnical Bearing Capacity for Foundation Rigs" (in Dutch) [27] present further information about how to determine the effective contact surface area for foundation equipment. In it, a distinction is made between a situation where equipment is placed directly on a hardstand surface (section 4.4) and on mats (section 4.5). Furthermore, Appendix C of that same publication provides an example calculation for foundation loads.

5.4.3 STEP 3: HORIZONTAL LOADS

Horizontal loads can act on the foundation of the crane. These arise from a wind load on the crane and/or the component to be lifted, and due to the rotational movements of the uppercarriage of the crane. For outrigger cranes, horizontal loads arise at the outriggers as a result of deformation of the outriggers due to the vertical load. Horizontal loads can also arise due to driving movements of the crane (for crawler cranes). These, however, will have the character of a short-acting impact load. The horizontal load on the crane produces a non-uniform vertical load under the outriggers or crawler tracks, as well as a horizontal load at the foundation level. The horizontal load at the foundation level will be transferred to the ground through friction between the outrigger plates/crawler tracks/dragline mats. These horizontal loads can have a substantial implications for the design, especially for a shallow foundation, but also for piled foundations. Whether horizontal loads can arise must therefore always be considered.

The following can be adhered to as rules of thumb, depending on the type of crane, for the magnitude of the horizontal loads at the foundation level:

- For outrigger cranes, the horizontal load equals at least 30% of the vertical load or 10% of the maximum permissible outrigger force in conformance with the operating manual of the machine.
- For crawler cranes, the horizontal load equals 5% to 10% of the vertical load. Adherence to a value of 10% is recommended. Note that this value applies to stationary cranes; the horizontal loads resulting from moving cranes can be considerably larger.

The aforementioned rules of thumb were derived based on measurements performed by Liebherr on a variety of crane types. Note that these rules of thumb were derived based on current, ongoing research by Liebherr and reflect the knowledge available at the time of this writing. If, after release of this handbook, new rules of thumb or values for horizontal loads become available from follow-up research, those rules will supersede the rules of thumb cited here.

Using the percentages above, the horizontal loads on the working surface can be obtained if the vertical loads are known.

Another option is to determine the horizontal loads on the crane. To obtain the wind load on a crane, additional information can be found in section 4.3.3 of the CUR/CROW publication "Accessibility of Building Sites: Geotechnical Bearing Capacity for Foundation Rigs" (in Dutch) and in ISO 4302 [39]. Keep in mind, however, that it will not necessarily be possible to use the design wind load to obtain a realistic value for the vertical pressures under the outriggers or crawler tracks of a crane. This is because for cranes with a boom longer than 100 m, the increase in vertical pressures under the outriggers or crawler tracks due to wind are largely the result of elastic deformation of the boom (and corresponding second-order effects). Only the crane manufacturer has the ability to determine this increase correctly. For further information, see section 3.5.3.

5.4.4 STEP 4: LOAD COMBINATIONS

When combining vertical and horizontal loads, the designer can select governing load combinations, whereby governing values for both loads do not necessarily have to be taken together. An example is the question of the extent that horizontal loads on the crane have to be considered in the situation of erecting the boom, as the wind loads on the crane will be considerably lower in this operation than when there is a fully raised boom and a load on the hook. For this the designer will have to weigh the effects expected in each situation, based on the loads expected to arise on the foundation. In this exercise, the origin of the horizontal load has to be considered: for outrigger cranes, the horizontal loads originate (as far as we know) from deformation of the outrigger feet as a result of the vertical load. Wind load, thus, has minimal influence in this case. For crawler cranes, the wind load makes a much larger contribution to the horizontal load.

In determining load combinations, formulas 6.10a and 6.10b are used as well as the guidelines in section 6.4.3.1 of NEN-EN 1990 [50]. Of key importance here is the ratio of permanent and variable loads.

5.4.5 STEP 5: STATIC VERSUS NON-STATIC LOADS

The loads provided by the crane hire company are generally static or quasi-static loads. Wind loads are usually considered to be a quasi-static load. In addition to these static or quasi-static loads, dynamic loads can arise; an example of a dynamic load is a sudden slewing of the crane.

In conformance with NEN 9997-1, art. 2.4.2 [46], the load duration must be taken into account in the geotechnical testing, considering the time effects in the material properties of the ground. Concretely, this means that in the drained analysis of load capacity for poorly permeable subsoil, short duration loads need not be considered. In the undrained analysis of the load capacity of poorly permeable subsoil, these short duration loads do need to be considered.

Here, a load is taken to be of short duration if its duration is relatively very small compared to the hydrodynamic period of the subsoil. In a lifting operation for a wind turbine, a large component of the loads (own-weight load, effects of wind and rotation of the crane) can be considered loads of short duration. In conformance with NEN 9997-1 [46], the undrained and drained situation must be tested separately, with the governing situation adhered to.

5.4.6 STEP 6: DESIGN LOAD VALUES

The loads as given by the crane hirer must be considered characteristic values, unless explicitly stated otherwise. For the purpose of designing the crane hardstand, load factors have to be applied to these. The size of the load factor must be justified by the designer, taking into account the fact that there is a permanent component and a variable component in the load on the crane hardstand. Analogous to the CUR/CROW publication "Accessibility of Building Sites: Geotechnical Bearing Capacity for Foundation Rigs", it is recommended that permanent loads be considered loads that cannot change in size or direction. In most cases these will be confined to the own-weight of any dragline mats used and of the undercarriage of the machine. The variable loads are the loads that can change in size or direction. These include loads from the own-weight of the uppercarriage and all the attached elements (including the lifting load among other things), along with the loads acting on them.

Partial factors must be adhered to in conformance with NEN 9997-1 Table A-3 [46].

5.5 STARTING POINTS

5.5.1 FUNCTIONS OF THE CRANE HARDSTAND AND INTERFACES

Before the design of the crane hardstand can be prepared, it must first be clear what functions the crane hardstand must be suitable for. Of course, the most important function is to offer a load-bearing working surface for lifting the turbine components. However, other functions can also be important in the design, for example:

- *Temporary storage of turbine components.* These loads also have to be considered when preparing the design
- *Use during construction of the turbine foundation.* Here there is an interface with the builder of the turbine foundation with regard to planning and loading:
  - With regard to planning, it is generally advisable to have the crane hardstand completed before the turbine foundation is built.
  - With regard to loading, a factor that must be considered is the often heavier weights of foundation rigs (in terms of total weight) compared to the weights involved in transporting the crane and turbine components.

    In addition, there can be an interface between the load on the crane hardstand and the turbine foundation. An example is soil deformations under the crane platform, which can exert a horizontal load on the piles under the wind turbine.
- *After installation, in the maintenance phase of the turbine.* In this phase, the crane hardstand is

sometimes used for storage by third parties (for example, farmers). This can be considered in the design choices made. Disputes about damages to hardstands can be avoided if clear agreements about such usages are reached early on.

5.5.2 SPACE REQUIREMENTS

When designing a crane hardstand, the space needed will have to be determined. Moreover, the space needed in the execution phase may be different than in the operation and maintenance phase.

EXECUTION PHASE

The space requirement during the execution phase is determined by the following factors:

- Type of crane to be utilized, including its turning circle and the space necessary for set-up
- Any superlift ballast to be used, as this requires considerably more space behind the crane
- Number of auxiliary cranes required for crane assembly or tailing operations
- Means of delivery. With 'Just In Time' (JIT) delivery, components are taken directly off the transport vehicle and anchored and installed onto the crane. With 'storage on site', the components are placed within the crane's reach on the hardstand (and/or on an extra assembly area adjacent to the hardstand within the lifting reach of the cranes) and there further prepared for installation. If that last option is chosen, the crane hardstand will need a larger surface area.
- Any compensation for increased paved surface area due to construction of the crane hardstand
- The user of the land. For example, farmers do not like small unused corners, in which case the developer and farmer may jointly agree to pave unused corners as part of the crane hardstand.

OPERATION AND MAINTENANCE PHASE

The space required for the crane hardstand during the operation and maintenance phase is determined by the type of crane to be used for maintenance. If a smaller area is required than in the execution phase, the decision may be made to remove part of a hardstand after turbine completion.

One consideration to keep in mind when determining space requirements is the need for adequate space to respond to a calamity. In this regard, in addition to costs and risks, the location of the crane hardstand will play a role. For example, if a hardstand is located on or near a primary flood defense, having a full-scale permanent hardstand will be of essential importance so that appropriate action can be taken immediately if a calamity strikes.

5.5.3 DRY ZONE AND DRAINAGE

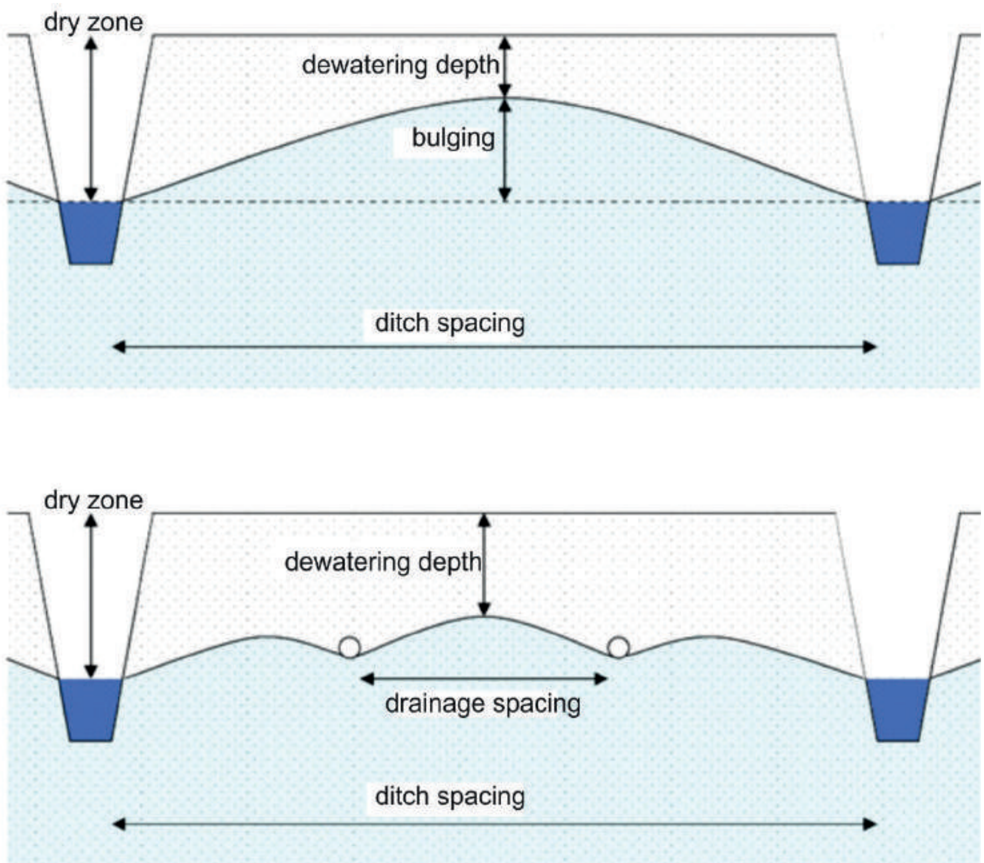
For good bearing capacity, the top part of the crane hardstand must be dry and stay dry. In practical terms, this means, first, that good rainwater drainage is needed, and second, that the groundwater level at the crane hardstand site cannot rise too high due to fluctuations or bulging of the phreatic groundwater level. This requirement can be met by ensuring an adequate dry zone and dewatering depth. Figure 5-9 schematically presents what is meant by the terms dry zone and dewatering depth.

The dewatering depth for a crane hardstand must be such that adequate bearing capacity is ensured and frost/thaw damage is prevented. For crane hardstands, a minimum dewatering depth of 0.70 m is used (this depth is also often employed for construction sites). That means the top of the capillary rise of groundwater in the foundation structure must remain at least 0.70 m beneath the hardstand surface.

The capillary rise is dependent on the foundation material used. For sand with an average grain diameter (d50) of 100-200 μm, the rise is approx. 0.3 m. Thus, if sand is used as the foundation material, a dry zone of 1.0 m is required from the top of the hardstand surface to the water level in the waterways (ditches).

The required dry zone can be reduced by using a freely-draining unbound aggregate base. The capillary rise is then so slight (< 0.10 m) that a dry zone of 0.80 m can be adhered to.

FIGURE 5-9 DEWATERING DEPTH AND DRY ZONE [1]



For adequate drainage, it is important for the surface of the crane hardstand to be sufficiently level. In addition, how the hardstand is finished is important. For example, is it to be finished with a permeable rubble layer or with much less permeable asphalt?

The crane type dictates requirements regarding slope. For a crawler crane, extremely strict requirements govern the permissible slope of the crane hardstand. For outrigger cranes these requirements are less strict. Section 3.4.1. discusses the requirements regarding levelness. Slope can be a necessary or least-costly solution for drainage of the crane hardstand. The drainage method employed must be coordinated with the different parties involved. This is important to avoid situations where, for example, crops next to a crane hardstand are submerged and damaged as a result. Water authorities can also require application of water compensation measures.

Finally, thought has to be given to the discharge of the rainwater that falls onto the crane hardstand. For this, trenches or ditches are often dug around the platform. Any such trenches and ditches will, however, negatively influence the bearing capacity of the platform. Therefore, the design of mechanisms for drainage and discharge need to be known and factored into the tests of the geotechnical load capacity.

An example of a water management measure to prevent undesirably high water levels on the crane hardstand is installation of horizontal drainage conduits in the foundation of the platform. A vacuum pump can be connected to these later if needed.

If preloading, in the form of a temporary extra layer of fill, is employed before hardstand construction, the risk of drain compression and blockage has to be considered, due to the substantial pressures preloading puts on the drains. Use of alternative drainage options can also be explored, such as gravel-filled drainage sinks or verge drains outside the primary load area.

5.5.4 SOIL PROFILE AND PARAMETERS

For reliable modelling, the strength parameters of the subsoil and foundation material must be known. Thorough soil investigation, interpretation and documentation is part of this. The methodology presented in Chapter 4 can be used to determine the required type and amount soil investigation in a risk-based fashion.
For safety tests, both characteristic and design values must be used for both the geometric and the soil parameters.

LAYERING

The subsoil is seldom homogeneous. The layering profile and corresponding layer heights relative to NAP (Normaal Amsterdams Peil) need to be understood. In an undrained situation, a thin cohesive layer is apt to be governing for the load capacity. Careful estimates must be used in determining the divisions between the layers.

STRENGTH AND COMPRESSION PARAMETERS

The characteristic values for the strength and compression parameters are determined or estimated based on NEN 9997-1 [46] Table 2.b and/or sampling based on statistical analyses. The methods are described in NEN 9997-1, art. 2.4.5.2. Soil parameters for the subsoil layers are often taken from Table 2.b. An important point to note here is that the soil parameters correspond to effective stresses of 100 kPa. For other stress levels, the table value must be corrected in line with art. 2.4.5.2.

Because the values from Table 2.b are conservative safe values, use of Table 2.b is a good option for the sketch and initiation phase. It is recommended that upon the start of the preliminary design phase, field and laboratory analyses also begin. Expertly chosen field and laboratory analyses can prevent any overestimation or underestimation of the strength and compression parameters.

The relevant strength parameters are:

- Internal angle of friction φ' [°]
- Effective cohesion c' [kPa]
- Volumetric weight (saturated and unsaturated) $\gamma_{sat}/\gamma_{nat}$ [kN/m^3]
- Undrained shear strength c_u [kPa]

The relevant compression parameters for, for example, Koppejan's model are the following:

- Primary compression constant C_p [-]
- Secondary compression constant C_s [-]

Strength and settlement calculations can be performed using different calculation models. The type of calculation dictates the type of soil parameter. If the design is prepared using a finite element method, more parameters will be required, depending on the soil model used. Important parameters are, in all cases, the neutral earth pressure coefficient K_0 and the modulus of elasticity E_{50}. Sections 4.5.2 and 4.5.3 provide an overview of the soil parameters required for the different types of calculations and the type of soil investigation needed to determine them.

In conformance with NEN-EN 9997-1 [46], design values for the strength parameters of the subsoil must be used in testing the geotechnical design. These are to be determined, in conformance with NEN 9997-1 art. 2.4.6, through application of partial factors to the characteristic values for the soil parameters and the indicative load values.

The partial factors differ, among other things, for the different failure mechanisms (bearing capacity or stability) and intended safety level (reliability class). It should be noted that material factors are not always derived for all geotechnical mechanisms per reliability class (see also section 5.3).

5.6 OPTIONS FOR FOUNDATIONS

This section briefly discusses some of the most commonly used design options or solutions for foundations for a crane hardstand at a wind turbine site. The most appropriate design should preferably be selected on the basis of a so-called decision matrix, or trade-off matrix (TOM). Useful information on the various alternatives can also be found in CUR 2006-2 (in Dutch) [11], which presents a number of approaches for designing road foundations on soft soil.

5.6.1 SHALLOW FOUNDATIONS

For shallow foundations, a foundation layer is laid on the supporting ground. It can be placed directly on the ground at the existing surface level, or it can be sunken into a shallow excavation or pit. The pit is a limited dug-out area where the top layer of soil is replaced by foundation material (once this is done it can, technically speaking, already be classified as a shallow foundation with soil improvement, as defined in section 5.6.2). For better load spreading, a layer of mats can then be laid on the foundation.

PHOTO 5-1 SHALLOW FOUNDATION WITH DRAGLINE MATS UNDER A CRAWLER CRANE

Advantages of a shallow foundation:
- Relatively inexpensive method
- Simple to execute over a large surface area
- No permanent foundation elements need to be placed in the supporting ground

Disadvantages of a shallow foundation:
- Risk of soil settlement due to increased load
- Limited applicability on sites with a low bearing capacity subsoil and/or a relatively high groundwater level

5.6.2 SHALLOW FOUNDATION COMBINED WITH SOIL IMPROVEMENT

If the soil bearing capacity is inadequate for a shallow foundation, the bearing capacity can be increased by substituting all or part of the poor bearing capacity soil with stronger material (sand/aggregate, etc.).

5.6.3 SHALLOW FOUNDATION REINFORCED WITH GEOSYNTHETICS

In a shallow foundation, the foundation layer serves, among other things, to spread the imposed loads over the ground beneath. To increase the spreading obtained with the foundation layer, it can be reinforced using one or more horizontal layers of a geosynthetic/geogrid. Another example of such reinforcement is the use of geocells. With these, a foundation layer is built up using geosynthetics with a three-dimensional honeycomb structure. The open spaces are then filled with foundation material, producing a very rigid foundation layer.

Use of geosynthetics in foundation layers creates an interlocking effect that increases load spreading to such an extent that the bearing capacity of the hardstand as a whole is greatly increased. The strength, stiffness and durability (service life) of geosynthetics and their installation specifications (depth, number of layers) are important in determining the behavior of the structure as a whole.

Geosynthetics can be a good option in cases where insufficient structural integrity can be obtained with a normal shallow foundation with soil improvement. For more information on the design/execution of geosynthetic-reinforced foundations, refer to the CUR/CROW publication on the topic (in Dutch), published in December 2017 [20].

PHOTO 5-2 STRUCTURE OF A HARDSTAND FOUNDATION USING A MIXED AGGREGATE REINFORCED WITH A GEOSYNTHETIC (MULTIPLE LAYERS OF HORIZONTALLY-LAID GEOGRIDS)

PHOTO 5-3 STRUCTURE OF A MIXED AGGREGATE PLATFORM FOUNDATION REINFORCED WITH A GEOSYNTHETIC (HORIZONTALLY-LAID GEOGRIDS)

5.6.4 SHALLOW FOUNDATION COMBINED WITH SOIL MIX/MIXED-IN-PLACE (MIP/MASS STABILIZATION)

If the bearing capacity of the subsoil is inadequate for a shallow foundation, the bearing capacity can be increased by adding stronger materials and mixing them into the poor bearing capacity layers (e.g., soil mix, mixed-in-place, mass stabilization), thus improving the subsoil characteristics.

Soil mix techniques include methods that use mass stabilization or soil mix constituents where poor bearing capacity soil layers (clay/peat) are mixed in their entirety with a binding agent (cement, lime). These can be a good option for sites with relatively shallow, weak layers (e.g., 3-4 m); though mixing to a greater depth is also possible (max. approx. 20 m).

Where the different soil layers have very different properties, it is of utmost importance to look at types of stabilization techniques (cutter soil mixing, tubular soil mixing, milling systems), to obtain as homogeneous a mix of soil layers and binding agents as possible.

A feasibility study must be done beforehand, with a geotechnical laboratory determining the required mixing ratio between soil and binding agent. After processing, the soil mix material needs time to develop its strength (28 days). Following the development time, the obtained parameters have to be checked and validated against the design specifications.

Regarding factors to consider in the design and implementation of soil mix/mixed-in-place solutions, refer to the CUR/CROW manual on soil mix wall design and execution (in Dutch), 2016 [23]. Although this manual was written for soil mix wall applications, it also contains a wealth of information about possible implementation methods, design, derivation of parameters and quality assurance.

5.6.5 FOUNDATION ON A PILED EMBANKMENT

A piled embankment consists of a ground body reinforced with geosynthetics (a ‘raft’) on a piling foundation. By using arching in the raft structure, the loads acting on the raft are transferred to the relatively stiffer part of the construction: the piles. A piled embankment is a suitable foundation for a crane hardstand in situations where the subsoil profile has poor bearing capacity. Photo 5-4 shows a piled embankment foundation under construction.

For more information on the design and execution of piled embankment foundations, refer to the CUR/CROW publication on the topic (in Dutch) [22].

PHOTO 5-4 **PILED EMBANKMENT**

5.6.6 FOUNDATION ON A FOOTING WITH PILES

For a footing with a piled foundation, separate concrete foundation footings on a pile foundation are built for the crane. This solution is also suitable for situations where the subsoil profile has a poor bearing capacity. Photo 5-5 shows a foundation on a footing with piles under construction.

PHOTO 5-5 **CONCRETE-FOOTED PILE FOUNDATION, STEEL REINFORCEMENT IN PROGRESS**

5.6.7 COMPARING THE OPTIONS (TRADE-OFF MATRIX)

The choice for a particular option can be made based on a decision matrix or trade-off matrix (TOM). Appendix D presents a brief TOM showing how the different types of foundations score on various aspects. This matrix was created to aid comparisons of the different foundations solutions in various regards. The scores it presents reflect how the foundation options perform. The matrix can help guide thinking in the preliminary design phase about the different foundation options. In parallel, of course, the technical feasibility of any preferred alternatives must also be explored.

Note that the scores in the TOM should be interpreted as indicative. Deviations from them are possible in certain situations if appropriate justifications are provided. Moreover, each project will differ in the importance attached to the various factors in the overall assessment.

Explanatory notes for the various aspects considered in the TOM are presented below.

- *Minimizing interfaces with the turbine foundation.* This concerns both physical interactions between the pile foundation of the wind turbine (if inclined piles are used) and the piles beneath a piled embankment foundation, as well as interactions due to the load exerted by the piled embankment on the pile foundation of the wind turbine.
- *Minimizing influences on the geohydrological state.* Both during the construction phase (drainage for the purpose of temporary excavations) as well as in the definitive situation or after removal (creation of seepage paths by pile removal).
- *Robustness to uncertainties in subsoil strength.* How robust is the design if the subsoil turns out to be weaker than expected? Would this have significant implications for the design, or only lead to minimal adaptations?
- *Robustness to differential settlements.* Consider here both differential settlements occurring during the lifting operation and long-term differential settlements across the crane hardstand.
- *Suitability of design if there are slopes nearby.* How suitable is the design if there are slopes near the crane hardstand or if slopes need to be created? Would this have significant implications for the design, or only lead to minimal adaptations?
- *Minimizing building time.* This includes any required preloading time to reduce long-term settlements.
- *Minimizing nuisance in the environment.* Think here of nuisance due to transport movements, noise and vibrations.
- *Robustness of design to execution quality.* Could problems that arise during execution or carelessness in execution create substantial risks regarding foundation performance, or is the design relatively insensitive to this?
- *Flexible location of loading possible.* Can the crane load act only on specific parts of the crane hardstand, or can loads be positioned at any arbitrary spot on the platform?
- *Robustness to exceeding maximum loading.* How robust is the foundation when the design load is exceeded? Would this cause immediate large-scale deformations, or would any deformations be local and limited?
- *Minimizing maintenance due to use damage.* What maintenance will the crane hardstand require, both during the installation phase and during the service life of the turbine. This pertains particularly to the risk of rutting or deformations in the hardstand structure and the relative ease of repairing these (for example, by levelling the top layer of mixed aggregate).
- *Minimizing costs.* This includes the costs involved in designing, building and maintaining the crane hardstand.

- *Ease of removal.* How straightforward is the crane hardstand to remove? Or are there permanent foundation elements that would be left in the ground?
- *Minimizing impact on the environment.* Think here of the raw materials needed for the crane hardstand, as well as the extent that permanent components would be left in the ground.

5.7 MODELLING

5.7.1 SHALLOW FOUNDATION

FAILURE MECHANISMS

In designing a crane hardstand with a shallow foundation, the following failure mechanisms must be tested:

- Exceeding the ground bearing capacity (including tests for punching and squeezing)
- Horizontal balance
- Overall stability
- Settlement

PRELIMINARY DESIGN

In a preliminary design the set of data already known is generally very limited. The testing of relevant failure mechanisms is therefore often done using analytical methods for undrained and drained soil behavior. A listing of those analytical methods can be found in section 6.5.2.2 of NEN 9997-1 [46]. For the drained situation, the method is based on Prandtl (1920) [60], Meyerhoff (1953) [45] and Brinch Hansen (1970) [6], among others.

If desired, advanced models can be used for the preliminary design (such as calculations with a finite element model, or FEA). For any calculations done in the preliminary design phase, the choice of model and starting points must always take adequate consideration of the uncertainties that are often still present at this stage, for example, by using conservative assumptions or with a sensitivity analysis.

Additionally, the CUR/CROW publication "Accessibility of Building Sites: Geotechnical Bearing Capacity for Foundation Rigs" (in Dutch) [27] describes the BR 470 method that is included in BR 470 "Hardstands For Tracked Plant" [5]. The disadvantage of the BR 470 method is the narrowness of its intended application, as it applies only to undrained behavior for subsoils with an undrained shear strength between 20 and 80 kPa. For crane hardstands at wind turbine sites, application of the BR 470 method is not advised, in view of its limited applicability to subsoils in the Netherlands.

Note that a shallow foundation for a crane hardstand at a wind turbine site cannot be designed based on the results of plate bearing tests. Plate bearing tests produce a value for the stiffness of the subsoil based on a pressure applied and deformation measured. However, the pressure applied in the plate bearing test cannot be compared to the required load on the crane hardstand foundation. Due to the very small size of the plate used in the plate bearing test compared to the surface area under a crawler track or outrigger, the zone of influence of the load on the subsoil from the test is very unlike the actual situation. This can lead to a faulty design. This is why the design must not be prepared based on results from plate bearing tests. A plate bearing test can be used to test the compaction of the foundation layer of the platform.

FINAL DESIGN

When the time arrives to prepare the final design, the type of crane to be used needs to be known. Or at the very least, some certainty is needed about an indicative type of crane. In the final design phase, the relevant failure mechanisms can be tested using an analytical model (see also the preliminary design phase). Another option is to use a finite element model (FEA) to test all failure mechanisms. For key considerations when modelling a crane hardstand in FEA, see see section 5.7.4. For the design of reinforced foundation layers, see also the CUR/CROW publication on geosynthetics for reinforcement of unbound base and subbase pavement layers [20].

FACTORS TO CONSIDER IN DESIGNING A SHALLOW FOUNDATION

The following factors should be considered when designing a shallow foundation for a crane hardstand at a wind turbine site.

- *Uncertainty in crane type:* In a preliminary design, the type of crane to be employed is often not yet known. In that case, designers themselves must provide justified assumptions for loads, bearing pressures and corresponding contact surface areas. These can be derived, for example, based on experience from comparable projects. When the final design is being prepared, the type of crane to be used does needs to be known. Or at the very least, some certainty is needed about an indicative type of crane.
- *Effective surface area of foundation:* In testing the bearing capacity of the subsoil the effective surface area of the foundation needs to be calculated (see section 5.3.2). In doing so, tests must also verify whether the mats can spread the load over the entire mat surface area. Geotechnical failure of a single mat under an outrigger or crawler track does not need to be tested separately, as long as the crawler tracks are oriented perpendicular to the mats. Any testing of whether the crane mats can provide the desired load spreading, and tests of the strength of the crane mats must be implemented by the designing party, and not by the crane hirer.
- *Test for punching shear:* Because a shallow foundation uses a stiff foundation layer, in most cases a test for punching shear will also have to be performed, in addition to the regular check of the bearing capacity in conformance with section 6.5.2.2 of NEN 9997-1 [46].
- *Test for squeezing:* In the presence of relatively shallow, weak layers in the subsoil, tests must be performed to determine if these weak layers can't be latterly deformed by the load, using a test for squeezing, in conformance with section 6.5.2.2 of NEN 9997-1 [46].
- *Influence of slopes:* If there are slopes within the zone of influence of the shallow foundation, the slope has a negative effect on the bearing capacity of the subsoil. That is, the length of the sliding surface is reduced, meaning that less friction can be mobilized in the subsoil and less counteracting ground weight is present. This will be the case if a crane hardstand is constructed on a raised embankment or if ditches are present or will be dug next to the crane hardstand (for example, to provide drainage for the hardstand). The influence of slopes can be included in an analytical calculation in accordance with section 6.5.2.2 of NEN 99971 [46]. It is important that this influence already be included in the preliminary design, because it can have implications for the design. For instance, it may change the preferred location for the crane hardstand, introduce a need for (temporary) culverts or require the foundation to be strengthened.

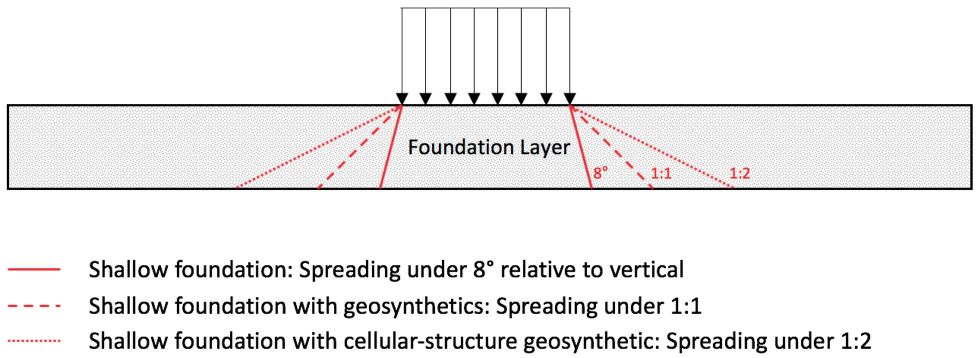
  For ground surfaces that are not horizontal, or where there is a slope nearby, the slope angle β must be determined in accordance with NEN 9997-1 section 6.5.2.2 (p) and (q) [46]. If $\beta > 0{,}5 \cdot \phi_{gem;d}$, then in addition to the test of the load capacity, the slope's overall stability (instability along a deep slip surface) must also be tested using a stability calculation and inputting the crane load as the load.

Note here that inclusion of relatively narrow and shallow ditches next to the crane hardstand as a slope in the bearing capacity calculation produces very conservative results. If ditches are of minimal size and depth, based on the calculated lateral influence of the sliding surface, an assessment can be made of whether there is a risk of the sliding surface coming out on the bank of the ditch. If no such risk is found, consideration could be given to not modeling the ditch as a slope, but only including it in the form of a reduction in the weight of the ground cover next to the foundation.

- *Horizontal loads:* In testing the vertical load capacity, the influence of the horizontal loads that arise from the crane and can act on the foundation must be taken into account.
- *Load spreading in the foundation layer.* When an unbound foundation layer is applied (for example, aggregate), this layer will provide for a spreading of the load from the crane. The extent of load spreading obtained depends on the ratio between the stiffness of the foundation layer and the stiffness of the ground beneath. The method of Brinch Hansen [6] in NEN 9997-1 [46] does not provide scope for modelling the foundation at the level of the bottom of the foundation layer, with a spreading in the foundation layer included: such modelling could lead to a too-optimistic design. According to NEN 9997-1 [46], in cases of unbound, not geosynthetically reinforced foundation layers, the foundation layer must be input into the model as a soil layer, and the top of the foundation layer must be adhered to as the foundation level. In the punching test, these models include a load distribution of 8° relative to the vertical. Note that this is a conservative modelling, certainly in situations where bound or geosynthetically reinforced foundation layers are used. In most cases, doing the calculations with more advanced models will result in greater spreading in the foundation layer (see also the next point).
- *Modelling geosynthetics:* In modeling a shallow foundation with geosynthetics, the positive contribution of the geosynthetics to load spreading and/or foundation strength can be included. Methods to account for this range from doing the calculations with extra load spreading to using a greater strength for the foundation.

  For a preliminary design, the following rules of thumb can be adhered to for stress distribution in reinforced foundation layers: a distribution of 1:1 in a foundation layer with geosynthetics or a foundation layer with stabilized soil and a distribution of 1:2 in a foundation layer with geosynthetics having a cellular structure (figure 5-10).

FIGURE 5-10 **RULES OF THUMB FOR STRESS DISTRIBUTION IN REINFORCED FOUNDATION LAYERS, TO BE ADHERED TO IN A PRELIMINARY DESIGN ANALYSIS**



When testing a shallow foundation reinforced with geosynthetics, the foundation level adhered to is the bottom of the foundation layer, with the load reduced by spreading and acting over a larger surface area. The extra load due to the own-weight of the foundation layer does need to be added to the vertical load.

In later design phases, the way the effect of geosynthetics is accounted for has to be justified using the literature or results from testing. In doing so, effects that may limit the positive contribution of the geosynthetics also have to be accounted for. Examples of these are reduced tensile strength of geosynthetics with increased elongation, and any effects of creep (these last can usually be ignored when dealing with the design of a crane hardstand at a wind turbine site, due to the short duration of the loads).

- *Settlement:* Here a distinction is made between:
  - *Settlement due to consolidation and creep as a result of the works involved in constructing the hardstand.* Large (residual) settlements as a consequence of the construction works for the crane hardstand are undesirable. Settlement of the hardstand can reduce the dewatering depth of the platform, rendering it unacceptably shallow; or unacceptable settlement differences might occur where the hardstand meets construction roads and other surrounding facilities. This can lead to the need to heighten the hardstand upon future uses for maintenance or disassembly. Predicted settlements can be calculated in the design phase and remedial measures can be taken if needed. Examples of such measures are construction of the hardstand on an embankment with excess height, or preloading the ground to counter predicted residual settlements. Note that preloading the ground at the site of the crane hardstand can significantly influence the planning of the wind farm. For example, waiting periods of 3-9 months may be needed for the cohesive soil layers to consolidate (dissipation of excess pore pressures). The consolidation period can sometimes be shortened by installing, for example, vertical drainage, which allows an accelerated consolidation process to occur.
  - *Settlement due to deformation of the foundation and subsoil as a result of loads arising from the lifting operation.* Under these loads, the subsoil (cohesive soil layers) will often exhibit undrained behavior. In sand, drained behavior will be observed. In many cases, limits will have been set for the maximum permissible (differential) settlement of a hardstand or the maximum rotation of the crane during the lifting operation. These (differential) settlements can be determined using analytical programs or finite element modelling (FEM).

5.7.2 FOUNDATION ON A PILED EMBANKMENT

The design of a piled embankment foundation is addressed in the CUR/CROW publication on piled embankment system design (in Dutch) [22]. In it, both analytical and numerical design methods are elaborated. The choice for one of these methods can be made in each of the different design phases (preliminary design, final design and execution/completion).

FACTORS TO CONSIDER WHEN DESIGNING A FOUNDATION ON A PILED EMBANKMENT

The following factors are of concern when designing a foundation on a piled embankment for a crane hardstand at a wind turbine site.

- Uncertainty in crane type: In a preliminary design, the type of crane that will be employed is often not yet known. In that case, designers themselves must provide justified assumptions for loads, bearing pressures and corresponding contact surface areas. These can be derived, for example, based on experience from comparable projects. When the time arrives to prepare the final design, the type of crane to be used does need to be known. Or at the very least, some certainty is needed about an indicative type of crane.
- The design must account for the way forces are transferred from the horizontal load on the crane, and the influence of this horizontal load on the geosynthetics and piles must be tested. These horizontal loads on the piles can be the determinative factor in the design of the (edge) piles.
- If relevant, allowances must be made for a horizontal ground pressure on the piles under the piled embankment. Such horizontal ground pressures will arise, for example, under

the slopes of a crane hardstand that is built higher than the surrounding ground surface, or they can occur if an elevated access road is constructed next to the hardstand.
- The interaction between the piled embankment and the wind turbine foundation has to be considered. This includes both physical interaction between the pile foundation of the wind turbine (where inclined piles are used) and the piles beneath the piled embankment, as well as interaction due to the load from the piled embankment on the pile foundation of the wind turbine.

For other important considerations regarding the design of a piled embankment, see the CUR/CROW publication on the topic (in Dutch) [22].

5.7.3 FOUNDATION ON A FOOTING WITH PILES

For a crane hardstand foundation on footings with piles, the design and testing of the piles must be carried out in conformance with Chapter 7 of NEN 9997-1 [46]. The structural design of the footing must be executed in accordance with NEN-EN 1992-1-1 [46].

FACTORS TO CONSIDER WHEN DESIGNING A FOUNDATION ON A FOOTING WITH PILES

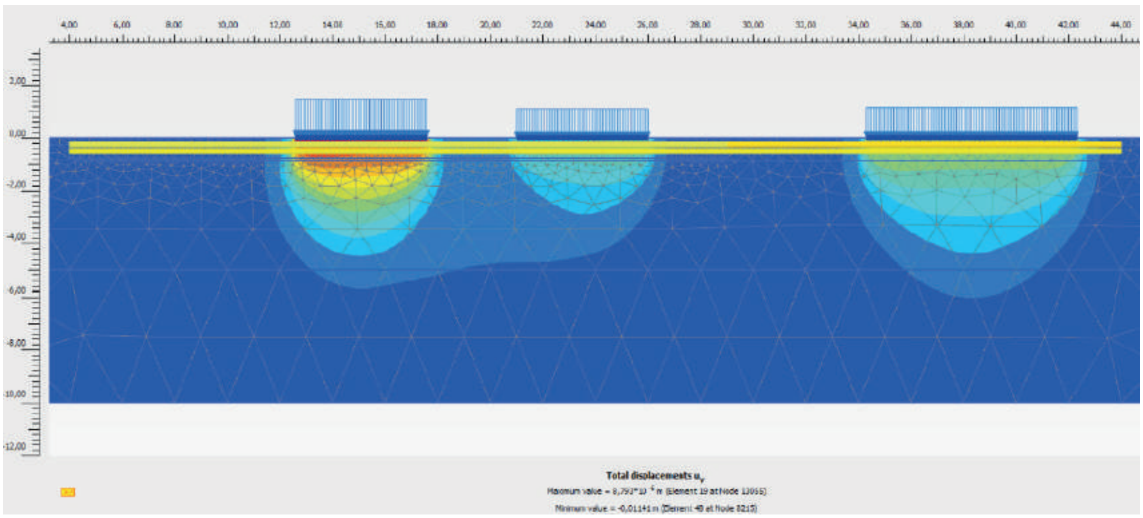
The following factors are of concern when designing a foundation on a footing with piles for a crane hardstand at a wind turbine site.
- Uncertainty in crane type: In a preliminary design, the type of crane that will be employed is often not yet known. In that case, designers themselves must provide justified assumptions for loads, bearing pressures and corresponding contact surface areas. These can be derived, for example, based on experience from comparable projects. When preparing the final design, the type of crane to be used does need to be known. Or, at the very least, some certainty is needed about an indicative type of crane.
- In the design, the way the forces from the horizontal load on the crane are transferred must be accounted for and the effect of this horizontal load on the piles must be tested.
- If relevant, allowances must be made for a horizontal ground pressure on the piles. Such horizontal ground pressures arise, for example, at the foot of the slopes in situations where a crane platform is constructed at a higher elevation than the surrounding ground surface, or it can occur if a raised access road is built next to the crane platform.
- In preparing the design, consideration has to be given to the suitability of the crane hardstand for multiple types of crane, as during the service life of the turbine, maintenance will need to be performed. For this work, considerably smaller cranes will likely be needed than for installing the turbine. A considered choice also has to be made as to whether the hardstand should be suitable for both crawler cranes and outrigger cranes. This can lead to the need for relatively large and complex-shaped footings.
- The interaction between the pile foundation of the crane hardstand and the foundation of the wind turbine must be taken into account. This includes both physical interaction between the pile foundation of the wind turbine (where inclined piles are used) and the piles beneath the crane hardstand, as well as interaction due to the load from the piling under the hardstand on the pile foundation of the turbine.
- In the design, it must be checked whether punching of piles through the concrete footing can occur.
- In the design of the crane hardstand, consideration must be given to possible settlement differences between the footings with piles and adjacent storage areas: the footings with piles will hardly settle at all, while storage areas will likely be built using a foundation type that is more prone to settlement. This can result in unacceptable settlement differences between the crane hardstand and the storage areas.

5.7.4 MODELLING IN FEA

When testing crane hardstands in finite element models (FEA), both deformations and resistance against failures can be investigated. The following considerations apply to the design of a crane hardstand in FEA:

- The choice of soil model is crucial for the outcome. In any case, the soil model used must be able to model plastic soil behavior. In most cases, it is worth the effort to use a more advanced soil model, because this usually produces less conservative results.
- The soil parameters needed for an FEA analysis must be determined with care. For a preliminary design, consideration could be given to deriving the parameters based on conservative rules of thumb. In the final design or execution/completion phase, it is strongly recommended to determine the soil parameters based on laboratory analyses. Otherwise, calculations done using an advanced soil model, but with parameters that are not precisely determined, will quickly lead to a false sense of accuracy. The most important parameters for the analyses are the strength and stiffness parameters and the neutral earth pressure coefficient $K_{0;NC}$. These can be determined using K_0-CRS tests and triaxial tests or direct simple shear tests.
- In most cases, settlement due to consolidation will not be of importance, because the loads on the crane hardstand will be present only for a short time. For situations where settlement due to consolidation is important (for example, settlement caused by the works to install the hardstand), an appropriate soil model must be chosen that takes consolidation and creep into account. Additionally, the relevant parameters (compression parameters and parameters relating to the stress history of the soil, such as OCR and preconsolidation pressure) must be determined by means of appropriate laboratory tests, such as compression tests.
- Depending on the type of subsoil and the duration of the load, a justified choice must be made to use undrained or drained conditions (or both) for the calculations.
- A choice must be made between a two dimensional (2D) or a three dimensional (3D) analysis. A 3D analysis can have added value because the load from a crane is often limited in size. If peripheral effects are important, such as the effects of the crane hardstand on the foundation of the wind turbine, a 3D analysis may be needed for reliable results.

FIGURE 5-11 **EXAMPLE FEA CALCULATION WITH LOADS ON A SHALLOW FOUNDATION REINFORCED WITH GEOSYNTHETICS**



5.8 DELIVERABLES

The design of a crane hardstand should result in the following deliverables:

- *Design report.* This is a description of the design, the starting points used in the design and the relevant tests.
- *Drawings.* The drawings present the design along with the corresponding materials and quantities. Furthermore, any necessary measures for water management (drainage, etc.) must be indicated on the drawing.
- *Technical descriptions/specifications and similar.* These must specify what tests, monitoring and data registrations will be done during execution.

6

EXECUTION, OPERATION AND MAINTENANCE

6.1 INTRODUCTION

This chapter addresses the execution, operation and maintenance of a crane hardstand. The key factors and considerations are presented in the following order:

- Construction of the hardstand (all the necessary surfaces for assembly, storage and transport)
- Execution of the lifting operation
- Operation and maintenance of the permanent crane hardstand
- Removal of temporary crane hardstand
- Monitoring and testing

Interactions are possible with, among other things, the installation of cables, the wind turbine foundation, site access and construction roads, and transport of the wind turbine itself.

6.2 CONSTRUCTION OF THE HARDSTAND

6.2.1 STARTING POINTS

The design is the starting point for the execution phase, as described in Chapter 5. A good design is an essential precondition for a problem-free execution, alongside a good description of the framework conditions needed for execution.

It is the executing party's job to develop work plans and schedules based on the design documents. The type of work plans developed will depend on the design solutions chosen. The work plans and schedules must be checked against the design documents. Furthermore, the way the quality of the execution will be tested must be documented.

It is also necessary to compare the situation actually encountered on the site to the starting points used in preparation of the design. This might include the following:

- The depth of a stable soil layer in cases where soil improvement will be applied
- Compaction of the subsoil in the event of a sandy top layer or soil improvement
- Follow-up CPTs in cases where a highly inhomogeneous subsoil is found

6.2.2 FACTORS TO CONSIDER

Practical experience has shown a number of considerations to be important. These relate to the design solutions chosen, among other things.

EXECUTION PERIOD
The execution period can potentially be limited by agricultural activities, hydrological conditions and legislation.

For flood defenses, an off-limits period generally applies (in the high water or storm season), during which no work activities may take place on or near flood defenses. Another possibility, when a site is in a flood-prone area, is that the subsoil may be saturated, making execution works temporarily impossible to carry out.

WEATHER CONDITIONS
Weather conditions and/or the seasons can affect the execution of works and even design preparation. For example, abundant rainfall can lead to inundation of excavation pits, which can cause substantial delays.

Whether or not the subsoil is submersed has a great impact on the bearing capacity of crane hardstands.

EXCAVATED SOIL
Depending on the amount of soil to be excavated, soil may need to be transported away from the site or put in a depot on-site. Whether the hardstand is temporary or is to be installed on a permanent basis will also play a role in this regard. When soil is to be removed, the possibility of contaminated soil may come into play. The cost of removal and processing soil that may be contaminated can be very high.

In deciding between removal or an on-site depot, the owner of the land will often need to be consulted. The soil may be of value to the landowner.

On and near flood defenses, no excavation works are allowed in off-limits periods.

GROUNDWATER
Depending on the depth of the excavation, a dewatering system may be needed. This must also take into account any field drainage already present. Existing drainage must be repaired/adapted to prevent adjacent agricultural lands from becoming too wet. Another consideration related to drainage is groundwater discharge.

INTERFACES WITH OTHER PARTIES
In many cases, the construction of civil infrastructure will be done by a different party than the one constructing the wind turbine foundations. Adequate management of this interface, for example, regarding the planning of works, is therefore essential. For instance, backfilling of the ground right next to the foundation might be scheduled to occur later, in which case, that part of the hardstand can only be constructed after the foundation is completed. Given that this is in fact the part of the hardstand that may receive the highest crane loads, attention to the quality of this last bit of backfilling is of essential importance.

Another interface is with cabling works. Cabling routes may run under the crane hardstand. To prevent this from leading to conflicts during execution, cable trays are often incorporated in the hardstand design.

PRELOADING

For design solutions with a shallow foundation, preloading the crane hardstand site, by applying a soil depot, can be a solution to minimize settlements during the lifting operation. Such preloading needs a certain amount of time before it can take effect, and that time must be taken into account in project design and planning. The preloading itself has consequences that can influence surrounding objects, such as cables, pipelines, ditches, buildings and the like.

VISIBILITY OF THE REINFORCED PART OF THE HARDSTAND

In an effort to optimize the design of the crane hardstand, the decision is sometimes made to distinguish between the part of the hardstand where the main crane will be placed and the part that is suitable for lighter loads. This can result in different layer thicknesses with differing strength and deformation properties. On the surface of the crane hardstand, however, this difference in thickness is not visible, leading to the danger that heavy loads will be placed at the edge of a weak part. It is therefore of key importance to clearly mark where the strong part of the crane hardstand is located.

The same applies to the distance that needs to be maintained between a heavy load and the edge of the hardstand. Here, too, clear markings are important. This is particularly the case where there are embankments and ditches next to the crane hardstand.

6.2.3 QUALITY REGISTRATION

Quality registration and the checks to be performed must be documented ahead of time in the specifications and work plans. The purpose of such quality registrations is to provide a guideline for later tests of the starting points for the design. This means that the goal of these registrations is emphatically not to test the bearing capacity of the hardstand. After all, this is ensured by a good design and assurance of its quality.

Examples of quality registrations are the following:

- Compaction of a mixed aggregate layer using a plate bearing test or Proctor test with density measurements (ring sampling or nuclear method)
- If geotextiles are to be applied, overlapping of geogrids and laying direction (laying plans)
- Grain composition from laboratory analysis
- Pile blow count
- Levelness of the hardstand
- Thickness of the applied soil improvement by (manual) boreholes
- Height and fluctuations in the groundwater level/hydraulic head from monitoring well measurements or possibly a CPT with piezocone

It must be emphasized that the sole purpose of the plate bearing tests that are so often prescribed is to check the stiffness (or provide an indication thereof) of a layer of limited thicknesses and <u>not</u> for use to assess the bearing capacity of the hardstand.

PHOTO 6-1 COMPACTION OF THE HARDSTAND AND FINISHED HEIGHTS REQUIRE VERY CAREFUL ATTENTION, AS VERY SMALL TOLERANCES ARE PERMITTED

6.2.4 HANDOVER/COMPLETION

Two handover points can be identified for crane hardstands:

- Prior to installation of the turbine. In the turbine installation phase, the crane hardstand must be suitable for the lifting operation.
- Prior to completion of the wind farm: The permanent crane hardstand must be finished after the wind turbine has been completed, at which time, part of the hardstand may need to have been removed and the rest finished.

The executing party must then hand over the work to, respectively, the crane hirer/turbine manufacturer and the owner of the wind farm. These parties must then accept the work delivered before the next phase can begin. In this process, the quality registrations serve as evidence of the quality delivered.

6.2.5 MONITORING DURING CONSTRUCTION OF THE HARDSTAND

During construction of the hardstand, settlement behavior has to be monitored during any heightening works (for example, preloading). Here, the purpose of monitoring is to compare actual settlement behavior in a particular period of time with that predicted in the design. This enables an assessment to be made of whether the settlement requirements for the hardstand will be fulfilled. Monitoring of settlement can be done using settlement rods.

Installation and extraction of sheet piling and/or pile driving can also have impacts on the surrounding environment. Examples are vibration damages, vibration nuisance and noise nuisance.
The way such impacts are to be monitored must be described in a monitoring plan formulated prior to the start of the works.

Works done on or near a flood defense will often have to be performed in a way that does not cause vibrations.
For every project (and project phase), an assessment must be done of the risk of impacts on the environment. Section 6.6 provides a further discussion of such monitoring.

6.3 THE LIFTING OPERATION

6.3.1 EXECUTION OF THE LIFTING OPERATION

Before the lifting operation is carried out, an exhaustive preparatory process takes place, culminating in the 'lifting plan'. In this regard, Directive 2009/104/EC on the use of work equipment [61] states the following in article 3.2.5 of Appendix 2:

All lifting operations must be properly planned, appropriately supervised and carried out in such a way as to protect the safety of workers.

The development of a lifting plan is a central part of the methodical preparations for a lifting operation. The lifting plan consists of agreements and documents detailing how the lifting activities are to be executed. The lifting plan can contain information about the load, rigging tools, the crane and environmental factors such as the supporting ground. Depending on the complexity of the lifting activities, the plan can be rather simple and straightforward, only including a work order with instructions. Or it can be made up of multiple elements, including a lift drawing and a Task Risk Analysis (TRA).

Responsibility for compiling the lifting plan and ensuring that the lifting operation is properly supervised lies with the party in charge of directing the works, represented by the Appointed Person. The agreement between the crane hire company and client specifies whether a 'crane hire contract' or a 'contract lift' applies to the services. It follows from the form of contract chosen which of the two is responsible for the lift planning and arranging the supervision.

Part of lift planning is assembly of the lifting team. From a legal viewpoint, safely executing a lifting operation requires fulfilment of at least three roles:

- Signaler. The signaler is responsible for directing the crane operator by relaying the right instructions.
- Slinger. The slinger is responsible for safely attaching or detaching the load. If necessary, the slinger must be capable of guiding the load (on the instructions of the signaler), for example, using taglines.
- Crane Operator. The crane operator is the person responsible for operating the mobile crane.

For some lifting activities, the slinger can also play the role of signaler.
Implementation of the lifting plan and assembly of the lifting team will vary depending on the complexity of the works and the expertise of the people involved. The same applies to the way supervision is organized. A grasp of the complexity of the lifting operation can be obtained using a risk analysis. For information about carrying out such a risk analysis and further details on the other abovementioned aspects, see the guideline on mobile cranes (www.richtlijnmobielekranen.nl) [71][2] or the website (in Dutch) of the Dutch crane hire association (the Vereniging Verticaal Transport, or VVT) [69].

2 Probably this link will still not work. It is expected that this guideline is available when this handbook kraanopstelplaatsen is available. The link will point to a working website.

Adherence to the steps set out in these documents will result in the safe execution of the lifting operation. This is because the operation:

- Is performed in the framework of an effective management system, with assessments done of potential risks, and based on those assessments, measures taken to manage the risks, including providing adequate instructions.
- Has been properly planned.
- Is performed by personnel with the requisite expertise.
- Is performed with the appropriate equipment.
- Is done under expert supervision.

6.3.2 MONITORING DURING THE LIFTING OPERATION

Monitoring impacts on the environment can be a key consideration in the use phase of a crane hardstand. This might pertain to vibrations, noise and/or tilting of a crane due to soil settlements. The way monitoring is to be done must be described in a monitoring plan formulated ahead of time.
For every project (and project phase), an assessment must be done of the risk of impacts on the environment. Section 6.6 discusses monitoring in more detail.

6.4 OPERATION AND MAINTENANCE OF THE PERMANENT HARDSTAND

6.4.1 INTRODUCTION

The permanent part of the crane hardstand must remain operational throughout the service life of the wind turbine so that a maintenance crane can be set up. The biggest challenge in this phase is prevention of erosion and time-dependent wear and tear on the platform. In some cases the appearance of the hardstand will be an important factor. Different hardstand construction and finishing techniques are therefore available, which can roughly be categorized as follows:

- Closed pavements such as asphalt or concrete
- Open surfaces such as mixed aggregate or loose paving materials
- Topsoil covers (grass after sowing)

These finishes bring different maintenance concerns.

Finally, it should be kept in mind that hardstands are often also used by farmers, for example, as a place to park agricultural machinery and as storage area for agricultural products (for example, beets).

6.4.2 ASPHALT PAVEMENT

Asphalt has a certain degree of flexibility. Therefore, asphalt can withstand some subsoil deformation without cracks developing. Since the subsoil will settle over time under the weight of the hardstand and/or due to so-called autonomous subsidence, it is to be expected that this settlement (and possibly settlement differences) will eventually be reflected in the asphalt. The extent this occurs will depend on the subsoil, the construction techniques used for the hardstand as a whole and any possible use of the hardstand for other purposes.

Two negative consequences can arise:

- Unevenness of the hardstand, making it more difficult to set up a crane
- Rainwater puddling or the hardstand no longer draining adequately, with the combination of water and frost causing the asphalt to deteriorate over time

6.4.3 CONCRETE PAVEMENT

Unlike asphalt, concrete is a rigid material. Concrete will therefore be less prone to deform with deformation of the subsoil. For concrete pavements, other issues will therefore play a role. In particular, crack formation is a point of concern. Concrete is very able to absorb pressure stresses, but it has less ability to absorb tensile stress. To solve this problem, reinforcement steel is generally added to the tensile zones of concrete structures. Tensile stresses can arise due to, for example, bending of the concrete pavement, whereupon the concrete first cracks before the reinforcement steel can absorb the tensile force. That is normal. However, we do want to minimize the extent of the cracking. If cracks become too large, there is a chance that the reinforcement steel will deteriorate (corrode) over time.

Crack formation in concrete can have various causes. Here we list a few:

- Loads due to, for example, a crane or storage
- Stress due to temperature
- So-called plastic cracking, which occurs right after the concrete is poured and can be prevented by measures taken during application of the concrete
- Shrinkage cracks, which arise due to the drying out of the concrete

It is good to realize that once cracks appear, they will look like they are growing over time. However, this appearance is not necessarily because the cracks themselves are getting larger. It can also be due to crumbling and erosion of the edges of the crack due to moisture and frost action.

Cracks up to 0.3 mm in width (officially measured at the location of the reinforcement) are considered acceptable. For wider cracks, treatments using injection or other repair methods can be considered.

6.4.4 CLOSED PAVEMENT AND DRAINAGE

Where impervious pavement is chosen (asphalt or concrete) extra attention must be given to drainage. After all, the entire pavement surface will receive a lot of rainwater. Preventing the adjacent (farm) lands from being submerged is another key concern. Installation of a ditch, possibly with drainage, is therefore often necessary.

6.4.5 PERVIOUS SURFACES AND TOPSOIL COVERS

Pervious surfaces have the advantage that rainwater can drain away through their surface. The speed of this water discharge, however, is dependent on the granular composition of the pavement. There is a greater chance of puddle formation in places with a lot of fine material.

Saturation of the pervious surface with rainwater due to a wet period and/or a low working surface height of the hardstand can create a (temporary) vulnerability of the pavement surface. If in such a period the platform is driven over, for example, by agricultural machinery, rut formation can occur.
Like asphalt, a pervious surface will deform with any deformations of the subsoil. This, too, can promote puddle forming. Equally, however, dust can be a problem in dry periods.

A consideration regarding pervious surfaces is the chance that rocks or gravel could find their way onto adjacent farmlands. This is undesirable. For that reason, pervious pavements are often enclosed and covered, for example, with a layer of topsoil.

The solution of a topsoil cover gives the platform a natural appearance. A disadvantage, however, is that the topsoil must first be removed before a maintenance crane can use the platform.

6.4.6 EDGES OF HARDSTANDS

If the surface of a hardstand is level with the surrounding terrain, there is a chance of damages to the edges of the platform due agricultural vehicles driving on and off it. A raised installation and/or a trench or ditch dug around the hardstand clearly marks the edges, therefore also diminishing the likelihood of such damages.

If the hardstand is constructed on a raised embankment, steps need to be taken to protect the banks against erosion. The stability of these banks will then be another important issue. In this respect, the distance of a vertical load (such as a crane or storage) from the edge is an important factor. A too-short distance can lead to instability and deterioration of the embankment slopes.

6.4.7 CABLES AND PIPELINES

If planned for ahead of time, cables and pipelines that cross a hardstand can be installed in a protective casing or tray. This makes laying and/or replacing cables easier. If cables and pipelines need to be added to a hardstand at a later stage, this will causedamage to the hardstand, and steps will need to be taken for repairs.

6.5 REMOVAL OF A TEMPORARY HARDSTAND

In many cases, it will not be necessary to keep the entire hardstand ready for use during the service life of the wind turbine. During turbine installation, more space is generally desired than in the operational phase of the turbine. For that reason, we make a distinction between a temporary and a permanent part of the hardstand. This also minimizes the amount of land that needs to be used on a permanent basis.

In general, the temporary part will be less heavily loaded. In keeping with its temporary nature, a design solution is often chosen involving a geotextile and mixed aggregate, preferably applied on the original ground surface. As such, materials can be easily removed and the original situation restored.

6.6 MONITORING AND TESTING

6.6.1 INTRODUCTION

During execution of the hardstand, impacts on the environment can arise due to preloading, insertion and removal of sheet piling and pile driving. Vibrations and soil deformations can cause damage and hinder to abutments, cables and pipes, as well as to other infrastructures.

During the lifting operation too there may be a need for monitoring, for example, regarding the risk of the crane tilting due to soil settlements, as well as vibrations and in some cases noise. The effects and importance of impacts on the environment will depend on the location of the crane hardstand. In an urban environment, the effects and their importance will often be greater than in a rural area.

To minimize the risk of damage and hinder to the greatest extent possible, and to manage such risks, employment of risk-based operational processes is important. See also section 4.1 on the application of Geotechnical Risk Management (GeoRM). GeoRM offers a structured way to deal with the uncertainties that give rise to the various geotechnical risks.

Using risk analysis, the chance of damages and their potential consequences are mapped out by gathering all available information and identifying and assessing the risks for all project phases. As such, the risk analysis provides a snapshot of the risk profile. Preventive and/or corrective management measures must be taken to counter the residual risks which inevitably remain.

Monitoring is not a management measure in itself, but based on monitoring the risk profile can be adjusted if needed. See also the instructions in the CUR/CROW guideline on measurement and monitoring related to ground excavations (in Dutch) [19].

During the execution process, monitoring can serve as an aid to gain greater insight into the impact of deformations (of both the soil and materials), vibrations and noise from the works on objects in the environment.

Monitoring can also be used during execution to assess decisions and assumptions made with a relatively large degree of uncertainty. On the basis of measurements of, for example, vibrations or deformations, a post-analysis grasp of the uncertainties can be obtained.

This technique is called the 'observational method'. If, for example, after the risk analysis in the design phase, substantial uncertainties remain about model parameters for vibrations and soil deformations, the observational method and ex post analyses can be used to adjust the risk profile, or execution methods can be adapted.

More information about application of the observational method is provided in the SBRCURnet/GeoImpuls manual on the topic (in Dutch) [65].

Through monitoring, the influence of the execution works in and on the environment is measured, registered and checked against the limits set. The methodology for measuring, registering, presenting and checking against signal and intervention values is described in a monitoring plan.

The monitoring procedure to be adhered to is set out in the monitoring plan. A wealth of additional information on measurements and monitoring of ground excavations can be found in the CUR guide on the topic (in Dutch) [19].

In particular, when monitoring is applied for the observational method, it is important that the measurements be graphically presented. This facilitates interpretation and understanding of the implications of the measurements.

The sections below examine these measurements in greater detail.

6.6.2 MONITORING DURING PRELOADING

If preloading of the crane hardstand site is to be employed, in addition to the net thickness of the working surface to be installed, an extra height or layer of fill is applied to compensate for settlement and accelerate the settlement process. The extra height of fill is removed once settlement measurements and settlement rod analyses indicate that sufficient settlement has occurred and the settlement requirements have been fulfilled. The settlement process can be artificially accelerated by installation of vertical drainage, possibly in combination with an even greater fill height or thickness.

The predicted settlement and degree of stability during the heightening and preloading process will be determined by a geotechnical consultant based on settlement and stability analyses.

During preloading, the following items are measured:

a. Settlement of the extra height or layer of fill
b. (Excess) pore pressure
c. Deformations of the subsoil and objects

Regarding (a) settlement of the preloading fill, this can be measured using settlement rods or extensometers (point measurement) or settlement markers (over the entire cross-section). The settlement rods are installed in a grid with a maximum spacing of 25 m. The number of settlement rods used is dependent on the size of the hardstand. Two settlement rods is generally taken as the minimum.

Measurements for horizontal soil deformations are discussed under (c).

Regarding (b), water pressure can be measured using water pressure gauges (point measurement in a soil layer). Water pressure gauges should preferably be placed next to a number of the settlement rods along the outer edges of the platform area and at the toe of the embankment.

Regarding (c), the extent of deformations under the soil surface is measured using inclinometer tubes. If needed, null measurements can be taken at the various structures before the construction works begin, to allow the deformations resulting from the construction works to be distinguished.

Deformations of structures are measured in the *x*, *y* and *z* directions using measuring bolts on the relevant structures. The *z* orientation is vertical (settlement). The measurements can be carried out, for example, using a theodolite/total station. For the *z* orientation, a (control) leveling is carried out. The specific measurement instruments to be used should be chosen by a measurement specialist in consultation with the geotechnical consultant.

To estimate the accuracy of the residual settlement prediction for the extra loading (settlement plate fit) the measurements and settlement plate fit must meet a number of conditions, in conformance with CROW 304 [10]:

MEASUREMENTS

- The *measurement period* must be no less than the estimated hydrodynamic period, and preferably twice its length. The *measurement frequency* is from once a week to once per two weeks. No less frequent.
- The precision of the measurement instrument must be ± 5 mm.

SETTLEMENT PLATE FIT

Based on a fit program with which the measured settlements can be compared to theoretical settlement models. In the analyses, the recommendations in CROW 304 section 4.2 [10] are followed and verified.

For the further requirements, a monitoring plan is drawn up which documents both the way the measurements will be done as well as the values to serve as signal and intervention values per object.

6.6.3 DEFORMATION MEASUREMENTS

To measure deformations in the environment of the job site, measurement points are installed (bolts, prisms, measurement stickers or nails, rod gauges). These measurement points must be evaluated prior to the construction activities (null measurement) and during the construction works. If the measurement period is sufficiently long, the null measurement will also reveal 'natural' deformations, for example, due to variations in temperature.

During the conduct of deformation measurements, deformations over time are followed and recorded in the x, y and z directions. The horizontal directions are x and y. The height (z orientation) of the measurement points is measured relative to NAP.

Depending on the situation, the measurements are performed with an RTS (robotic total station), oftentimes automatically, and/or with a digital level and staff. The RTS measures both horizontal and vertical deformations. With a level, only vertical deformations can be measured.

The precision of these instruments is approx. 0.5 to 1.0 mm. The precision of the final measurement results are dependent on site conditions and distances over which the measurements are performed.

DIGITAL LEVEL

To measure the height (z orientation), a digital level and staff are used. The horizontal directions, x and y, are then not measured at the same time. The measurement points (often measurement bolts) are measured-in relative to a reference point, which is located outside the zone of influence, or relative to a fixed point not subject to settlement.

The relative precision of the instrument is at minimum approx. 0.5 mm. Furthermore, temperature, weather and seasonal factors influence the precision of the measurements. This means that errors of up to 1.0 to 1.5 mm cannot be ruled out. Weather conditions must therefore be noted on the respective measurement days.

Using a level, measurements can be done over relatively large distances. Control measurements can be performed with the RTS.

ROBOTIC TOTAL STATION (RTS)

To measure both horizontal and vertical deformations, an RTS can be used. RTS measurements can be done either manually or automatically. The precision of the automatic monitoring system is ± 1 mm.

Measured distances are limited by any obstacles present, but with a clear line of sight can reach a maximum of 75 m.

During monitoring for deformations, both the absolute value (in relation to the null measurement) and the rotational difference (displacement between two consecutive points) are calculated. The measurement results are assessed in conjunction with the work activities underway, the risk analysis and the monitoring plan. If needed, measurement frequencies can be adjusted upwards or downwards or adjustments made in the execution of the works.

Reports from the deformation measurements must include the following:
- Description of the location of the measurement points (which building, bolt/prism numbering, etc.), with measurement locations indicated on a drawing
- An overview of the measurement period with, among other things, dates and weather conditions
- Specification of the instruments used and the data acquisition system
- Log of the measurements and an explanation of all relevant details
- Presentation of the results (null and subsequent measurements)

6.6.4 VIBRATION MEASUREMENTS AND ASSESSMENT FRAMEWORK

With regard to vibration damages, a distinction can be made between direct and indirect damages. Indirect damages are caused by settlements resulting from compaction of soil layers. Submersion or softening of the ground can also lead to damages. Vibrations in the ground can generate (excess) pore water pressure. These excess pore pressures can produce a temporarily lower grain tension, which reduces the soil bearing capacity. Potential consequences of this are failure of foundations and instability of flood defenses. Excess pore water pressures are generated particularly in layered soil profiles in which dissipation to the environment is limited. Direct damages occur as a direct result of the vibrations. The discussion here concerns vibrations and how to assess the chance of direct damages due to them.

The SBR Vibrations Guideline A: “Damage to Building Structures”, 2017 [62] provides no definition of what is meant by damages. In order to be somewhat able to qualify the chance of damages due to vibrations, we can use, for example, the damage category groups from COB F530 [9]. The zone of influence in which there is a chance of damages and residual settlements due to vibrations must be identified ahead of time based pile-driving and vibrations risk analyses. For more general categorizations of damages, see also COB [9], which describes the Limiting Tensile Strain Method (LTSM) for buildings and presents various assessment methods for pipelines.

Vibration measurements provide a better understanding of the strength of vibrations produced in relation to intervention values. Several SBR guidelines are available (in Dutch) on how to measure and assess vibrations:
- SBR Vibrations Guideline A: Damages to Buildings, 2017 [62]
- SBR Vibrations Guideline B: Nuisance to Persons in Buildings [63]
- SBR Vibrations Guideline C: Interference with Instruments [64]

Vibrations can be predicted using the CUR 166 method [13].

The strength of the vibration must, in accordance with the SBR guidelines, be measured and checked against intervention values. When testing in line with SBR Vibration Guidelines A and C, the intervention value is taken as a limit value. In SBR Vibration Guideline B, the intervention values are referred to explicitly as target values. Management measures must be geared to ensure conformance with the limits set.

Different measurement systems are available which are designed in line with the SBR guidelines. One measuring system is linked to a 3D sensor that measures vibrations (in the *x*, *y* and *z* directions). Signal processing and data storage are usually performed automatically, but this can differ per system. Per programmed sample (time interval) the highest vibration velocity and corresponding frequencies are saved. After a certain period, the measuring system is read out and the data processed. A web-based program can be linked to the measurement results, in which case daily measurement reports can be generated.

The vibration measurements can be carried out manned or unmanned, that is, with or without direct human intervention.

UNMANNED MEASUREMENTS

Unmanned measurements often incorporate a ‘work' alarm (by SMS, e-mail, etc.), since there is no operator who can immediately see and interpret the size of vibration intensities and the danger of possible overruns of boundary values in relation to the work activities underway. The alarm activates when signal values set in advance are exceeded.

MANNED MEASUREMENTS

At the start of the works or in response to limits being exceeded (if such occurs) or if work is being conducted near vulnerable objects, in consultation with the client, measurements can be performed under an operator's supervision.

During such manned measurements, the work activities underway can be directly associated with the measurements. Based on early or preliminary measurement results, the operator can indicate whether there is a danger of boundary value overruns. Depending on the vibration intensities measured, a decision may be made to continue the manned measurements, to adapt execution methods or to switch to unmanned measurements or reduce the measurement set up.

Reports on the vibration measurements and assessments must contain the following elements:

- Description of the location of the measurement points
- Overview of the measurement period
- Log of the vibro-piling or pile-driving activities with block used
- Indication of when the measurements began, when problems may have arisen and when they were ended
- Specification of the instruments used and the data acquisition system
- Log of the measurements and an explanation of all relevant details, meaning, among other things, that the most pronounced vibration properties must be reported along with the activities taking place at that time
- Presentation of the measurement results is in two parts, and must include a graphic presentation, including an assessment and check of the most pronounced measurements. Graphs with values versus time and values versus frequency should also be provided (the assessment graphs).

6.6.5 NOISE

Unacceptable noise levels can be caused by the works executed at a site where a wind turbine is being installed. During installation of sheet piling, driving piles and other activities, disturbing levels of noise can be produced. Article 8.3 of the Buildings Decree 2012 sets out statutory requirements concerning noise levels in the environment. Noise levels can be predicted prior to the works, followed by measurements of noise levels during the works. Such a procedure enables noise levels to be assessed and verified, to ensure they remain within the norms and meet the requirements set.

A monitoring plan for noise is part of a noise management plan, which documents the following:

- The results of a noise prognosis
- The works and the equipment to be used with their sound propagation capacities
- Planning/scheduling of works
- Measures to be taken to comply with the stipulated norms

Noise level measurements must be carried out in conformance with the guidelines on measuring and calculating industrial noise provided by the Ministry of VROM [34].

When monitoring noise levels, the following measurements should be distinguished:

- Measurements of ambient noise (null measurement)
- Continual measurement of noise, to monitor the noise level produced
- Source measurements, to determine the sound pressure caused by activities

For the measurement of *ambient noise* the following quantities must be monitored:

- $L_{Aeq,}$ equivalent continuous sound level, per minute and shift
- $L_{Amax,}$ maximum impulsive sound level, per minute and shift

A measurement must be performed to determine the ambient noise level. That measurement must take place on a representative day, during a continuous one-day period (7:00 AM – 7:00 PM).

For the *continuous* measurements, the following quantities must be monitored at the emission locations:

- $L_{Aeq,}$ equivalent continuous sound level, per minute and shift
- $L_{Amax,}$ maximum impulsive sound level, per minute and shift.

The measurement points must be arranged in such a way as to be representative of the incoming sound. Measurements must be performed on all working days and in all hours during which works are being done. This includes Saturday and Sunday if the works take place in the weekend.

For the source measurements, for each component activity (e.g., demolition and vibrating in or out) the sound pressure of the sound propagating works must be determined. On the first day that sound propagating equipment are deployed or works performed, a number of source measurements must be carried out at intervals throughout the day, including when equipment is swapped out.

For measurement of the sound source the following quantities must be monitored:

- L_{WR}, emission-relevant source strength
- L_{Amax}, maximum noise level

These measurements are carried out during a representative period of the individual activity (meter reading).

Article 8.3 of the Buildings Decree 2012 stipulates multiple maximum noise exposure values, as well as a number of days of exposure (figure 6-1).

FIGURE 6-1 ARTICLE 8.3 OF THE BUILDINGS DECREE 2012

The measures to be taken pursuant to Article 8.2 shall be laid down in a construction or demolition safety plan. The measures shall concern at least the following:

1. Construction or demolition works shall be carried out on working days and on Saturday between 7:00 and 19:00.
2. In carrying out such works as defined in paragraph 1, the daily exposure values given in table 8.3 and the associated maximum exposure durations shall not be exceeded.

TABLE 8.3

Daily exposure	< 60 dB(A)	> 60 dB(A)	> 65 dB(A)	> 70 dB(A)	> 75 dB(A)	> 80 dB(A)
Maximum exposure time	unlimited	50 days	30 days	15 days	5 days	0 days

3. The competent authority may grant an exemption from the first and second paragraph. Where construction or demolition works are carried out with an exemption from the competent authority, they shall use the most silent techniques available and optimal working methods, irrespective of the provisions of the exemption.
4. If the competent authority has laid down policy rules relating to the execution of construction or demolition works as referred to in title 4.3 of the General Administrative Law Act, by derogation from the third paragraph, no exemption is required if the execution of the work complies with those policy rules and the competent authority has been informed of the commencement of the work at least two working days before the actual commencement of the work

DAILY EXPOSURE LEVELS

The construction works must comply with the exposure levels as set out in article 8.3 of the Buildings Decree (see figure 6-2). The maximum exposure values and allowable number of exposure days apply to workdays from Monday up to and including Saturday between 7 AM and 7 PM.

NIGHTTIME EXPOSURE LEVELS

For works that take place outside the daytime period (that is, in the evening and night periods) and in the weekend, an exemption must be requested, in conformance with paragraph 3. If, in conformance with paragraph 4, local policy concerning noise from construction activities has been established and is complied with, then no exemption is required.

FIGURE 6-2 **ASSESSMENT FRAMEWORK AS STIPULATED IN THE BUILDINGS DECREE ARTICLE 8.3**

MAXIMUM NOISE EXPOSURE LEVELS

Noise level		**Daytime on weekends and holidays, 7 AM to 7 PM**	**Evenings, 7 PM to 11 PM**	**Nights, 11 PM to 7 AM**
Average noise level over a period of 30 minutes*)	$L_{Aeq,\ 30min}$ *)	70 dB(A) (maximum value)	65 dB(A) (maximum value)	60 dB(A) (maximum value)
	$L_{Aeq,\ 30min}$ *)	between 65 dB(A) and 70 dB(A) maximum 10 days with compensation **)	between 60 dB(A) and 65 dB(A) maximxum 10 evenings with compensation **)	between 55 dB(A) and 60 dB(A) maximum 5 nights with compensation **)
	$L_{Aeq,\ 30min}$ *)	between 55 dB(A) and 65 dB(A) maximum 20 days **)	between 50 dB(A) and 60 dB(A) maximum 40 evenings **)	between 45 dB(A) and 55 dB(A) maximum 20 nights **)
	$L_{Aeq,\ 30min}$ *)	lower than 55 dB(A), unlimited number of days **)	lower than 50 dB(A), unlimited number of evenings **)	lower than 45 dB(A), unlimited number of nights **)
Peak level	L_{Amax} *)	85 dB(A)	80 dB(A)	75 dB(A)

*) In conformance with the Guideline for Measuring and Calculating Industrial Noise (VROM, 1999), LAeq, 30min is defined as "the A weighted equivalent sound level relative to a reference pressure of 20µPa during a period of 30 minutes".
**) The limitation to a maximum number of days, evenings and nights applies per year and from the point of reference of the affected residence or other noise-sensitive building. The applicant for the exemption, but also the competent authority, has an obligation to investigate if multiple works are planned to occur in the same area. If these construction or demolition works take place in the evenings after 9 PM or at night, compensation must be offered by the entity causing the disturbance, for example, in the form of a place to sleep elsewhere, a financial compensation, placement of insulating windows, or some in-kind compensation (flowers, tickets to an event, etc.)
***) In conformance with the Guideline for Measuring and Calculating Industrial Noise (VROM, 1999), LAmax is defined as the maximum A weighted sound level measured with the meter set to "fast".

All building works may not exceed the maximum exposure values in conformance with the Buildings Decree. If such values are exceeded there is a chance that the works will be mandated to stop or be shut down until the contractor has ensured such measures whereby the activities are demonstrated to remain within the statutory limits.

Measures to be taken in case of exceeding the maximum exposure values must be agreed with the competent authority.

If there is a possibility that maximum exposure values could be exceeded, the risk of execution works being delayed, with all the correspondent consequences, must be considered.

7

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8

GLOSSARY OF TERMS

Glossary spanning the fields of geotechnical engineering, turbine manufacturers and crane suppliers

Auxiliary cranes	Auxiliary cranes, also called 'assist cranes', are mobile cranes utilized to provide assistance during works such as assembly and disassembly of another mobile crane.
Ballast	Counter-weight of a mobile crane.
Bearing pressure	Pressure from the crane that acts on the supporting ground. In the case of an outrigger crane, this is the force under the outrigger plate; in the case of a crawler crane, it is the pressure under the crawler tracks.
Boom assembly area	The space required to assemble the boom and/or fly jib of a crane.
Boom extension	An informal term for a fixed fly jib that is mounted in a stationary position at the top of the main boom.
Boom lowering	Laying down, or bringing to a horizontal position, the main boom (and fly jib).
Bulge	The maximum height difference between the water table in waterways (ditches) and the phreatic groundwater level. The degree of bulging is dependent on the capillary rise of the groundwater, which is determined by permeability of the type of soil present and the air pressure. Sand, for example, has a high permeability and therefore relatively little bulge, unlike clay and peat.
Clearance	The shortest distance between the load to be lifted or any obstacle to the boom or fly jib of a crane.
Consolidation	The process of pressing the groundwater out of the soil pores during a hydrodynamic period. During the consolidation period the ground temporarily has less or no strength.
Contact area	The surface area on which the bearing pressure acts. For eccentric loading, this is not equivalent to the surface area of the outrigger plate or crawler track.
Crane hardstand	This is the area (or platform) where the crane is set up. The hardstand provides sufficient space and surface strength for the crane in the operational mode. In many cases, extra space is needed around the hardstand for crane assembly and disassembly (see boom assembly area).
Dewatering depth	The height difference between the phreatic groundwater level and the hardstand pavement surface.
Dry zone	The difference between the water level in a waterway (ditch) and the surface of the crane hardstand.
Drained soil behavior	Arises as a consequence of a short or dynamic load, when there is for a very short duration, excess water pressure in the pores of the soil. Arises in sand. The hydrodynamic period is then very short.

Excess pore pressure	Sudden increase in pore pressure within a soil due to rapidly applied loading conditions (undrained loading). Generated particularly in layered soil profiles in which dissipation to the environment is limited.
Fly jib	An attachment part to extend the main boom. Types of fly jibs are the stationary fly jib, referred to as the 'fixed fly jib' and the articulated jib, which is called a 'luffing fly jib'.
Hydrodynamic period	The time period in which excess water pressure in soil pores diminishes to zero due to consolidation. In this period, the soil strength recovers.
Lattice boom	A main boom made up of several lattice structure sections which are attached to each other using pins. Cranes with a lattice boom are also called lattice boom cranes.
Lift drawing	A drawing showing the top and side views of one or more crane set-up arrangements and the corresponding data. A lift drawing can be part of the (compulsory) lifting plan.
Lifting plan	The lifting plan is a compilation of agreements and documents with information about execution of the lifting operation. The lifting plan can contain information about the load, the rigging tools , the crane and environmental factors such as the supporting ground. The lifting plan can be simple, containing only a work order and instructions, but it can also consist of multiple components such as a lift drawing and a task risk analyses (TRA).
Luffing	Reduction of the radius of a crane by raising up the main boom. The main boom thus becomes more vertical.
Main boom	The basic boom of a mobile crane. The main boom can be made up of several telescopic sections or of lattice structure sections attached to each other.
Nacelles	The encasement at the top of the turbine mast which houses the wind-power generating components.
Notice time	The period between placement of an order for a crane and the time that the crane needs to be mobilized.
Off-limits period	High water or storm season.
Operating mode	The situation between assembly and disassembly of the crane; the crane is either 'ready to lift' or lifting is being performed with it.
Outriggers	A crane equipped with outriggers (usually) has four hydraulic support feet which allow the crane to be set up level.
Phreatic groundwater level	The level of the groundwater where the pores in the soil are saturated with water. This is also referred to as the 'free groundwater level' or 'phreatic surface level'.
Radius	The horizontal distance from the center of the slewing ring of a mobile crane to the vertical projection of the centerline of the lifting hook (also called the 'working radius').
Risk-based soil investigation	Soil investigation in which the scope and content are determined based on a prior risk assessment, the aim being to minimize the geotechnical risks as effectively as possible.
Rotor hub	Central connection of the rotor blades.

Signaler	The signaler is responsible for directing the crane operator by relaying the right instructions. This can be done using hand and arm signals, but also via a walkie-talkie. The law requires the role of signaler to be filled during every lifting activity. Depending on the complexity of the lift and the expertise of the worker involved, it is possible for the signaler to also fill the role of slinger .
Slinger	The slinger is responsible for safely attaching and detaching the load. If necessary, the slinger must be able to guide the load (at the instruction of the signaler), for example, using taglines. By law the role of the slinger must be filled during every lifting activity. Depending on the complexity of the lift and the expertise of the workers involved, it is possible for the slinger to also fill the role of signaler.
Stability (crane foundation)	The ground-mechanical or foundation stability indicates the extent to which the supporting ground is resistant to failure due to the driving loads on the crane hardstand. The capacity of the soil to resist failure is termed the load capacity, or bearing capacity. Failure of the supporting ground can arise in various forms, from collapse or slip surfaces. The load capacity of the supporting ground must provide a certain safety margin beyond the planned load. This margin is specified for various failure mechanisms in the geotechnical standard NEN 9997-1.
Stability (crane)	The extent to which the crane itself is capable of remaining in equilibrium when the moment balance is exceeded due to a load being lifted or other static and dynamic forces.
Stability	The ability of an object to resist forces that can bring the object out of an equilibrium state.
Superlift attachment	An auxiliary attachment that can be mounted to a variety of lattice boom cranes with which a remarkable increase in the capacity of the crane can be achieved. The attachment is made up of a backwards facing superlift boom (also called the ‘derrick’ boom) with extra ballast attached to it. Sometimes the superlift attachment is only needed for the boom erection of a lattice boom crane into an upright position.
Superlift ballast	The ballast that is attached to the superlift boom. The minimum and maximum amount of superlift ballast differs depending on the lifting activity (or boom configuration).
Superlift tray	The basic frame onto which the superlift ballast is placed. The frame is attached to the tip of the superlift boom using pendants .
Tandem lift	Lifting operation executed with two cranes.
Telehandler	A multifunctional self-propelled vehicle that, dependent on the attached fittings, can raise or lift loads. Applications such as a forklift, a crane, an aerial hardstand and an earth moving machine are possible. Telehandlers have a telescopic main boom. The upper carriage can be fixed or rotating.
Telescopic boom	A main boom made up of several telescopic sections.
Telescopic crane	As used in this handbook, refers to a crane with a telescopic main boom and an undercarriage on wheels equipped with outriggers.

TOM	Trade-off matrix or decision matrix. Provides an overview of the different alternatives, in addition to a list of decision criteria. The values assigned to the different alternatives in the decision matrix are also dependent on the value of the criteria (their level of importance). Criteria might be, for example, price, quality, feasibility, impact on the environment, etc.
Top slewer	Informal name for tower cranes with the slewing ring at the top of the crane.
TRA	Task Risk Analysis. The goal of the task risk analysis is to identify and eliminate, or reduce, the risks involved in certain risky tasks. It serves to enable activities to be carried out more efficiently and to prevent accidents.
Truck pusher	The truck pusher is a logistical coordinator responsible for directing freight traffic on a job site.
Undrained soil behavior	Arises as a consequence of a short or dynamic loading, in which there is excess water pressure in the pores of the soil for just a very short time. In this period, the ground has very little, or only a constant and limited strength, and responds in this period more or less elastic. Occurs in cohesive soil layer such as clay and peat. The hydrodynamic period is then relatively long.
Uppercarriage	The upper body of a crane. The uppercarriage is mounted on the crane slewing ring . During slewing it rotates relative to the undercarriage. The uppercarriage is made up of, among other things, the main boom, the hoisting winch and (in most cases) the operator’s cab.
Wind kit	An extra fly jib, approx. 6 to 14 m long, which can be mounted at a fixed angle at the top of the boom extension.

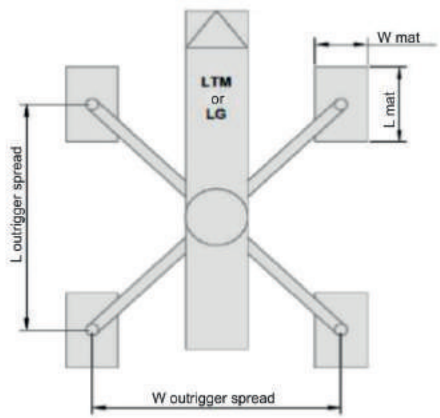
APPENDIX A

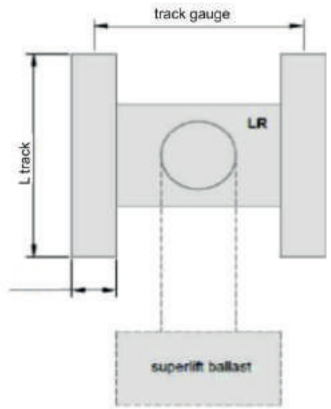
TABLE OF CRANE LOADS

The values in this table are intended for indicative purposes only, to raise awareness of the magnitudes involved. For every load case other crane types and/or configurations are available which will have different outrigger forces and/or crawler track pressures. For every project the crane hirer must confirm the ground pressures arising via the lifting plan.

Load Case		Crane Technical Data							Boom erection				Operational Mode, Lifting Nacelle					
Nr	Crane	Config-uration	Nacelle weight	Hub height	Crane mass	Outrigger spread LxW/ track gauge	Mat dimen-sions[2] LxW	Track dimen-sions[3] LxW	Required SL ballast	Total crane mass	Max. outrigger force	Max. track pressure	Hook height	Crane radius	Required SL ballast	Total crane mass	Max. outrigger force	Max. track pressure
			(ton)	(m)	(ton)	(m)	(m)	(m)	(ton)	(ton)	(kN)	(kN/m^2)	(m)	(m)	(ton)	(ton)	(kN)	(kN/m^2)
1	LTM 1500-8.1	TY3SN	70	60	290	10.0 x 9.6	4.0x2.4	-	n.a.	290	942	-	75	18	n.a.	290	1472	-
2	LTM 1750-9.1	TYV2EN	80	80	395	12.0 x 12.0	4.5x2.4	-	n.a.	395	1236	-	90	20	n.a.	395	1815[5]	-
3	LTM 11200-9.1	T3YV2VEN	80	105	430	13.0 x 13.0	5.8x2.4	-	n.a.	430	1432	-	115	24	n.a.	430	2129[5]	-
4	LR 1600/2	SL3F	80	105	485	8.4	-	8.7x1.34	n.a.	485	1550[4]	315[4]	120	18	n.a.	485	-	473
5	LG 1750	SL8HS	80	105	495	16.0 x 16.0	6.0x2.5	-	n.a.	495	2276	-	125	18	n.a.	495	1864[5]	-
6	LR 1600/2	HSL4DF	80	120	560	8.4	-	8.7x1.34	250	810	-	942	135	20	0-70	560-630	-	545
7	LG 1750	SL8HDS	80	120	460	12.0 x 12.0	6.0x2.5	-	200	660	2276	-	140	20	-	460	1991	-
8	LR 1600/2	SL13DFB	80	140	565	8.4	-	8.7x1.34	300	865	-	816	155	24	45-90	610-655	-	498
9	LG 1750	SL7DHS	80	140	520	12.0 x 12.0	6.0x2.5	-	250	770	2766	-	150	24	-	520	2325	-
10	LR 1750/2	HSL7DHS	80	140	630	8.8	-	9.1x1.34	290	920	-	904	155	24	-	630	-	739
11	LR 1750/2	SX3D4F2B	105	165	830	8.8	-	9.1x1.8	400	1230	-	587	180	28	105-175	935-1005	-	421
12	LG 1750	SX3D4F2B	110	165	725	12.0 x 12.0	6.0x2.5	-	400	1125	2943	-	180	28	110-180	835-905	2560	-
13	LG 1750	SL12D2FB	140	130	750	12.0 x 12.0	6.0x2.5	-	340	1090	2502	-	145	28	130-190	880-940	2609	-

Notes:
1. Excluding any superlift (SL) ballast required to raise the boom or in the operational mode.
2. Indicative only (generally differs per crane hirer); it is allowed to position the mats in a rotated position.
3. Most crawler cranes in this class can be equipped with tracks 1.5 m or 2.0 m in width (the effective width on a hard surface is, respectively, 1.34 m and 1.84 m).
4. The boom is raised using mechanical outriggers; the full crane mass is distributed over the two outriggers (max. 1550 kN per outrigger) and one crawler track (max. 315 kN/m2).
5. In the operational mode, the greatest pressures may arise without a load on the hook, with a fully luffed main boom (related to a backwards-acting moment produced by the crane ballast).





APPENDIX B

PRINCIPLES OF RISK-BASED SOIL INVESTIGATION

B.1 INTRODUCTION

Risk-based soil investigation is organized in line with the Geo-Risk Management (GeoRM) methodology. The approach is described in CUR Geo-Impuls Report 247 on risk-based soil investigation, from the planning stage to execution (in Dutch) [17].

A geotechnical risk can be defined in general terms as an undesired event with a geotechnical cause, a probability of occurring and an impact on the achievement of an objective.

GeoRM stands for 'Geotechnical Risk Management' and comprises a cyclical work process accepted throughout the industry, in which geotechnical risks are dealt with continuously, explicitly and with open lines of communication with the aim of *achieving project objectives as efficiently and effectively as possible.*

Most of the geotechnical risks related to crane hardstand design concern strength and deformation of the subsoil and working surface. The phreatic groundwater level and hydraulic head have a large influence on the stresses in the ground and play an important role in this.

With GeoRM, the geotechnical risks are made transparent and explicit, and a risk-aware operational procedure is pursued in projects. Application of GeoRM provides a structured way to deal with the uncertainties that arise from the different geotechnical risks.

The GeoRM methodology comprises six sequential steps:

1. Gathering information and identification of the objectives
2. Identification and assessment of geotechnical risks
3. Classification of geotechnical risks
4. Selection and implementation of preventative and corrective management measures
5. Evaluation of whether the established management measures resulted in the intended risk reduction
6. Handover of all relevant risk information within the project organization to the next project phases

B.2 GEOTECHNICAL SOIL INVESTIGATION

Geotechnical soil investigation is an important tool for management of the geotechnical risks. Information about the composition and geotechnical properties of the subsoil play an important role in each of the six risk management steps. However, the importance of soil investigation is greatest in the identification (2), classification (3) and evaluation (5) steps. Table B.1, from CUR/Geo-Impuls [17] is presented below to clarify the principles and practice of geotechnical soil investigation.

TABLE B.1 THE ROLE OF GEOTECHNICAL INVESTIGATION IN THE SIX RISK MANAGEMENT STEPS; SOURCE [17]

Risk management step		Role of geotechnical soil investigation
Nr.	**Description**	
1	Gathering the available project information and defining project objectives	Check whether the project objectives specified for the phase under study (the upcoming phase) are acceptable based on the expected geotechnical properties of the soil and the data currently available
2	*Identification* and *assessment* of risks (what are the risks?)	Identification of (new) geotechnical risks based on the available data
3	*Classification* of risks (how large are the probabilities and consequences of the risks?)	Qualitative and, if necessary and if possible, quantitative classification of geotechnical risks
4	*Establishing and implementing* risk management measures (reduction of probability and/or consequences)	Implement (additional) research or (additional) analyses and/or monitoring (depending on the project phase)
5	*Evaluation* of the risk management measures (will the intended risk reduction be achieved?)	Based on the measures implemented in the previous step, analyze whether the identified risks have been adequately contained and whether additional risks were found in the preceding step. If the risks are deemed sufficiently small for someone to bear, the transition to the next step is possible
6	*Handover* of the resulting risk dossier to the next project phase	Using geo-data management principles, transfer all information about the geotechnical properties of the soil -- both monitoring data and the results of (additional) soil investigation -- in or linked to a uniform and accessible risk dossier

The above steps are part of a cyclical process carried out in each project phase.

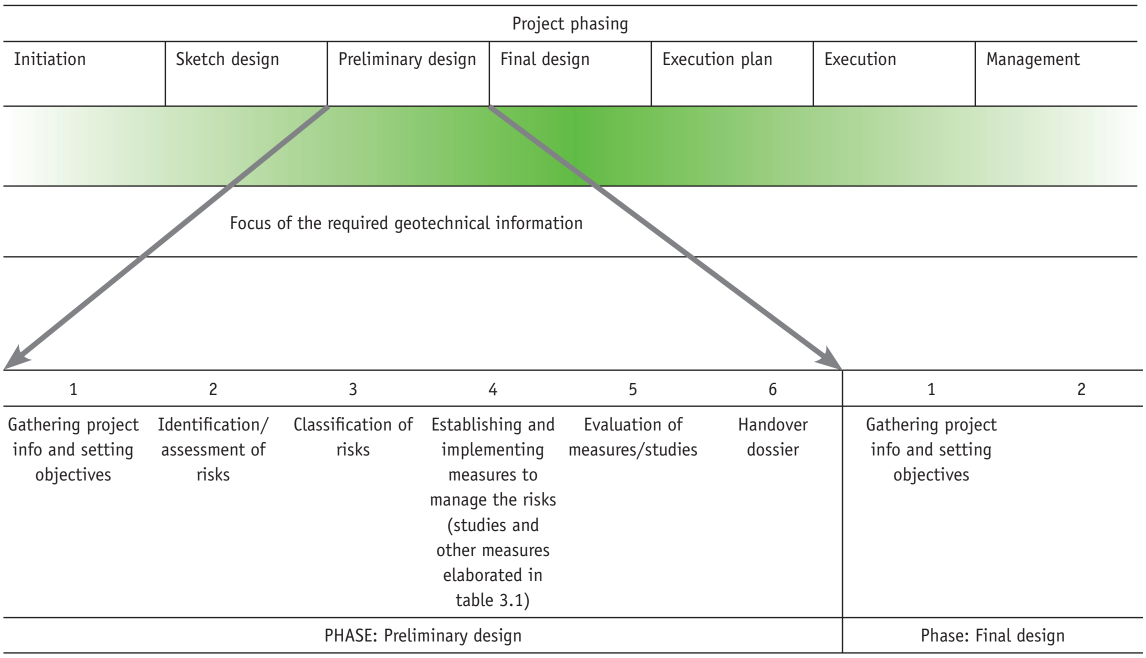
Note that due to new insights obtained from additional geotechnical soil investigation, the probability of geotechnical risks and their correspondent consequences may not only diminish, but can increase as well. This would mean a previously unknown project risk is identified, and that the prior risk identification/assessment was incomplete. Prompt acknowledgement of such a situation, alongside appropriate measures, will serve to effectively contain the increased geotechnical risk.

B.3 NEED FOR GEOTECHNICAL INFORMATION

The need within a project for information on the subsoil will differ depending on the project phase. Figure B.1 shows that the greatest need for such information will be particularly in the phases from the Preliminary Design up to and including Execution. The nature of the information (e.g., the amount and desired level of detail) will also differ in the different project phases. These varying needs can be planned for and accommodated by applying risk-based soil investigation.

Because the risk management cycle is implemented anew upon each transition to a new phase, the identification and investigation of risks anticipated in the next phase(s) comes up 'automatically' as well as the question of how these risks will be dealt with.

FIGURE B.1 CYCLE WITHIN ONE OF THE PROJECT PHASES



B.4 SIX QUESTIONS FOR A RISK-BASED SOIL INVESTIGATION

In carrying out a risk-based soil investigation using the method described above, it is important to run through a fixed number of generic questions to identify and manage risks.

Table B.2 presents six generic questions with the corresponding actions for the design and implementation of a risk-based soil investigation (or commission thereof). The table additionally provides a brief flow chart example.

TABLE B.2 SIX QUESTIONS AND CORRESPONDING ACTIONS IN RISK-BASED SOIL INVESTIGATION

Nr.	Question	Actions	Example
1	What type of structures?	Determine the subsoil-related structures involved in the project.	Crane hardstand constructed as a shallow foundation or on piles
2	What risks?	Determine undesired events (consequences).	Subsoil failure, tipping over of crane, permanent loss of soil strength, schedule and cost overruns
3	What mechanisms?	Determine the significant geotechnical mechanisms (cause).	Shear and deformation
4	What methods?	Identify methods to allow determination of the extent that the mechanism will occur.*	Calculation models, Prandtl, Koppejan, Darcy, finite element methods
5	What soil parameters?	Determine the most critical soil parameter(s) involved.	Density, strength and stiffness properties
6	What soil investigation/ measure or monitoring?	Given the geological heterogeneity, determine the type, quantity and quality of the soil investigation needed to determine these soil parameters.	Number and types of CPTs, borings with sampling and laboratory analyses/quality of the working surface, settlement of the crane, both in the static situation and during lifting

Note: * These can be both design methodologies and execution methods.

This basic framework is used to elaborate the soil investigation necessary for crane hardstands to install wind turbines.

B.5 RELATIONSHIP BETWEEN SOIL INVESTIGATION AND CONTRACT FORM

GENERAL

In the Netherlands, both traditional contracts, in conformance with UAV1989 [67], and integrated contracts, in conformance with UAVgc [68], are used. The client determines which form of contract will be used. If an abnormality in soil properties comes to light in the execution or use phase, the contract form may influence how the geotechnical risks are allocated between the client and contractor.

CONTRACT FORMS

In a traditional contract there is a strict division between design and execution. Design tasks are performed by the client; which is then responsible for adapting the design to the expected soil properties. The contractor is responsible for work preparations and the actual execution of the works.

In integrated forms of contract, the contractor is responsible for some or all design tasks, and therefore also for adapting the design to the soil properties. In this way of working, the client and contractor make explicit agreements on the roles and responsibilities that each will take on and bear in each project phase. This enables the results of the soil investigation to be closely aligned to the intended risk allocation for the specific project in question.

GEOTECHNICAL RISK ALLOCATION

If the responsibilities and risks are not clearly allocated and abnormalities in soil properties do come to light, conflicts may arise between the client and contractor. It is therefore preferable to make prior contractual agreements regarding how to proceed if such abnormalities occur and how the risks and responsibilities will be allocated.

A guide to the allocation of geotechnical risks in the form of a Geotechnical Risk Allocation [18] can help answer questions that may come up in any particular situation about whether abnormalities in soil properties and exceptional circumstances can be said to exist.

As an annex to the specification requirements, the Geotechnical Risk Allocation is contractually and legally binding. It is therefore of utmost importance to understand at a very early stage the geotechnical risks, so that adequate agreements can be reached concerning responsibilities.

B.6 GENERAL REQUIREMENTS FOR IMPLEMENTATION OF SOIL INVESTIGATION

For general implementation requirements, see Chapter 6 of CUR/Geo-Impuls Report 247 on risk-based soil investigation, from the planning phase to execution (in Dutch) [17]. The standards referenced in that chapter are now outdated. Appendix C provides a revised version of Chapter 6.

B.7 DOCUMENTATION AND HANDOVER OF GEOTECHNICAL DATA

In each phase of the design and of the corresponding soil investigation, a time arrives at which the phase is completed and all the data gathered, along with the conclusions drawn based on them, are documented for use in the next design phase, for example, from a preliminary design to a more detailed phase.

Accessible and structured reports documenting all data and conclusions may well be the most important part of a soil investigation. These are particularly key in cases where all data, and often also the attendant responsibilities, are handed over to another party.

For more information on documentation and handover of geotechnical data, see Chapter 7 of CUR/Geo-Impuls Report 247 on risk-based soil investigation from the planning phase to execution [17].

APPENDIX C

GENERAL REQUIREMENTS FOR SOIL INVESTIGATION

This appendix discusses specific considerations and requirements to be adhered to in every soil investigation. The requirements for geotechnical laboratory tests and field surveys must, compliant with NEN9997-1 [46], be in fulfilment of NEN-EN 1997-2 [47] and [48].

The geotechnical investigation for crane hardstands falls into geotechnical category 2 or 3 (GC2 or GC3) at minimum. For guidance on this choice, see NEN 9997-1 [46].

C.1 SURVEY LOCATIONS

For all survey locations, the RD coordinates must be documented and the elevation with respect to NAP measured. The locations where surveys are done must be indicated on a site drawing. The drawing must show the locations of any tests previously implemented as well.

If the elevation and coordinates of the survey locations are given in NAP and RD coordinates, the maximum deviation of the coordinate measurements is approx. 10 cm and the maximum deviation of the elevation measurement is approx. 5 cm.

For projects in which CPTs reference a local fixed point, the maximum deviation in elevation is approx. 5 cm. The maximum deviation in measurements done using traditional markings with a measuring tape is approx. 25 cm.

If the survey locations do not reference a fixed elevation, the tests deviate from the stipulations of NEN-EN-ISO 22476-1 [58].

C.2 CPTS

NEN9997-1 specifies in article 3.1 (b) that for GC2-categorized structures, class 3 or 4 electronic CPTs must be executed in line with NEN-EN-ISO 22476. For GC3-categorized structures, this must be at least class 2. The class of the CPTs, in conformance with NENEN-ISO 22476-1 [58], must be indicated on the results graph.

The class division relates mainly to the precision of the measured parameters.

It is most practical to always implement CPTs with measurement of cone resistance, slope and sleeve friction, in conformance with NEN-EN-ISO 22476-1 class 2 [58]. This procedure may be deviated from in special cases where the subsoil contains rubble or gravel, meaning that there is a large chance of damage to equipment.

C.2.1 REQUIRED SURVEY DEPTH

In view of the need for settlement analyses, CPTs must be implemented to a depth of at least the first sand layer of greater than 5 m in thickness. For calculations related to shallow foundation bearing capacity, the survey depth corresponds to the depth of influence. The required CPT depth is then approx. 2 times the width of the foundation element under the foundation level.
The CPTs should then preferably be done within a width of influence of approx. 2 to 6 times the foundation width.

If a piled foundation is used, the depth of the CPTs must be at least 5 m below the estimated pile tip level. An impression of the minimum required CPT lengths can be obtained based on historical or archive research.

C.2.2 PRE-BORING

The top 1.5 m is often pre-bored due to the risk of damage to cables and pipelines. In that case, the description must be included on the CPT chart.

C.2.3 CPTS WITH WATER PRESSURE MEASUREMENT

It is recommended that several CPTs be implemented with water pressure measurement. The water pressure measurements provide additional information to aid in classification of the soil and subsoil layers. Water pressure measurements also provide information about the groundwater head in relation to depth.

The exact number of CPTs to be carried out with water pressure measurement is highly dependent on the specific project, but if settlements play an important role, 10% of the total can be adhered to as a rule of thumb. For foundation and construction levels below the groundwater level, implementation of at least one CPT with water pressure measurement is recommended.

Depending on the situation, a special type of CPT cone can be used to obtain measurements of additional quantities, such as magnetic field (metal objects), groundwater conductivity (fresh/salt boundary and chloride content), temperature, vibrations (shear waves and velocities), in-situ stress-strain behavior and strength (CPM), an image of grain structures (video), and hydrocarbons (MIP, ROST).

C.3 BORINGS AND LABORATORY ANALYSIS

C.3.1 EXECUTION OF BORINGS

Borings must be executed in conformance with NEN-EN-ISO 22475-1 [57]. To enable the classified soil layers to be correlated to the implemented CPTs, each borehole must be executed in combination with a CPT at the same location. The depth of the borehole must be determined based on the CPT data; at minimum to the uppermost sand layer of at least 5 m in thickness. Due to the costs involved, it is frequently efficient to carry out a much larger number of CPTs than borings. Because the findings from the borings and the corresponding laboratory analysis are often a key input in determining the final soil parameter dataset, it is important to utilize the available boring meters efficiently. For that reason, soil investigation should preferably be phased in such a way that the borehole locations can be chosen based on the results from the CPTs.

Choosing borehole locations based on the CPTs is a job for a geotechnical specialist. The same applies to identification of the borehole samples on which particular tests are to be performed. If the project lends itself, it is recommended that these choices be made by the geotechnical specialist involved in engineering the work.

Soil samples can be taken in disturbed or undisturbed state. The soil taken from both mechanical and manual borings must be classified in accordance with NEN-EN-ISO-14688-1 and 2 [55 and 56] (replaces NEN 5104) and described in a borehole log.

The boring methods and obtained sample class must be indicated on the borehole description/log, in conformance with NEN-EN-ISO 22475-1 [57].

Classification tests and, possibly also additional geotechnical tests, are usually performed. The requirements to be adhered to for borings and taking samples depend in part on the tests to be performed on the samples from the borings. The sections below elaborate on this relation.

C.3.2 GROUNDWATER MONITORING WELLS

Placement of groundwater monitoring wells in boreholes must be done in conformance with NEN-EN-ISO 22475-1 [57].

After boring, at minimum the current groundwater level in the borehole must be determined and recorded. For measurements in the borehole, however, false groundwater readings can occur. Borings can also be utilized for placement of groundwater monitoring wells. These must then be situated at different depths in the borehole, as indicated by the CPT data, so that the hydraulic gradient can be plotted in multiple layers simultaneously.

It is recommendable to choose the borings that will be completed as monitoring wells keeping in mind the need to minimize the chance that they will be lost.

C.3.3 CLASSIFICATION TESTS

In the Netherlands, current practice for cohesive layers is to use at least wet/dry density and water content to get an impression of the division of soil types and corresponding densities. In combination with the other tests carried out, a substantiated classification of soil types and corresponding parameters can then be obtained for the design. Often a simple frequency distribution of the measured densities is sufficient to obtain a clear picture of the dominant soil types. However, this requires that enough classification tests have been performed to do a meaningful statistical assessment for NEN 9997-1 [46].

If the strength of the soil is important for the project, it is recommendable to also do pocket penetrometer or torvane tests on the samples taken from the cohesive layers of every borehole. These tests provide a quick indication of the undrained shear strength of the material of each layer.

For all the abovementioned classification tests, access to undisturbed samples is required.

Sand samples can almost always be obtained only in disturbed state. Borings in sand are usually done with a pulse or auger. The samples obtained are then unsuitable for use in the abovementioned classification tests.

C.3.4 COMPRESSION TESTS

Compression tests or Oedometer tests are carried out in conformance with NEN-EN 17892-5 [59] in situations where soil compression is important. The samples must be undisturbed. Moreover, the diameter of the borehole must be sufficiently large, preferably at least 66 mm. Samples for compression tests have a diameter of 50 mm.

The results of the compression tests play an important role in all project phases. Special care should therefore be taken in the execution of these tests. For key considerations and guidelines in ordering compression tests, readers are emphatically advised to consult the CUR/CROW guideline on geotechnical laboratory analysis (in Dutch) [21].

In addition, the following aspects are essential for meaningful interpretation of the test results:

1. CHOICE OF LOAD STEPS

The load steps used must be chosen to correspond at least to the highest expected in-situ load steps. Too low load steps in the test will produce an incorrect primary compression coefficient for higher loads and therefore an incorrect settlement prediction. It is particularly important to keep in mind that much larger load increases often occur locally. For example, if mounds are to be part of the works, but in a design phase too, scenarios are possible where loads might be temporarily greater than the (net) final loading.

It is recommended that a highest load step of at least 150 kPa be used, even for a relatively small surcharge loading.

2. UNLOADING AND RELOADING TESTS

To perform settlement predictions when preloading or temporary surcharge loading is used, the soil behavior after surcharge removal and reloading will be of key importance. Because the test results obtained before the preconsolidation phase are often unreliable due to sample disturbance, a better indication of the soil behavior upon unloading can be obtained by planning in unloading and reloading tests.

3. ELABORATION OF TEST RESULTS USING DIFFERENT METHODS

The test results must be elaborated according to NEN, a,b,c and the Koppejan method, so that a calculation model can be chosen for the design.

4. DETERMINING THE CONSOLIDATION COEFFICIENT ACCORDING TO TAYLOR AND CASAGRANDE

In the Netherlands, the tests are often elaborated using only the Taylor method. However, elaboration according to the Casagrande method is sometimes also desirable, because in certain
cases greater precision is obtained with the latter. Moreover, the results of the methods often differ. It is therefore advisable to include elaboration using both methods.

5. DETERMINING PERCENTAGE OF ORGANIC MATTER

For humus (organic) samples, it is important to determine the percentage of organic matter, because this is essential for obtaining the void ratio. Calculations according to NEN-Bjerrum are highly sensitive to this.

C.3.5 TRIAXIAL TESTS

Triaxial tests are performed in situations where soil strength is important, see also NEN-EN-ISO 17892-8 and 9 (E) [37 and 38] and NEN 5117 [49]. For key considerations and guidelines in ordering triaxial tests, readers are emphatically advised to consult the CUR/CROW guideline on geotechnical laboratory analysis (in Dutch) [21].

For implementation of triaxial tests on cohesive layers, undisturbed samples must be available; this constraint does not apply for tests on sand. The minimum diameter of a sample for a triaxial test is 35 or 50 mm.

Obviously the borehole diameter must be adequately large. For multi-stage tests, at least 66 mm is recommended, and for single-stage tests at least 100 mm; see also the comments under 'CU tests'.
In general, triaxial tests can be categorized into three types:

- C(I)U (Consolidated Undrained). The sample is allowed to consolidate under different pressure gradients to the so-called consolidation pressure; the shear test is executed undrained, by measurement of the water pressure.
- C(I)U (Consolidated Drained). The sample is allowed to consolidate under different pressure gradients; the shear test is executed drained.
- UU (Unconsolidated Undrained). The sample is not allowed to consolidate under different pressure gradients; the shear test is executed undrained, by measurement of the water pressure.

Generally speaking, the CU and CD tests are performed in an isotropic (I) stress field, in which the initial consolidation pressures are equivalent in the horizontal and vertical direction. For closer conformance with the actual in-situ stress state, the CU test can also be executed in anisotropic state (A) in which the horizontal consolidation pressure is less than the vertical. This method takes longer and therefore is higher in price.

CU TEST

For cohesive soils, a CU triaxial test is almost always carried out, in order to determine the internal angle of friction and cohesion. To obtain these values reliably from a CU triaxial test, the test must be executed at three consolidation pressures. In the Netherlands, multi-stage triaxial tests are often used in which the same sample is tested at three (sometimes even four) different consolidation pressures. For single-stage tests, a new sample is used for each test. A disadvantage of multi-stage tests is the risk of sample disturbance during test execution. Moreover, the sample can only be subjected to a limited deformation, so the strength properties at failure cannot be determined.

A disadvantage of single-stage tests is that multiple samples are needed, so differences in properties between the samples can influence the results. To compensate for this disadvantage, borings with a diameter of at least 100 mm can be used. In that case, three samples can be taken from one borehole level so as to minimize differences between the samples.

Especially if the strength at failure is to be determined, application of the aforementioned larger borehole diameter in combination with single-stage triaxial tests is preferred. BS 5930 states, "Multi-stage tests are not recommended when single stage tests can be carried out."

CD TEST

The strength and stiffness parameters of sand can be determined based on CD triaxial tests. A good approximation of these parameters is obtained by carrying out the tests in the stress field of the in-situ stresses and corresponding density. The in-situ stresses are determined by the (effective) weight of the layers above, and thus from the results of classification tests on the borehole samples. In-situ density can be approximated from the local cone resistance and correlation with the vertical grain tension by determination of the theoretical relative density, for example, with the correlation of Lunne [42, 43, 44].

By obtaining the minimum and maximum density of the sand in the laboratory, the in-situ density can then be calculated. This is then implemented in the CD test.

If the project scope allows enough tests to be carried out on the same sand layer, it is often advisable to perform the tests at various densities, so that the relation between density and strength can be obtained.

UU TEST

The UU test is less common. It is almost always carried out on cohesive material to get an impression of the undrained shear strength of the soil.

C.3.6 DETERMINING PARAMETERS FROM LABORATORY TESTS

To use the results obtained from the laboratory tests in the design, the specifications in NEN 99971 [46] for determining the characteristic value of the soil parameter have to be considered. For every relevant distinguishable soil layer at least three parameter determinations have to be performed. In all other cases, the target values stated in Table 2.b of NEN 9997-1 [46] determine the characteristic value of the soil parameter, because in that case too little insight is obtained in actual variation in the size of the observed soil parameter at the project site. In many cases, this lack of insight will lead to the use of more conservative, and therefore, more costly design, and in some cases, it will lead to greater risks.

APPENDIX D

TRADE-OFF MATRIX FOR FOUNDATION DESIGN SOLUTIONS

Trade-off matrix: Foundation solutions for crane hardstands for wind turbine installation

Type foundation/aspect	Design					Execution			Use			Other		
	Minimizing interfaces with turbine foundation	Minimizing influences on the geohydrological situation	Robustness to uncertainties in subsoil strength	Robustness to differential settlements	Robustness if slopes are nearby	Minimizing building time	Minimizing nuisance in the environment	Robustness of design to execution quality	Flexible placement of loads possible	Robustness to exceeding maximum loads	Minimizing maintenance due to use damage	Minimizing costs	Ease of removal	Minimizing impact on the environment
Shallow foundation	+	+	-	-	-	+	+	+	0	-	-	+	+	+
Shallow foundation – ground improveme	+	0	0	0	-	0	+	0	0	-	-	0	0	0
Shallow foundation – soil mix/mix in plac	-	0	-	0	-	-	+	-	0	-	0	0	-	0
Shallow foundation – geosynthetics	+	+	0	0	0	+	+	0	0	0	0	+	+	+
Piled embankment	-	0	+	+	0	-	0	0	0	+	0	-	-	-
Footing with piles	-	0	+	0	+	-	-	0	-	+	+	-	-	-

Explanation of scores:

+	Scores high on this aspect compared to other types of foundation
0	Scores average on this aspect compared to other types of foundation
-	Scores low on this aspect compared to other types of foundation