SYSTEMS APPROACH AND QUANTITATIVE DECISION TOOLS FOR TECHNOLOGY SELECTION IN ENVIRONMENTALLY FRIENDLY DRILLING

A Dissertation

by

OK-YOUN YU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2009

Major Subject: Civil Engineering

SYSTEMS APPROACH AND QUANTITATIVE DECISION TOOLS FOR TECHNOLOGY SELECTION IN ENVIRONMENTALLY FRIENDLY DRILLING

A Dissertation

by

OK-YOUN YU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Chair of Committee,	Jean-Louis Briaud
Committee Members,	Roy Hann
	Seth Guikema
	David Burnett
Head of Department,	David V. Rosowsky

May 2009

Major Subject: Civil Engineering

ABSTRACT

Systems Approach and Quantitative Decision Tools for Technology Selection in Environmentally Friendly Drilling. (May 2009)

Ok-Youn Yu, B.S., KonKuk University; M.S., Texas A&M University

Chair of Advisory Committee: Dr. Jean-Louis Briaud

One of the petroleum industry's goals is to reduce the environmental impact of oil and gas operations in environmentally sensitive areas. To achieve this, a number of Environmentally Friendly Drilling (EFD) technologies have been developed to varying degrees. For example, the use of an elevated platform as an alternative to the gravel pad is less intrusive and leads to a more environmentally friendly approach to drilling operations. Elevated drilling platforms will require the use of piles. Another alternative to the gravel pad is the use of composite mats. Since the demand of low impact technologies for drill site construction has rapidly increased, the parametric study for the feasibility of using pile foundations and composite mats is conducted in this research.

Even though a number of EFD technologies have already been developed to varying degrees, few have been integrated into a field demonstrable drilling system (i.e., combination of technologies) compatible with ecologically sensitive areas. In general, it is difficult to select the best combination of EFD technologies for a given site because there are many possible combinations and many different evaluation criteria. The proposed technology evaluation method is based on a systems analysis that can be used for integrating current and new EFD technologies into an optimal EFD system. An optimization scheme is suggested based on a combination of multi-attribute utility theory and exhaustively enumerating all possible technology combinations to provide a quantitative rationale and suggest the best set of systems according to a set of criteria, with the relative importance of the different criteria defined by the decision-maker. In this research, the sensitivity of the optimal solution to the weight factors and the effects of the uncertainty of input scores are also discussed using a case study.

An application of the proposed approach is described by conducting a case study in Green Lake at McFaddin, TX. The main purpose of this case study is to test the proposed technology evaluation protocol in a real site and then to refine the protocol. This research describes the results of the case study which provided a more logical and comprehensive approach that maximized the economic and environmental goals of both the landowner and the oil company leaseholder.

DEDICATION

My father, In-Bok Yu, and mother, Sook-Ja Hyun, for their unconditional support, and

My wife, Hei-Young, for her unconditional help and lovely nagging, and

My son, Jimin, and Daughter, Soomin, for their lovely smile

ACKNOWLEDGEMENTS

To help me come this far, I received strong support and encouragement from my family. My parents financed me through my Ph.D. study and my wife, Hei-Young, had to give up many opportunities and quality of life. Big smile from my kids, Jimin and Soomin, helped me keep going forward. My accomplishment would have not been possible without their love.

I must express my sincere appreciation to my committee chair, Dr. Briaud, and my committee members, Dr. Guikema, Dr. Burnett, and Dr. Hann, for their guidance and support throughout the course of this research.

I also would like to thank the EFD subject matter experts for their assistance with this research, particularly Dr. Jerome Schubert, Ms. Carole Fleming, Dr. John Rogers, and Dr. Richard Haut. I also want to extend my gratitude to all other EFD project participants who shared their knowledge of drilling operations with me, and to Mr. JongWha Chang for helping me find emission standards of various drilling technologies.

The information contained in this dissertation is part of the research project entitled “Field Testing of Environmentally Friendly Drilling Systems” sponsored by the U.S. Department of Energy and companies from the oil and gas industry. I would like to thank all of the sponsors.

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

LIST OF TABLES

TABLE Page

TABLE Page

1. INTRODUCTION

1.1 Background

In the past 100 years the petroleum industry has provided important economic contributions and benefits to society through energy, wealth generation, and employment creation (Rogers et al. 2006). In the 21st century the industry is being metamorphosed by the need to meet its social obligations and the need to improve economic performance by considering environmental impact of oil and gas operations. Recent studies conducted by the Department of the Interior show that almost 80% of federal lands containing more than 20 billion barrels of untapped oil is currently off limits to drilling. Only by utilizing low impact drilling practices can industry gain access to these environmentally sensitive areas.

Nowadays, the petroleum industry is endeavoring to develop such low impact or Environmentally Friendly Drilling (EFD) technologies to minimize the environmental impact during drilling operations. In environmentally sensitive areas, managing environmental impact will lead to greater access to large potential reserves in areas that are currently off-limit (Rogers et al. 2006). For example, directional drilling technology has allowed the industry to contact almost 60 times the volume of subsurface rock material that could be accessed in 1970 while occupying only one-third the surface area (Harrison 2005). Moreover, reducing the environmental footprint during drilling operations using a reusable Modular Platform and small mobile rig in the Arctic was demonstrated in 2003 by Anadarko and Noble's Subsidiary, Maurer technology Inc.. The objective was to drill in an ecologically sensitive area without disturbing the ground surface. The successful demonstration used a small mining rig to evaluate the potential of drilling for hydrates under the frozen tundra of the Alaska North Slope and showed the usefulness of an onshore platform to drill in environmentally sensitive areas (Kadaster and Millheim 2004).

This dissertation follows the style of the *Journal of Geotechnical and Geoenvironmental Engineering.*

1.2 Problems

One of the petroleum industry's goals is to reduce the environmental impact of oil and gas operations in environmentally sensitive areas. To achieve this, a number of EFD technologies have been developed to varying degrees. For example, the use of an elevated platform as an alternative to the gravel pad for leveling and carrying capacity purposes is less intrusive and leads to a more environmentally friendly approach to oil and gas drilling operations. Elevated drilling platforms will require the use of piles. Another alternative to the gravel pad is the use of composite mats. As the demand of low impact technologies for drill site construction is rapidly increasing, parametric studies for the feasibility of using these technologies have become a more important part of the petroleum industry. In this research, the parametric study for the feasibility of using pile foundations and composite mats is conducted for various soil conditions and applied load areas.

Even though a number of EFD technologies and concepts have already been developed to varying degrees, few have been integrated into a field demonstrable drilling system (i.e., combination of technologies) compatible with ecologically sensitive or off-limits areas. Such sensitive areas include wetlands of the Gulf Coast and federal lands in the Western U.S. In general, it is difficult to select the best combination of EFD technologies for a given site because there are many possible combinations and many different and perhaps competing evaluation criteria. How to logically measure and select the best available EFD system for a specific site is fully described in this research.

1.3 Research Objectives

The key objectives of this research are to:

1. Help the petroleum industry engineers to get a basic idea about environmentally friendly foundation designs of a rig or an elevated platform for various weights and soil conditions in environmentally sensitive areas (e.g., desert environments and wetland applications). In order to encourage petroleum industry people to use environmentally friendly foundations such as elevated platforms and composite mat systems more often for their drilling sites instead of using gravel pads, it is an essential task in this research.
2. Develop a technology evaluation protocol based on a systems analysis to synergistically incorporate a number of current and emerging EFD technologies into a single and clean drilling system with limited environmental impact and then to suggest a small number of systems that should be particularly attractive for a given site. This decision-analytic model will help decision-makers select an optimal drilling system for a given site to minimize environmental impact and maximize profit at that specific site.
3. Develop a prototype of a web-based decision optimization tool to help decision-makers easily follow the proposed technology evaluation procedure and then select an optimal drilling system for a specific site. The web-based application can also help to manage used input parameters permanently if a central repository is maintained regularly so that decision-makers or drilling operators can easily retrieve a previously designed well model for their future operations in different ecosystems.

2. METHODOLOGY

2.1 Parametric Study of Foundations for Drill Sites

Three different types of foundations for drill sites are considered in this research.

1. Two different types of pile foundations (i.e., driven pile and bored pile): elevated platforms will require the use of piles. About one thousand different cases of pile capacity calculations are conducted depending on various soil types, pile types, and design methods. The results of these calculations are organized into a series of tables for the petroleum industry engineer to choose an appropriate pile size for a given condition without performing an extensive pile design analysis. The optimal pile selection procedure is also described in this research.
2. Dura-Base Composite Mat: feasibility study of using the Dura-Base Composite Mat System for the drill site construction is demonstrated with various applied load areas from 6 inches to 10 feets in diameter and soil types.

2.2 Development of a Systems Approach to Technology Evaluation

The information contained in this research is part of the research project entitled "Field Testing of Environmentally Friendly Drilling Systems" sponsored by the U.S. Department of Energy and companies from the oil and gas industry. The main purpose of this project is to integrate current and new EFD technologies into a viable drilling system compatible with environmentally sensitive areas and finally to suggest a small number of systems (1~5) that should be particularly attractive for a given site. The proposed method is based on a systems analysis that can be used for integrating current and new EFD technologies into an optimal EFD system. The system draws upon a large number of technologies (more than 100) identified by a government-industry joint venture studying low impact operations in sensitive ecological areas. In order to provide flexibility to the user, a small number of systems (1~5) are proposed for a given site, instead of a single best system. An optimization scheme is suggested based on a combination of multi-attribute utility theory and exhaustively enumerating all possible technology combinations (i.e., exhaustive search optimization) to provide a quantitative rationale and suggest the best set of systems according to a set of criteria, with the relative importance of the different criteria defined by the decision-maker.

Since an optimal system for a specific site would be based on subjectively assessed data, there can be considerable uncertainty about the input parameters used. Therefore, even if finding the optimal system is valuable to the decision-makers, they also would like to know how robust the decision is to changes in the input parameters such as the attribute scales, weight factors for attributes, risk-attitude (i.e., risk-neutral, risk-averse, and risk-seeking), and single-attribute utility functions assessed by different individuals (Guikema and Milke 2003). In this research, a sensitivity analysis is conducted using a case study to address this problem.

The methodology described in this research is designed to help decision-makers select an optimal drilling system for a given site in order to minimize environmental impact and maximize profit at that specific site. The technology evaluation protocol can be refined based on EFD experts' inputs and feedbacks if necessary. Further interaction with appropriate experts would be valuable in revising this evaluation protocol. The overall procedure is briefly illustrated as follows:

Step 1: Identify the main subsystems, subsets, and technologies within each subset for the EFD operations.

Step 2: Define attributes and develop attribute scales to evaluate technologies.

Step 3: Assign scores to all technologies using the attribute scales.

Step 4: For each attribute, calculate the overall attribute score of a system by adding the technology scores or selecting the minimum technology score.

Step 5: For each attribute and in order to homogenize the scores, develop a "utility function (u_i)" to convert the overall dimensional score of a system (e.g., $, acres, and grades) into a non-dimensional utility value (between 0 and 1) of the system that reflects the decision-maker(s) value.

Step 6: Decide on a weight factor (k_i) for each attribute (i^{th}).

Step 7: Calculate the overall score of the system as "$\sum k_i u_i$" (multi-attribute utility function).

Step 8: Use optimization technique to evaluate all possible systems and to find the best system for a specific site. Once all possible systems have been evaluated, the system with the highest overall score is the best system.

Step 9: Conduct a sensitivity analysis to examine the impacts of possible changes in the attribute scores, weight factors, and utility functions on the optimal system.

Step 10: Suggest a small number of systems that should be attractive for a given site.

2.3 A Case Study with Pre-Specified Systems

An application of the proposed approach is described by conducting a case study in Green Lake at McFaddin, TX; some of the difficulties in using this approach in practice are also discussed. The main purpose of this case study is to test the proposed technology evaluation protocol in a real site and then to refine the protocol. Three different systems are pre-specified by an EFD expert in order to identify possible drilling technologies for Green Lake drilling site: (1) conventional drilling; (2) moderately improved drilling; and (3) EFD in five years. First, all technologies selected in these three systems are evaluated with respect to the nine attributes. Second, these three systems' overall scores are evaluated by the proposed technology evaluation protocol. Third, use optimization technique to evaluate all possible systems and to find the best system for Green Lake drilling site. The best system is the system with the highest overall score among all possible systems. After that, a sensitivity analysis is conducted to examine the impacts of possible changes in the attribute scores and weight factors on the optimal system. Finally, a small number of systems (1~5) that should be attractive for the site are suggested.

The results of the case study which provided a more logical and comprehensive approach that maximized the economic and environmental goals of both the landowner and the oil company leaseholder are described in this research.

3. EXISTING KNOWLEDGE

3.1 Onshore Drilling Sequence

According to Dyke (1997), the standard drilling operation procedure is briefly illustrated as follows:

Step 1: Receive initial well planning information including Surface Hole Location (SHL) with Bottom Hole Location (BHL) if applicable.

Step 2: Confirm lease issues including surface ownership.

Step 3: Check the site specific state permit requirements.

Step 4: Check the topographical/ cultural requirements.

Step 5: Confirm operational parameters including mud system and disposal options (onsite vs. offsite).

Step 6: Construct access road.

Step 7: Construct pad (site preparation) including mud reserve pits if applicable.

Step 8: Place a rig and other required components.

Step 9: Drill the hole.

3.2 Pile Foundation Design

Use of a raised platform in environmentally sensitive areas will require the use of piles to support the elevated platform instead of gravel pads as used in a conventional platform. Piles are used to transfer the load from the structures on/above the ground surface to the underlying soil mass. The axially transferred loads are resisted by the friction between the pile and the surrounding soil as well as the end bearing resistance at the bottom of the pile. It is critical in pile designs to estimate the proper axial capacity of the pile depending on the pile and soil types. In addition, the lateral capacity of the pile also should be checked since most piles must resist the horizontal component of the applied loads. In other words, the designed pile should meet not only the axial capacity criterion but also the lateral capacity criterion. The estimated capacities of piles are checked against the applied loads according to a design method, such as the Load and Resistance Factor Design (LRFD) and the Working Stress Design (WSD).

3.2.1 Axial Pile Capacity

The ultimate capacity of the pipe piles is obtained by adding the outside skin friction and the end bearing resistance. The end bearing resistance assumes that the bottom of the pile is closed or that the open ended pipe pile would plug during static loading. The ultimate axial bearing capacity of a pile (Figure 3-1) can be expressed as the sum of the skin friction and end bearing resistances in Eq. (3-1):

$$Q_u = Q_f + Q_p = \sum f_i \times A_{s\,i} + q \times A_p \tag{3-1}$$

where, Q_u = ultimate bearing capacity (kN, lbs),

Q_f = skin friction resistance (kN, lbs)

Q_p = total end bearing (kN, lbs),

f_i = unit skin friction capacity in ith layer (kPa, lb/ft^2)

A_{si} = side surface area of pile in ith layer (m^2, ft^2),

A_p = gross end area of pile (m^2, ft^2)

q = unit end bearing capacity (kPa, lb/ft^2)

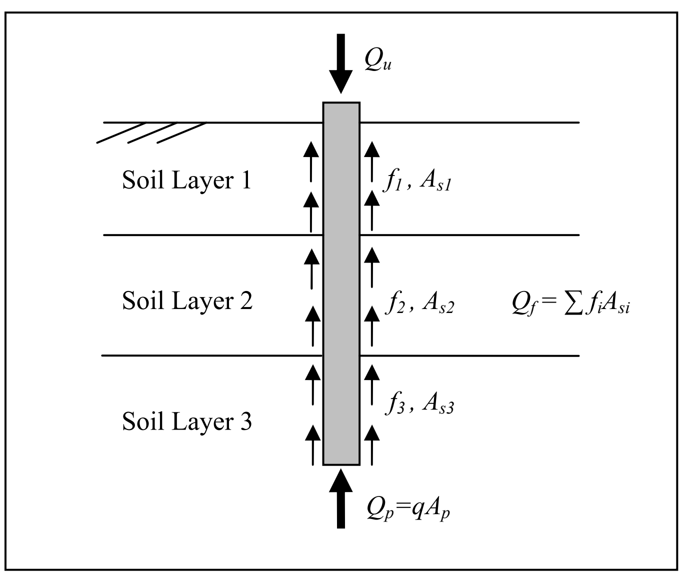


Figure 3-1. Schematic drawing of an axially loaded pile

The skin friction and end bearing resistances are calculated in different ways depending on the pile type such as driven piles or bored piles. The type of underlying soil (i.e., fine grained or coarse grained soil) also affects the calculation method. The API RP2A-LRFD (2003), API RP2A-WSD (2000), and the ADSC (1999) are referred to the calculation procedures for the unit skin friction, f_i, and the end bearing resistance, q, of driven piles and bored piles.

3.2.1.1 Driven Pile

The unit skin friction is the shear stress between the pile and soil at failure. According to the API RP2A-LRFD (2003) and API RP2A-WSD (2000), the unit skin friction of a driven pile in coarse grained soils can be calculated by Eq. (3-2):

$$f = K \times p_0' \times \tan\delta \qquad (3\text{-}2)$$

where, K = dimensionless coefficient of lateral earth pressure

p_0' = effective overburden pressure at the point in question (kPa, lb/ft^2)

δ = friction angle between the soil and pile wall

For open-ended pipe piles driven unplugged, it is usually suggested to assume K as 0.8 for both tension and compression loadings while values of K for full displacement piles (plugged or closed end) may be assumed to be 1.0. The friction angle of a soil, φ, corresponds to the friction coefficient μ_1 of a soil-soil interface through: $\mu_1 = \tan\varphi$. The angle δ is the friction angle which corresponds to the friction coefficient μ_2 of the soil-pile interface through $\mu_2 = \tan\delta$. The unit end bearing of a driven pile in coarse grained soils can be computed by Eq. (3-3):

$$q = p_0' \times N_q \qquad (3\text{-}3)$$

where, N_q = dimensionless bearing capacity factor. Recommended values of N_q are tabulated in Table 3-1.

Table 3-1. Design parameters for coarse grained soils (API RP2A-LRFD, 2003)

Density	Soil Description	Friction Angle, δ (deg)	Limiting Skin Friction kPa (kips/ft^2)	N_q	Limiting Unit End Bearing MPa (kips/ft^2)
Very Loose Loose Medium	Sand Sand-Silt Silt	15	47.8 (1.0)	8	1.9 (40)
Loose Medium Dense	Sand Sand-Silt Silt	20	67.0 (1.4)	12	2.9 (60)
Medium Dense	Sand Sand-Silt	25	81.3 (1.7)	20	4.8 (100)
Dense Very Dense	Sand Sand-Silt	30	95.7 (2.0)	40	9.6 (200)
Dense Very Dense	Gravel Sand	35	114.8 (2.4)	50	12.0 (250)

According to the API RP2A-LRFD (2003) and WSD (2000), the unit skin friction of a driven pile in fine grained soils can be calculated by Eq. (3-4):

$$f = \alpha_1 \times s_u \tag{3-4}$$

where, α_1 = dimensionless adhesion factor

s_u = undrained shear strength of the soil (kPa, lb/ft^2)

The factor, α_1 is an empirical adhesive factor for reduction of the average undrained shear strength. The α_1 value can be calculated by Eq. (3-5) with the constraint that $\alpha_1 \leq 1$.

$$\begin{aligned} \alpha_1 &= 0.5 \times \psi^{-0.5} \quad (\psi \leq 1.0) \\ \alpha_1 &= 0.5 \times \psi^{-0.25} \quad (\psi > 1.0) \end{aligned} \tag{3-5}$$

where, $\psi = s_u / p_0'$

The shaft friction acts on both the inside and outside of the pile. The total shaft resistance is the sum of the external friction and the internal shaft friction if the internal shaft friction is less than the end bearing capacity.

The unit end bearing a driven pile in fine grained soils can be computed by Eq. (3-6):

$$q = 9 \times s_u \tag{3-6}$$

where, s_u = undrained shear strength (kPa, lb/ft^2)

In fine grained soils, the capacity of piles follows an undrained analysis using s_u. The reason is that a fine grained soil does not have time to drain during the loading and this corresponds to the time where the fine grained soil is the weakest. Indeed right after the loading the pore pressures are high and the effective stress is low while in the long term the pore pressures generated by the loading dissipate, the effective stress increases and so does the shear strength of the fine grained soil. In coarse grained soils, the capacity of piles follows a drained analysis because a coarse grained soil has time to drain during loading.

3.2.1.2 Bored Pile

According to the ADSC (1999), the unit skin friction of a bored pile in coarse grained soils can be calculated by Eq. (3-7):

$$f = \beta \times p_0' \tag{3-7}$$

where, β = dimensionless correlation factor

Suggested values of β for granular soils classified as sand can be obtained by Eq. (3-8) if $N_{SPT} \geq 15$ blows per 0.3m:

$$\beta = 1.5 - 0.245 \times z(m)^{0.5}, \qquad (0.25 \leq \beta \leq 1.20) \tag{3-8}$$

where, z = depth below the ground surface in meter

If $N_{SPT} < 15$ blows per 0.3m, β value can be computed by Eq. (3-9):

$$\beta = (N_{SPT}/15)\left[1.5 - 0.245 \times z(m)^{0.5}\right], \qquad (0.25 \leq \beta \leq 1.20) \tag{3-9}$$

The unit end bearing of a bored pile in coarse grained soils can be computed by Eq. (3-10):

$$q\ (tsf) = 0.60 \times N_{SPT} \tag{3-10}$$

where, N_{SPT} = uncorrected SPT blow count (blows/ft)

The Standard Penetration Test (SPT) is a geotechnical field test. It is performed at the bottom of a borehole which is about 4 inches in diameter. The SPT consists of driving a standard sampler about 2.5 inches in diameter called the split spoon sampler starting at the bottom of an open borehole while using a standard 140 lbs hammer. This hammer is raised 30 inches above the anvil and dropped freely for each blow. The number of blows required to drive the sampler one foot into the soil is recorded as the blow count N (bpf). The N values are obtained every 5 to 10 feet with depth and a blow count profile is generated.

According to the ADSC (1999), the unit skin friction of a bored pile in fine grained soils can be calculated by Eq. (3-11):

$$f = \alpha_2 \times s_u \tag{3-11}$$

where, α_2 = shear strength reduction factor

= 0 between the ground surface and a depth of 1.5m (5ft)

= 0 for a distance of B_b above the base

= 0.55 for $s_u / P_a \leq 1.5$

= $0.55 - 0.1(s_u / P_a - 1.5)$ for $1.5 \leq s_u / P_a \leq 2.5$

B_b = diameter on the base of the bored pile (m, ft)

P_a = atmospheric pressure (101kPa or 2116 lb/ft^2)

s_u = undrained shear strength of the soil (kPa, lb/ft^2)

The α_2 values are developed from measured data on full-scale load tests and depend on the undrained shear strength, s_u. If the fine grained soil has a value of $s_u \geq 96$ kPa (2000lb/ft^2), the unit end bearing of a bored pile in fine grained soils can be computed by Eq. (3-12):

$$q = 9 \times s_u \tag{3-12}$$

However, if the embedded pile length (L_p) is less than three times the diameter of the base of the bored pile ($3B_b$), then the unit end bearing capacity (q) should be reduced as follows:

$$q = 0.667\left[1 + 0.1667(L_p / B_b)\right] N^*{}_c \times s_u \tag{3-13}$$

where, L_p = embedded pile length (m, ft)

B_b = diameter on the base of the bored pile (m, ft)

$N^*{}_c$ = modified bearing capacity factor

Recommended values of $N^*{}_c$ are tabulated in Table 3-2.

Table 3-2. N^*_c values (ADSC, 1999)

s_u	N^*_c
24 kPa (500lb/ft^2)	6.5
48 kPa (1000lb/ft^2)	8.0
96 kPa (2000lb/ft^2)	8.7
192 kPa (4000lb/ft^2)	8.9

3.2.2 Lateral Pile Capacity

Piles are often subjected to relatively large horizontal loads and overturning moment due to wind loads, seismic loads, etc. In this case, the lateral pile capacity should be checked for two criteria. The piles should have enough lateral soil bearing capacity to resist against the horizontal loads and the horizontal deflection of the pile should be within an allowable limit. The methods for performing lateral capacity analyses depend on the type of connection between the pile and the structure. If the pile is connected to the structure in such a way that the top of the pile may freely move laterally and rotate (Figure 3-2 a), it may be assumed to be a free head condition. If the top of the pile may move laterally but is not allowed to rotate (Figure 3-2 b), it may be assumed to be a fixed head condition.

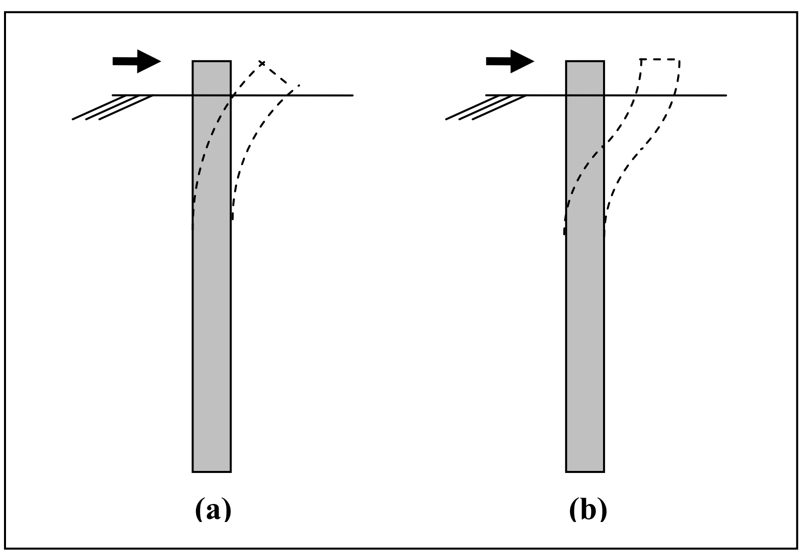


Figure 3-2. Types of connections. (a) free head, and (b) fixed head

3.2.2.1 Free Head Case

The spring constant, K_s, is the ratio of the lateral resistance of the soil per unit length of a pile to the lateral displacement of the pile. It can be obtained by Eq. (3-14) (Briaud 1997):

$$K_s = 2.3E_0 \tag{3-14}$$

E_0 is the first load pressuremeter (PMT) modulus. The pressuremeter is a geotechnical field test. It consist of drilling a 3 inch borehole, removing the drilling tool, lowering a cylindrical probe about 2.5 ft in length and 3 inch in diameter, and expanding that probe laterally against the borehole walls while recording the volume of the probe and the pressure exerted on the soil. This gives an in situ stress strain curve from which a soil modulus (E_0) and a horizontal limit pressure (P_L) are obtained. E_0 can be obtained by using the following correlations if PMT tests are not available:

E_0 (kPa) $= 383N_{SPT}(blow/30cm)$, or E_0 (tsf) = $4N_{SPT}(blow/ft)$ (Briaud 1992)

= average pressuremeter modulus (kPa, tsf)

where, N_{SPT} = blow count in Standard Penetration Test

The factor 2.3 is determined empirically by comparing measured deflections for over twenty full scale lateral load tests and the predicted deflections (Briaud 1997). For a pipe pile, the moment of inertia of the pile, I (m^4, ft^4), can be calculated by Eq. (3-15):

$$I = \frac{\left(\pi D_o{}^4\right)}{64} - \frac{\left(\pi D_i{}^4\right)}{64} \tag{3-15}$$

where, D_0 = outside diameter of the pile (m, ft)

D_i = inside diameter of the pile (m, ft)

The transfer length, l_0, is a parameter which comes from the differential equation. It has no physical meaning except that it indicates the relative stiffness between the pile and the soil in units of length. The transfer length l_0 can be computed by Eq. (3-16):

$$l_0 = \left(\frac{4EI}{K_s}\right)^{1/4} \tag{3-16}$$

where, E = modulus of elasticity for the pile material (kPa, lb/ft^2)

If the embedded pile length, L_p, is larger than three times the transfer length, the pile can be treated as a long flexible pile. If $L_p < l_0$, the pile is short and rigid. Since most piles satisfy $L_p \geq 3l_0$, the equations only for long flexible piles are considered in this report. The zero-shear depth, D_v, shown in Figure 3-3 can be determined by Eq. (3-17) depending on the value of l_0 for the pile:

$$D_v = l_0 \tan^{-1}\left(\frac{1}{1+\frac{2M_0}{l_0 H_0}}\right), \quad if\ L_p \geq 3l_0 \qquad (3.17)$$

where, L_p = embedded pile length (m, ft)

H_0 = applied horizontal load at the ground surface (kN, lbs)

M_0 = applied moment at the ground surface (kN-m, lbs-ft) = $H_0 h$

h = height of the point of application of the load, H_0 above ground surface (m, ft)

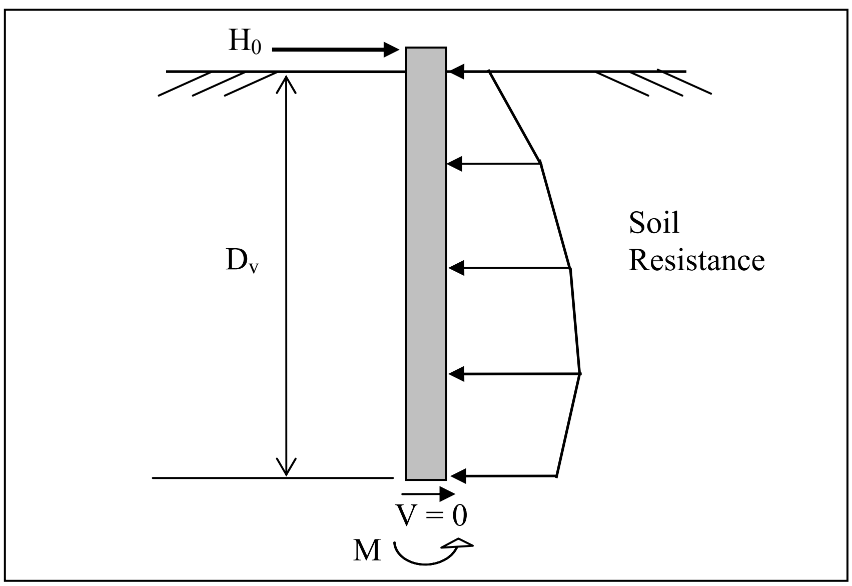


Figure 3-3. Free body diagram of pile down to zero-shear depth (Briaud 1997)

The ultimate lateral capacity of the pile with respect to soil capacity, H_{ou}, is computed by Eq. (3-18) (Briaud 1997):

$$H_{ou} = 0.75 P_L D_o D_v \qquad (3\text{-}18)$$

P_L is the pre-boring pressuremeter (PMT) limit pressure within D_v (kPa, lb/ft^2). If P_L is not available from PMT tests at the site, then the following correlations can be used with reduced accuracy:

P_L (kPa) = $47.9N_{SPT}(blow/30cm)$, or P_L (tsf)= $0.5N_{SPT}(blow/ft)$ (Briaud 1992)

In addition to the lateral capacity of the pile, both the deflections of the pile at the ground surface and the pile head should be checked and satisfy a certain limit. A deflection of 0.5 inches is a common limit of deflection for many structures. For that reason it is used in this report as a target value. The deflection of a long flexible pile at the ground surface can be calculated by Eq. (3-19) (KNR 1999) and should be less than 0.5 in.:

$$y_0 = \frac{(1 + h/l_0)H_0 l_0^{\ 3}}{2EI} \tag{3.19}$$

where, h = height of the pile above the ground surface (m, ft)

The deflection at the long flexible pile head can be obtained by Eq. (3-20) (KNR 1999):

$$y_h = \frac{\left[(1 + h/l_0)^3 + 0.5\right]H_0 l_0^{\ 3}}{3EI} \tag{3-20}$$

where, h = height of the pile above the ground surface (m, ft)

Finally, the maximum bending moment, M_{max} in the pile should be less than or equal to the allowable moment for the pile. The value of M_{max} for a long flexible pile can be calculated by Eq. (3-21) (KNR 1999):

$$M_{max} = \frac{H_0 l_0}{2}\sqrt{(1 + 2h/l_0)^2 + 1}\,e^{-(Z_{max}/l_0)} \tag{3-21}$$

where, $Z_{max} = D_v$ since M_{max} occurs where the shear stress is equal to zero

The equation for M_{max} for a short and rigid pile is not included since all of the piles calculated in this report turned out to be long flexible piles. Although the maximum bending moments are computed, they are not checked against the yield moment of the pile material. In other words, the lateral pile capacity is checked only against failure of the surrounding soil, not failure of the pile itself.

The procedures for the lateral pile capacity in the fine grained soils are almost the same as those in the case of coarse grained soils. The average pressuremeter modulus, E_0 and the pre-boring pressuremeter limit pressure within D_v, P_L in the fine grained soils can be determined by Eq. (3-22) and Eq. (3-23), respectively (Briaud 1992);

$$E_0 = 100 s_u \tag{3-22}$$

$$P_L = 7.5 s_u \tag{3-23}$$

Once these two values are obtained, the same procedures as described in the previous section should be applied to check the lateral pile capacity.

3.2.2.2 Fixed Head Case

The spring constant, K_s, is the ratio of the lateral resistance of the soil per unit length of a pile to the lateral displacement of the pile. It can be obtained by Eq. (3-24) (Briaud 1997):

$$K_s = 2.3 E_0 \tag{3-24}$$

E_0 is the first load pressuremeter (PMT) modulus and can be obtained by using the following correlations if PMT tests are not available:

E_0 (kPa) $= 383 N_{SPT}(blow/30cm)$, or E_0 (tsf) = $4 N_{SPT}(blow/ft)$ (Briaud 1992)

= average pressuremeter modulus (kPa, tsf)

where, N_{SPT} = blow count in Standard Penetration Test

The moment of inertia of the pipe pile, I (m^4, ft^4), can be calculated by Eq. (3-25):

$$I = \frac{\left(\pi D_0^{\,4}\right)}{64} - \frac{\left(\pi D_i^{\,4}\right)}{64} \tag{3-25}$$

where, D_0 = outside diameter of the pile (m, ft)

D_i = inside diameter of the pile (m, ft)

The transfer length, l_0, is a function of the relative stiffness between the pile and the soil, and it can be computed by Eq. (3-26):

$$l_0 = \left(\frac{4EI}{K_s}\right)^{1/4} \tag{3.26}$$

where, E = modulus of elasticity for the pile material (kPa, lb/ft^2)

The moment at the pile head can be computed by Eq. (3-27):

$$M_h = -0.5\left(1+\frac{h}{l_0}\right)H_0 l_0 \tag{3-27}$$

where, H_0 = applied horizontal load (kN, lbs)

If the embedded pile length, L_p, is larger than three times of the transfer length, the pile can be treated as a long flexible pile. If $L_p < l_0$, the pile is short and rigid. Since most piles satisfy $L_p \geq 3l_0$, the equations only for long flexible piles are considered in this report. The zero-shear depth, D_v, can be determined by Eq. (3-28) (KNR 1999) depending on the value of l_0 for the pile:

$$D_v = l_0 \tan^{-1}\left(\frac{l_0}{h}\right), \quad if \; L_p \geq 3l_0 \tag{3-28}$$

where, L_p = embedded pile length (m, ft)

The lateral capacity of the pile, H_{ou}, is computed by Eq. (3-29) (Briaud 1997):

$$H_{ou} = 0.75 P_L D_o D_v \tag{3-29}$$

P_L is the pre-boring pressuremeter (PMT) limit pressure within D_v (kPa, lb/ft^2). If P_L is not available from PMT tests at the site, then the following correlations can be used with reduced accuraty:

P_L (kPa) = $47.9 N_{SPT}(blow/30cm)$, or P_L (tsf)= $0.5 N_{SPT}(blow/ft)$ (Briaud 1992)

As checked in the free head case, the deflections of the pile at the ground surface and the pile head should meet the 0.5 in. criterion. The deflection of a long flexible pile at the ground surface can be calculated by Eq. (3-30) (KNR 1999):

$$y_0 = \frac{(1+h/l_0)H_0 l_0^{\,3}}{4EI} \tag{3-30}$$

The deflection at the long flexible pile head can be obtained by Eq. (3-31):

$$y_h = \frac{\left[(1+h/l_0)^3 + 2\right]H_0 l_0^{\,3}}{12EI} \tag{3-31}$$

where, h = height of the pile above the ground surface (m, ft)

Finally, the maximum bending moment, M_{max} in the pile should be less than or equal to the allowable moment for the pile. The value of M_{max} for a long flexible pile can be calculated by Eq. (3-32):

$$M_{max} = 0.5 H_0 l_0 e^{-(Z_{max}/l_0)} \sqrt{\left[1 + (h/l_0)^2\right]} \qquad (3\text{-}32)$$

where, $Z_{max} = D_v$ since M_{max} occurs where the shear stress is equal to zero

The equation of M_{max} for a short and rigid pile is not included since all of the piles calculated in this report turned to be long flexible. Although the maximum bending moments are computed, these are not checked with the yield moment of the pile material. In other words, the lateral pile capacities are checked only against failure of the surrounding soil.

The procedures for lateral pile capacity in fine grained soils are almost the same as those in coarse grained soils. In the absence of site specific pressuremeter data, the average pressuremeter modulus, E_0 and the pre-boring pressuremeter limit pressure, P_L within D_v, in fine grained soils can be determined by Eq. (3-33) and Eq. (3-34), respectively with reduced precision (Briaud 1992);

$$E_0 = 100 s_u \qquad (3\text{-}33)$$

$$P_L = 7.5 s_u \qquad (3\text{-}34)$$

Once these two values are obtained, the same procedures as described in the previous section should be applied to check the lateral pile capacity.

3.2.3 Pile Capacity Check

Once the axial and lateral pile capacities are estimated, they should be compared with the applied loads to check if the pile is safe against the loads. There are two different methods used extensively in the field: Load and Resistance Factor Design (LRFD) and Working Stress Design (WSD).

3.2.3.1 Load and Resistance Factor Design (LRFD) Method

The Load and Resistance Factor Design (LRFD) method is based on a reliability approach to provide a more uniform level of safety on both loads and resistance. The LRFD factors are developed on the basis of a probability of failure varying between 0.0005 to 0.001. In the LRFD method the applied loads are multiplied by load factors, λ_i which are equal or larger than 1. The resistances are multiplied by resistance factors, ϕ_i which are equal or less than 1. The magnitude of these factors depends on the types of loads and the types of resistance components, respectively. The λ_i and ϕ_i values are found in various guidelines including AASHTO and API RP2A. All calculations of driven pile capacities in this report followed API RP2A-LRFD (2003), and these values are shown in Table 2.3. The worst case among the three different conditions in Table 3-3 should be checked with correspondingly factored resistance. For bored piles, the values of load factors are obtained from those values for driven piles, and the values of resistance factors in Table 3-4 can be used.

Table 3-3. Load and resistance factors for driven piles (API RP2A-LRFD, 2003)

Load Condition	Load Factors	Resistance Factor
Gravity Loads	$1.3DL+1.5LL$	0.70
Operating environmental	$1.3DL+1.5LL+1.2W_o$	0.70
Extreme environmental	$1.1DL+1.1LL+1.35W_e$	0.80
Lateral Capacity	-	0.75

Note: DL = dead load; LL = live load;

W_o = wind load for operating environmental condition;

W_e = wind load for extreme environmental condition

Table 3.4. Recommended resistance factors for bored piles (ADSC, 1999)

Load Condition	Capacity Term	Resistance Factor	
		Sand	Clay
Operating environmental	End Bearing	0.50	0.55
	Skin Friction	0.65	0.65
	Uplift	0.65	0.55
Extreme environmental	Overall	1.00	1.00
Lateral Capacity	Overall	0.75	

According to API RP2A-LRFD (2003), "The operating environmental condition should be representative of moderately severe conditions at the platform. Typically, a 1-year to 5-year winter storm is used as an operating wind condition in the Gulf of Mexico. On the other hand, the extreme environmental condition uses a 100-year return period event. Return period means the average interval of time between exceedances of the magnitude of an event."

The general equation in the LRFD method can be expressed as:

$$\sum \lambda_i \times L_i \ (Loads) = \sum \phi_i \times R_i \ (Resistance) \tag{3-35}$$

where, λ_i = load factors (≥ 1.0)

ϕ_i = resistance factors (≤ 1.0)

For the pile capacity check, the appropriate factors for the resistance (capacity) obtained in the previous sections should be selected according to the guideline. Then, the factored resistance is to be compared with the factored loads and it should be larger or equal to the factored loads.

3.2.3.2 Working Stress Design (WSD) Method

Working Stress Design (WSD) is a traditional method to achieve a level of conservatism against various uncertainties in many aspects. In the WSD method, the factor of safety is employed to reduce the risk level against failure and it is the ratio of resistance to the applied load:

$$Factor\ of\ Safety\ (SF) = \frac{Resistance\,(R)}{Load\ (L)} \tag{3-36}$$

The allowable pile capacities are determined by dividing the ultimate pile capacity by the proper factor of safety. The API RP2A-WSD recommends the following minimum values for driven piles in Table 3-5 depending on the load condition. For bored piles the values in Table 3-6 can be used according to the ADSC (1999).

Table 3-5. Recommended factor of safety for driven piles (API RP2A-WSD, 2000)

Load Condition	Factor of Safety
Operating environmental conditions	2.0
Extreme environmental conditions	1.5
Uplift (pullout) conditions	2.0
Lateral Capacity	3.0

Table 3-6. Recommended factor of safety for bored piles (ADSC, 1999)

Load Condition	Factor of Safety
Operating environmental conditions	3.0
Extreme environmental conditions	2.0
Uplift (pullout) conditions	3.0
Lateral Capacity	3.0

Briaud (1997) recommend a factor of safety of 3 for their lateral capacity calculation method. In the case of LRFD, it is decided to use a resistance factor for lateral capacity equal to 0.75. This is a relatively high resistance factor because the data shown by Briaud (1997) indicates little scatter in the predicted vs. measured comparison. For the pile capacity check, the actual resistance (capacity) obtained in the previous sections is to be divided by the actual loads. It becomes the factor of safety for the pile and it should be higher than the recommended value.

3.3 Decision Analysis

In general, it is almost impossible to predict with certainty what the best result of each strategy will be because there are many uncertainties in real problems. Therefore, formal analysis is required to consider many complex problems. The goal of decision analysis is to structure and simplify the task of making hard decisions through quantitative basis (Jimenez et al. 2003). This approach provides logical analysis of the alternatives and quantitative rationale for the recommendation. Decision analysis is usually concerned with multiple conflicting objectives for many real world problems and, therefore, it is simply not true that "qualitatively speaking, business decisions are simple because the objective function is crystal clear (Keeney and Raiffa 1976)."

According to Keeney and Raiffa (1976) and Keeney (1992), the simple paradigm of decision analysis can be summarized in a five-step process as follows:

1. Preanalysis: the problem has been identified and the viable alternatives are given.
2. Structural analysis: the decision-maker structures the problem which includes specifying objectives, attributes, and attributes scales.
3. Uncertainty analysis: the decision-maker assigns probabilities to the branches emanating from chance nodes. These assignments are based on past empirical data and expert judgment.
4. Utility or value analysis: the decision-maker quantifies his/her preferences and then converts these preferences into utility numbers. The assignment of utility numbers to consequences must be such that the maximization of expected utility becomes the appropriate criterion for the decision-maker's optimal action.
5. Optimization Analysis: once decision-maker assigns utilities, he/she calculates his/her optimal strategy – the strategy that maximizes expected utility. There are various techniques to obtain an optimal strategy for a specific problem.

3.3.1 The Assumption of Utility Function

In order to be able to decompose the general multi-attribute utility function with i attributes into a simple functional form of the i individual attributes, two assumptions about the nature of the decision-maker's preferences for the underlying attributes must be specified and verified (Hardaker 2004). These two assumptions are mutually preferential independence and utility independence. The preferential independence concerns only ordinal preferences and no probabilistic elements are involved (Keeney and Raiffa 1976). For example, suppose there are two attributes, X and Y. If preferences for levels of attribute X do not depend on the level of attribute Y, an attribute X is said to be preference independent of another attribute Y. Utility independence, on the other hand, concerns the cardinal preferences of the decision-maker (Keeney and Raiffa 1976). For example, if preferences for uncertain choices such as lotteries involving different levels of attribute X do not depend on the level of attribute Y, an attribute X is said to be utility independent of another attribute Y. Full mutual utility independence is almost impossible in reality, but the assumption is commonly made since to do otherwise would make the analysis too difficult (Hardaker 2004). It is very important to ascertain whether any of the preferential independence or utility independence assumptions discussed above is appropriate for this research.

3.3.2 Forms of the Utility Function

If mutual preferential and utility independence are satisfied, it is possible to define the multi-attribute utility function in the general form (Clemen and Reilly 2001):

$$U\left(x_1, x_2, \ldots, x_I\right) = U\left\{u_1(x_1), u_2(x_2), \ldots, u_I(x_I)\right\} \tag{3-37}$$

Once each single-attribute utility function $u_i(x_i)$ is derived for its attribute measure, these individual utility values are combined in some way into a final utility value.

If single-attribute utility functions $u_i(x_i)$ are scaled from zero to one, and if U is also scaled from zero to one, the function U is either of the additive form (Hardaker 2004):

$$U\left(x_1, x_2, \ldots, x_I\right) = \sum_{i=1}^{I} k_i u_i\left(x_i\right) \tag{3-38}$$

or of the multiplicative form (Hardaker 2004):

$$U\left(x_1, x_2, \ldots, x_I\right) = \left\{\prod_{i=1}^{I}\left(K \cdot k_i u_i\left(x_i\right) + 1\right) - 1\right\} / K \tag{3-39}$$

where $u_i(x_i)$ is a single-attribute utility function scaled from 0 to 1, k_i is a scaling factor between zero and one for $u_i(x_i)$. K is another scaling constant and the value of K depends on the values k_i. If $\Sigma k_i = 1$, then $K = 0$ and U takes the additive form as expressed in Eq. (3-38) and it indicates there is no interaction between each attribute. In contrast, if $\Sigma k_i \neq 1$, then $K \neq 0$ and U takes the multiplicative form as expressed in Eq. (3-39). If K is greater than 0, then the attributes interact destructively so that a low utility for one attribute can result in a low overall utility U. On the other hand, when K is less than 0, the attributes interact constructively so that a high individual attribute utility results in a high overall utility U. Keeney (1974) describes more detail information about the derivation of K from the k_i values in the multiplicative case.

3.3.3 Sensitivity Analysis

Sensitivity analysis for multi-attribute utility problems can be categorized based on the number of times an optimization routine needs to be run to analyze sensitivity (Guikema and Milke 2003). If various individuals have distinct weight combinations for multi-attribute utility problems, each combination could be given as a discrete weight combination to the optimization routine and any result change in the technology selected would indicate sensitivity to an individual's choice of weight combination. In this case, not only does relatively few optimization need to be run, but also relatively little post-processing of the optimization results is needed to evaluate sensitivity (Guikema and Milke 2003). The sensitivity analysis for discrete weight combinations of multi-attribute utility problems has been addressed many times in the literature. Call and Merkhofer (1988), for example, developed one approach to sensitivity analysis using predefined weight combinations (i.e., high and low for each attribute).

On the other hand, if decision-makers do not feel confident enough in their assessments to specify precise values, uncertainties of input parameters such as the weights of each attribute in multi-attribute utility problems can arise. In this case the proper values can lie anywhere within a possibly wide range of values specified by the decision-makers. For this type of sensitivity analysis, multiple optimizations need to be run and the breakpoints become important. In this research, for example, the breakpoints where the optimal drilling systems change are very important aspect. This type of sensitivity analysis is more difficult and time consuming than discrete sensitivity analysis. Significantly less has been addressed for this type of sensitivity analysis in the literature than for the discrete sensitivity analysis.

4. PARAMETRIC STUDY OF FOUNDATIONS FOR DRILL SITES

4.1 Foundation Options for Drill Sites

After having several meetings with EFD foundation experts, some of possible foundation options for a drilling site containing the advantage and disadvantage associated with those options are identified as shown in Table 4-1.

Table 4-1. Foundation options for a drilling site

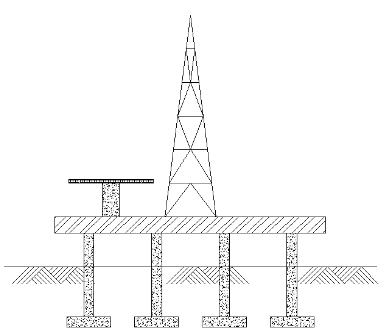
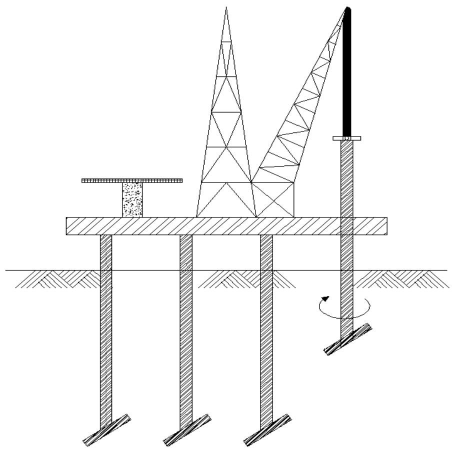
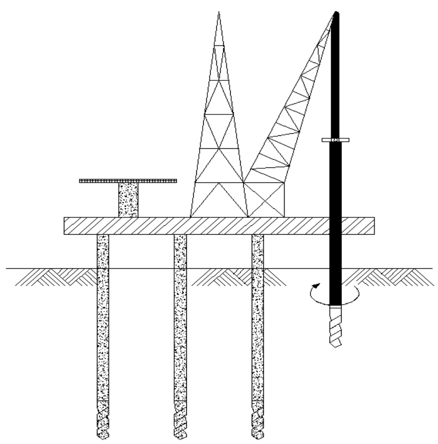
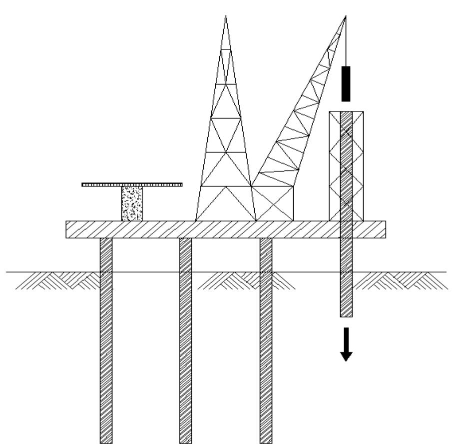
1. Gravel pad	Advantages
	• Easier and faster installation • Maybe cheaper in construction stage
	Disadvantages
	• Less environmentally friendly • Non-resuable
2. Composite mat	Advantages
	• Easier and faster installation • Great effect on small loading area over soft soil (E<10 MPa)
	Disadvantages
	• Less effect on large loading area over stiff soil (E>50 MPa)
3. Spread footing	Advantages
	• Simple and no discharge • Uplift on marshes • Easy to remove on rock
	Disadvantages
	• No uplift on rock • Suitable contact on rock • Hard to remove on marsh

Table 4-1. Continued

4. Screw anchor	Advantages
	• Light equipment • No discharge • Removable • Uplift capacity
	Disadvantages
	• Limited to soft soils
5. Bored pile	**Advantages**
	• Drill through any soil • Noise level is low • Familiar technology
	Disadvantages
	• Drilling fluid in marsh • Equipment heavier • Access • More complicated
6. Driven pile	**Advantages**
	• Uplift capacity • Minimal imprint • Vibratory is less noisy
	Disadvantages
	• Equipment heavier • Access • More complicated • Vibratory limited to some soils

Among those foundation options, three different foundations (i.e., driven pile, bored pile, and composite mat) for drill sites are considered for the parametric study in the following Section 4.2 through 4.3. In order to encourage site location engineers to use environmentally friendly foundations such as elevated platforms and composite mat systems more often for their drilling sites instead of using gravel pads, the parametric study is an essential task in this research.

4.2 Pile Foundation Designs for Low Impact Onshore Platforms

Environmental issues are a significant part of every industry. The petroleum industry endeavors to minimize the existing environmental impact during drilling operations whether developing new resources or extending field in environmentally sensitive areas. For example, reducing the environmental footprint during drilling operations using a reusable Modular Platform and small mobile rig in the Arctic was demonstrated in 2003 by Anadarko and Noble's Subsidiary, Maurer technology Inc.. The objective was to drill in an ecologically sensitive area without disturbing the ground surface. The successful demonstration used a small mining rig to evaluate the potential of drilling for hydrates under the frozen tundra of the Alaska North Slope (Kadaster and Millheim 2004) and showed the usefulness of an onshore platform to drill in sensitive areas.

The objective of this study is to help the petroleum industry engineers to get a basic idea regarding pile designs of a platform for various platform weights and soil conditions in environmentally sensitive areas (e.g., desert environments and wetland applications). Use of a raised platform in environmentally sensitive areas will require the use of piles to support the elevated platform instead of gravel pads as used in a conventional platform. About one thousand different cases of pile capacity calculations are conducted depending on various soil types, pile types, and design methods. The results of these calculations are organized into a series of tables in order for the engineer to be able to easily choose an appropriate pile size for a given condition from these tables without performing an extensive pile design analysis.

4.2.1 Description of the General Case

Anadarko's onshore platform in Alaska (Kadaster and Millheim 2004) is adopted for the foundation design of the general case. The platform consists of "bucket" modules (12.5 ft wide, 50 ft long, and 3.5 ft deep), piles for its leg, and drilling rig components. Figure 4-1 shows the dimension of one module, Figure 4-2 shows the plan view of several modules connected each other, and Figure 4-3 shows the cross sectional view of the platform. It is assumed that the mast is 90 ft high, 10 ft long and the living quarter is 28 ft high, 40 ft long, respectively.

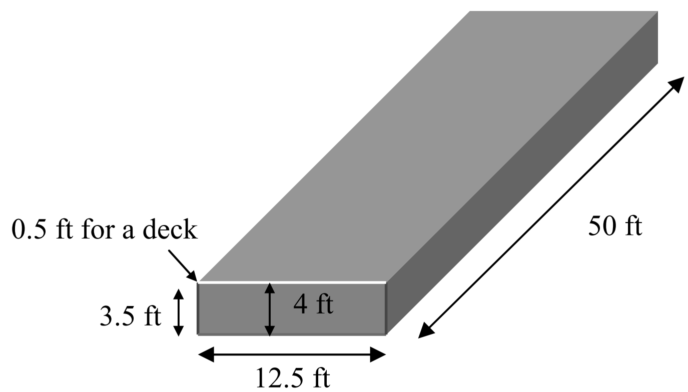


Figure 4-1. Module dimension

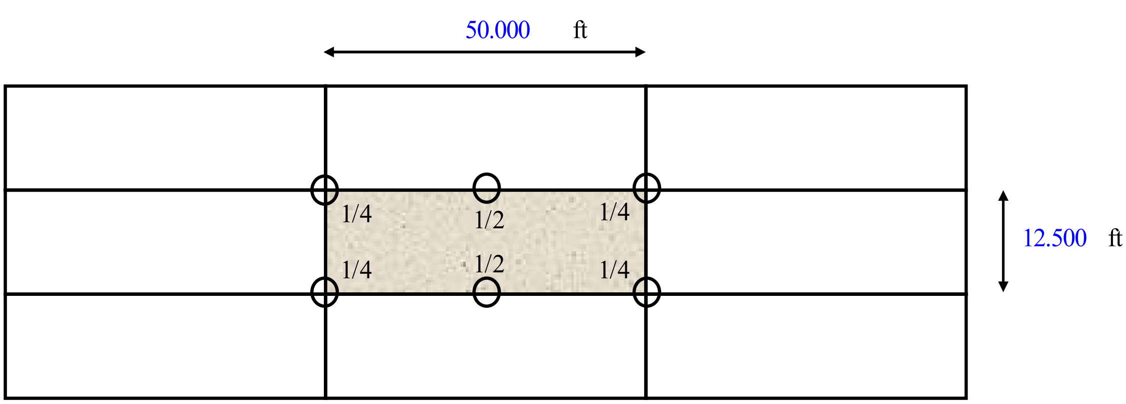


Figure 4-2. Plan view of modules

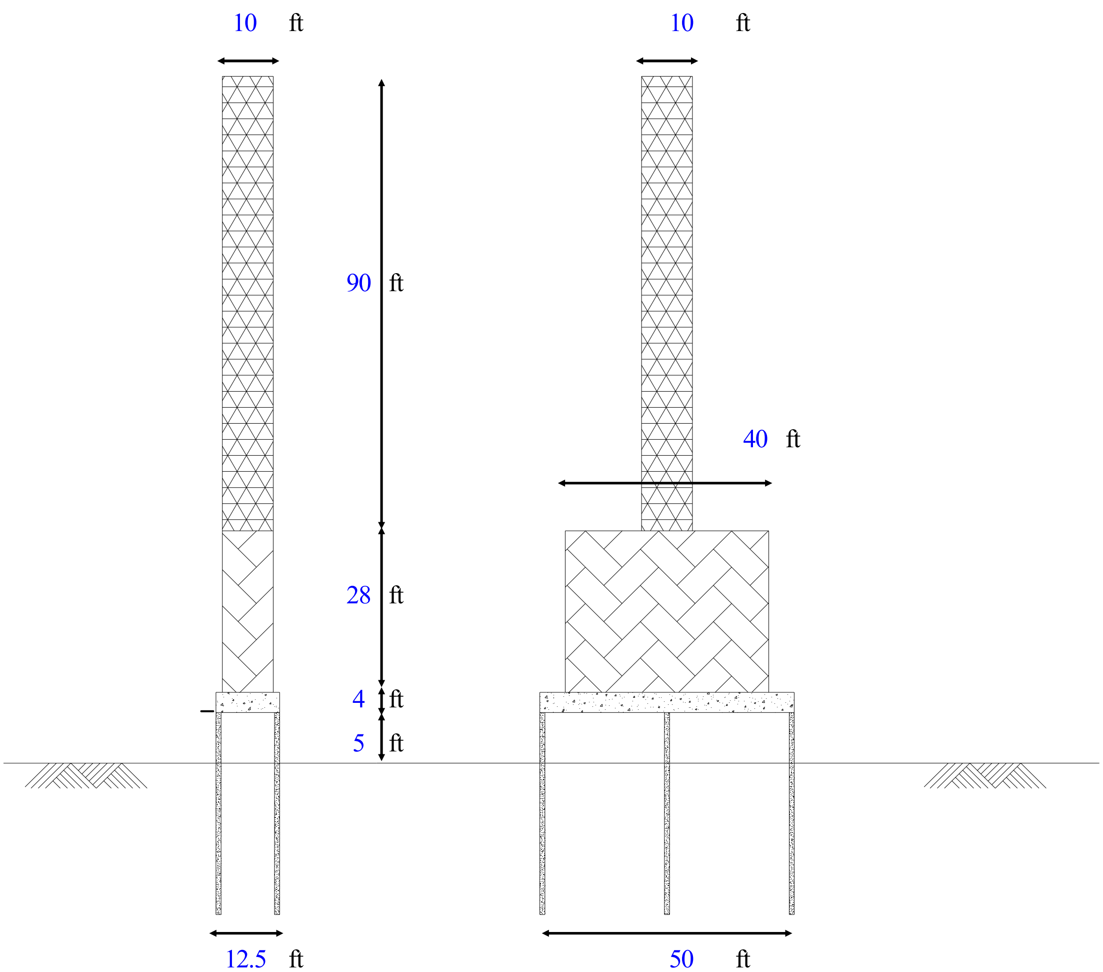


Figure 4-3 Cross section of the platform for one module in design

4.2.1.1 Soil Conditions

Pile capacities are strongly affected by the underlying soil type. If there is very dense sand under the ground, a pile will resist a much higher applied load than a pile in loose sand. Although it is highly desirable to calculate pile capacities in a site specific fashion, six typical types of soils are considered in this report. Furthermore, a homogeneous condition with respect to depth is assumed for simplicity in the calculations. The engineering properties of these soils are shown in Table 4-2.

Table 4-2. Soil conditions of pile capacity calculations

Gravels & Sands			Silts & Clays		
Type I (very dense)	Type II (medium)	Type III (very loose)	Type IV (hard)	Type V (medium)	Type VI (soft)
γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft s_u = 2090 psf	γ_{sat} = 120 pcf G.W.L = 10 ft s_u = 1255 psf	γ_{sat} = 115 pcf G.W.L = 0 ft s_u = 0.25 P_0'

Note: P_0' = effective overburden pressure (psf)

G.W.L = ground water depth measured from the ground surface

4.2.1.2 Weight Distribution on Platform

For the general case, it is assumed that 65% of the total vertical loads are evenly distributed over 6 modules and that this load consists of dead load (30%) and live load (70%).

The wind load is one of the primary sources of horizontal loads against a structure. According to API RP2A-LRFD (2003), wind load may be computed by Eq. (4-1);

$$W = \frac{\rho}{2} V^2 C_s A \tag{4-1}$$

where, W = wind force, V = wind speed

C_s = dimensionless shape coefficient for perpendicular wind approach angles with respect to each projected area

A = area of object perpendicular to the wind

ρ = mass density of air at standard temperature and pressures

= 1.226 kg/m^3 = 0.00238 lb·sec^2/ft^4)

The one hour mean wind speed at elevation z can be calculated by Eq. (4-2);

$$V(1hr, z) = V(1hr, z_R)\left(\frac{z}{z_R}\right)^{0.125} \tag{4-2}$$

where, $V(1hr, z_R)$ = one hour mean speed at the reference elevation (m/s, ft/s)

z_R = reference elevation (= 10m or 33ft)

According to API RP2A-LRFD (2003), the extreme wind speed to be considered in design for the Gulf of Mexico area is 49 m/s. In this report, 25m/s and 49m/s are assumed for operational and extreme wind speeds, respectively. More detailed load calculations in the general case can be found in APPENDIX A.

4.2.1.3 Pile Capacity Check

For the general case, the capacities of the driven steel pipe piles and bored piles are calculated in accordance with the LRFD and WSD methods. The step-by-step calculations can be found in APPENDIX A. First, the axial capacity is checked against the applied loads. Second, the lateral capacity is checked for the free head condition. Finally, the lateral capacity in the fixed head condition is evaluated.

4.2.1.4 Results Summary

Based on the pile capacity calculations in the general case, the following four tables (Table 4-3 ~ 4-6) provide a simple way to choose an appropriate pile size for a given condition. Once the soil type and the applied loads are known, the desirable pile size can be decided by following procedure;

1. Choose a design method: LRFD or WSD
2. Choose a pile type: driven or bored
3. Go to a table corresponding to the selected design method and pile type
4. Read the recommended diameter and length of the pile in the table

Table 4-3. Recommended size of driven piles in the general case (LRFD)

Weight of Rigs & Accessories (Unfactored)	Soil types / Factored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1000 kips	178.0 kips	D = 24 in.	D = 24 in.	D = 12 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 58 ft	L = 26 ft	L = 28 ft	L = 70 ft	L = 41 ft	L = 27 ft
1500 kips	207.8 kips	D = 24 in.	D = 24 in.	D = 16 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 64 ft	L = 30 ft	L = 21 ft	L = 75 ft	L = 47 ft	L = 32 ft
2000 kips	237.6 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 69 ft	L = 33 ft	L = 17 ft	L = 81 ft	L = 52 ft	L = 36 ft
3000 kips	297.1 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 79 ft	L = 40 ft	L = 21 ft	L = 91 ft	L = 63 ft	L = 45 ft
4000 kips	356.7 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 20 in.
		L = 94 ft	L = 48 ft	L = 27 ft	L = 104 ft	L = 77 ft	L = 66 ft

Table 4-4. Recommended size of driven piles in the general case (WSD)

Weight of Rigs & Accessories (Unfactored)	Soil types / Unfactored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1000 kips	141.9 kips	D = 24 in.	D = 24 in.	D = 16 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 57 ft	L = 25 ft	L = 20 ft	L = 68 ft	L = 39 ft	L = 26 ft
1500 kips	169.0 kips	D = 24 in.	D = 24 in.	D = 16 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 63 ft	L = 29 ft	L = 21 ft	L = 74 ft	L = 46 ft	L = 31 ft
2000 kips	196.0 kips	D = 20 in.	D = 24 in.	D = 20 in.	D = 20 in.	D = 24 in.	D = 24 in.
		L = 79 ft	L = 33 ft	L = 17 ft	L = 89 ft	L = 52 ft	L = 36 ft
3000 kips	250.2 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 20 in.	D = 20 in.	D = 24 in.
		L = 79 ft	L = 40 ft	L = 21 ft	L = 101 ft	L = 74 ft	L = 45 ft
4000 kips	304.4 kips	D = 24 in.	D = 20 in.	D = 16 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 93 ft	L = 58 ft	L = 37 ft	L = 104 ft	L = 77 ft	L = 56 ft

Table 4-5. Recommended size of bored piles in the general case (LRFD)

Weight of Rigs & Accessories (Unfactored)	Soil types / Factored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1000 kips	178.0 kips	D = 24 in.	D = 20 in.	D = 16 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 38 ft	L = 19 ft	L = 19 ft	L = 85 ft	L = 41 ft	L = 24 ft
1500 kips	207.8 kips	D = 24 in.	D = 20 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 46 ft	L = 26 ft	L = 19 ft	L = 97 ft	L = 53 ft	L = 31 ft
2000 kips	237.6 kips	D = 24 in.	D = 20 in.	D = 16 in.	D = 24 in.	D = 24 in.	D = 20 in.
		L = 54 ft	L = 32 ft	L = 31 ft	L = 109 ft	L = 66 ft	L = 48 ft
3000 kips	297.1 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 70 ft	L = 36 ft	L = 33 ft	L = 131 ft	L = 94 ft	L = 56 ft
4000 kips	356.7 kips	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 86 ft	L = 46 ft	L = 34 ft	L = 149 ft	L = 122 ft	L = 73 ft

(where, P_o' = effective overburden pressure, G.W.L. = ground water depth measured from the ground surface,

Table 4-6. Recommended size of bored piles in the general case (WSD)

Weight of Rigs & Accessories (Unfactored)	Soil types / Unfactored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1000 kips	141.9 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 53 ft	L = 24 ft	L = 21 ft	L = 108 ft	L = 65 ft	L = 39 ft
1500 kips	169.0 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 60 ft	L = 29 ft	L = 26 ft	L = 118 ft	L = 78 ft	L = 46 ft
2000 kips	196.0 kips	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 68 ft	L = 34 ft	L = 23 ft	L = 128 ft	L = 91 ft	L = 54 ft
3000 kips	250.2 kips	D = 24 in.	D = 20 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 89 ft	L = 57 ft	L = 43 ft	L = 153 ft	L = 129 ft	L = 77 ft
4000 kips	304.4 kips	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 114 ft	L = 59 ft	L = 44 ft	L = 174 ft	L = 166 ft	L = 99 ft

4.2.2 Description of an Elevated Platform with Rapid Rig

In May 2006, National Oilwell Varco (NOV) began offering a smaller, fully automatic land drilling rig called "Rapid Rig." The total vertical load of Rapid Rig is used for the foundation calculation of the proposed modular platform. The load breakdown and the layout of Rapid Rig are shown in Table 4-7, Figure 4-4, and Figure 4-5, respectively. In this case, the operating environmental condition governs the foundation calculation.

Table 4-7. Load breakdown structure of Rapid Rig in operating condition

No.	COMPONENTS	WEIGHTS [lbs] (DEAD)	WEIGHTS [lbs] (LIVE)	Factored Weights [lbs] D.L = 1.3 L.L = 1.5	Dimension W	Dimension L	Notes
1.	Substructure/Drillfloor package	80,000		104,000	10	58.5	
2.	Mast including installed equipment	100,000		130,000	18	25	
3.	Drawworks package includes Accumulator unit	70,000		91,000	10	29	
4.	Utilities Skid	25,000		32,500	10	28	
5.	Service Skid	20,000		26,000	10	38.75	
6.	Electrical Control House	30,000		39,000	10	42	
7.	Generator House #1	40,000		52,000	10	27.5	
8.	Generator House #2	40,000		52,000	10	27.5	
9.	Air Compressor House	30,000		39,000	10	27.5	
10.	Mud Pump #1	55,000		71,500	8.75	22	
11.	Mud Pump #2	55,000		71,500	8.75	22	
12.	Pipe Handling equipment	35,000		45,500	3	80	
13.	Control House skid including choke manifold	23,000		29,900	18	12.5	
	Choke Manifold hauled on same trailer	15,000		19,500	7.5	14	
14.	Mud Tank Skid #1 (Empty)	40,000		52,000	11.25	55	
	Mud Tank Skid #1 (Full)		204,750	307,125	11.25	55	375 barrels, 13 lbs/gal
15.	Mud Tank Skid #2 (Empty)	40,000		52,000	11.25	55	
	Mud Tank Skid #2 (Full)		204,750	307,125	11.25	55	375 barrels, 13 lbs/gal
16.	Water Tank (Empty)	20,000		26,000	7.5	45	
	Water Tank (Full)		139,440	209,160	7.5	45	400 barrels, 8.3 lbs/gal
17.	Work shop/Storage Skid	20,000		26,000	10	27.5	
18.	Fuel Tank Skid	10,000		13,000	8	30	
19.	Casing		530,000	795,000	18	25	53 lbs/ft, 10000 ft
20.	Pipes		234,000	351,000	18	25	19.5 lbs/ft, 12000 ft
21.	Collars		2,720	4,080	18	25	80 lbs/ft, 34 ft
22.	Drill collars		60,000	90,000	18	25	6000 lbs x 10
Total Weights without Casing		**748,000**	**845,660**	**2,240,890**			
Total Weights		**748,000**	**1,375,660**	**3,035,890**			

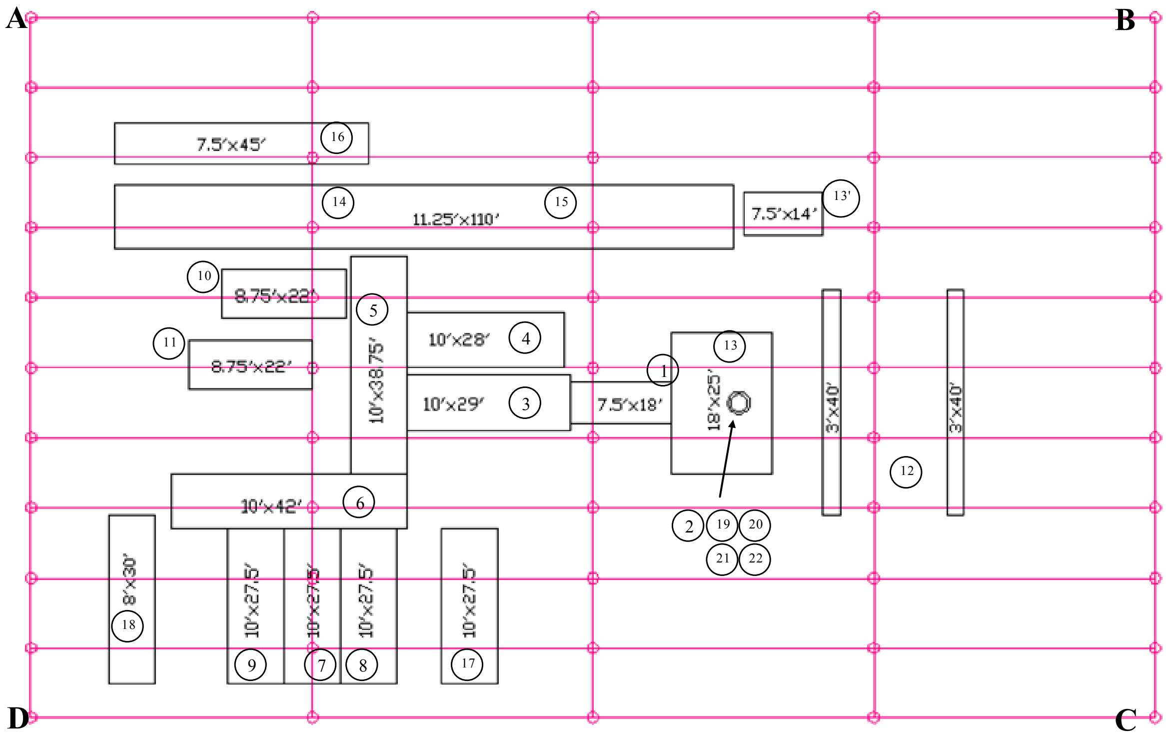


Figure 4-4. Rapid Rig layout

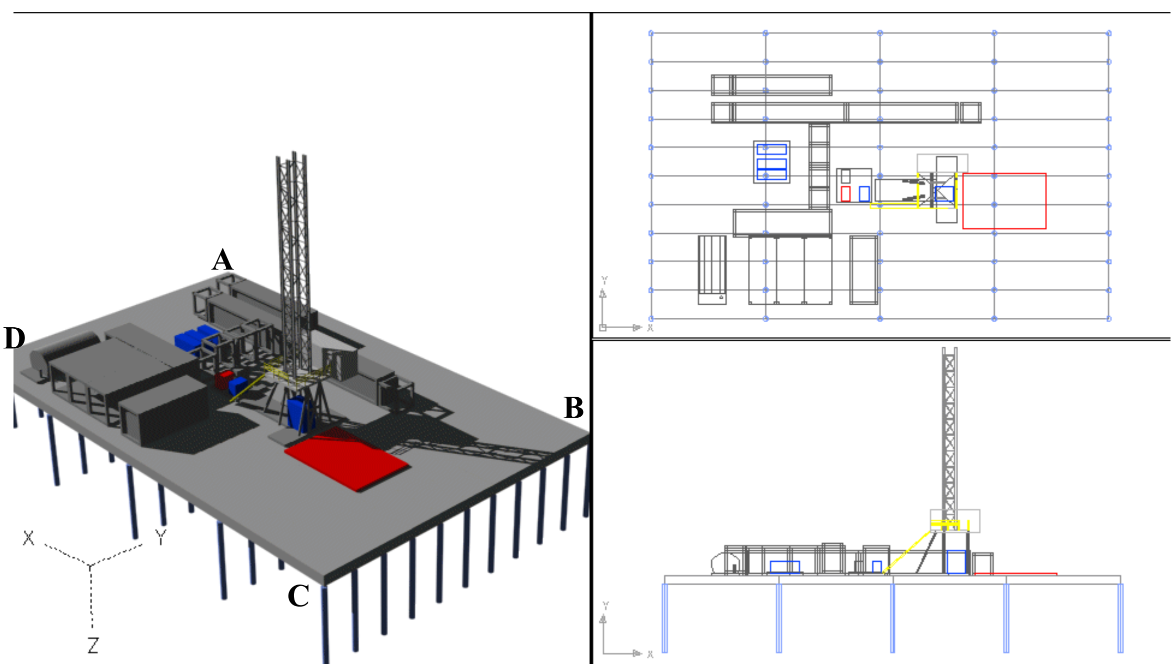


Figure 4-5. Three dimensional (3-D) layout of Rapid Rig

4.2.2.1 Soil Conditions

The six soil conditions adopted for the general foundation calculations are used for the Rapid Rig foundation calculation (i.e., very dense, medium, and very loose for sand; hard, medium, and soft for clay).

4.2.2.2 Weight Distribution on the Platform

In order to calculate the load distribution of Rapid Rig on the proposed modular platform, a numerical analysis program, VisualFEA, is used. Since the wind load in Rapid Rig is significantly smaller than that in the general case, the dead and live loads governed the design. The following assumptions are made to perform the numerical analysis for this problem:

1. Young's modulus (E) for the aluminum material of each module is 1.44E + 09 psf.
2. The modules are in the form of upside down aluminum boxes. The deck of these modules is 6 inches thick. In order to simplify the mesh generation for the numerical simulations, the modules are modeled as flat plates (called thin shells in Finite Element Analysis) which are 6 inches thick. This is a conservative assumption since it ignores the stiffness benefit derived from the 4 ft thickness of the side beams (Figure 4-1).
3. Self weight of modules is not considered in this analysis.
4. Rigid boundary conditions are adopted (The supports of the platform do not settle).

Four node quadrilateral elements are used in this analysis and the applied load layout of Rapid Rig is shown in Figure 4-6.

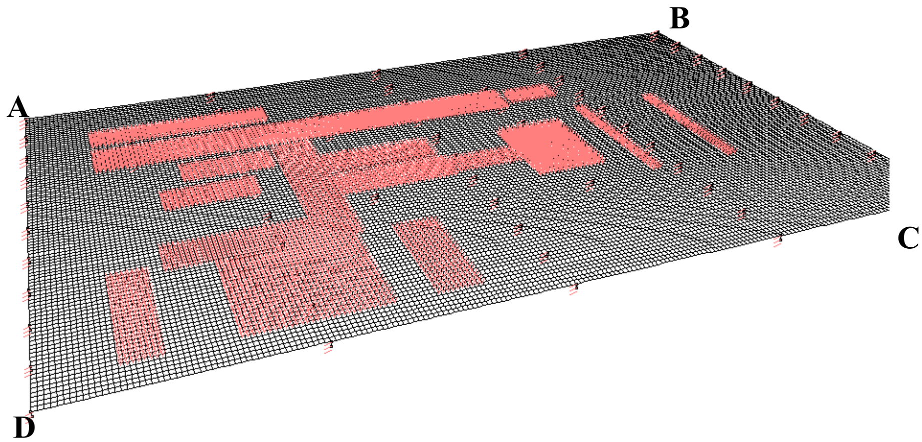


Figure 4-6. The applied load layout of Rapid Rig on the proposed platform

The pile reaction forces and the deformation of the deck on the modules are calculated by using only four piles for each module as shown in Figures 4-7 ~ 4-9. According to the results, the most critical pile reaction force and deformation are 208.3 kips, and 0.934 ft, respectively. Since 0.934 ft is not an acceptable deformation, several critical modules are required to have six piles, each. The results of the analysis using six piles for critical modules are shown in Figures 4-10 ~ 4-12.

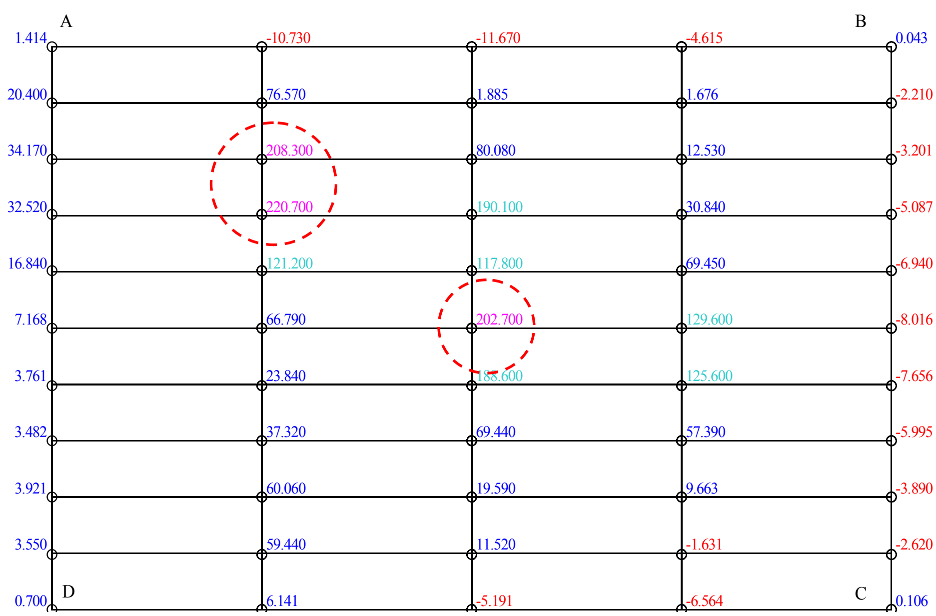


Figure 4-7. Pile reaction force [kips], (using only four piles per module)

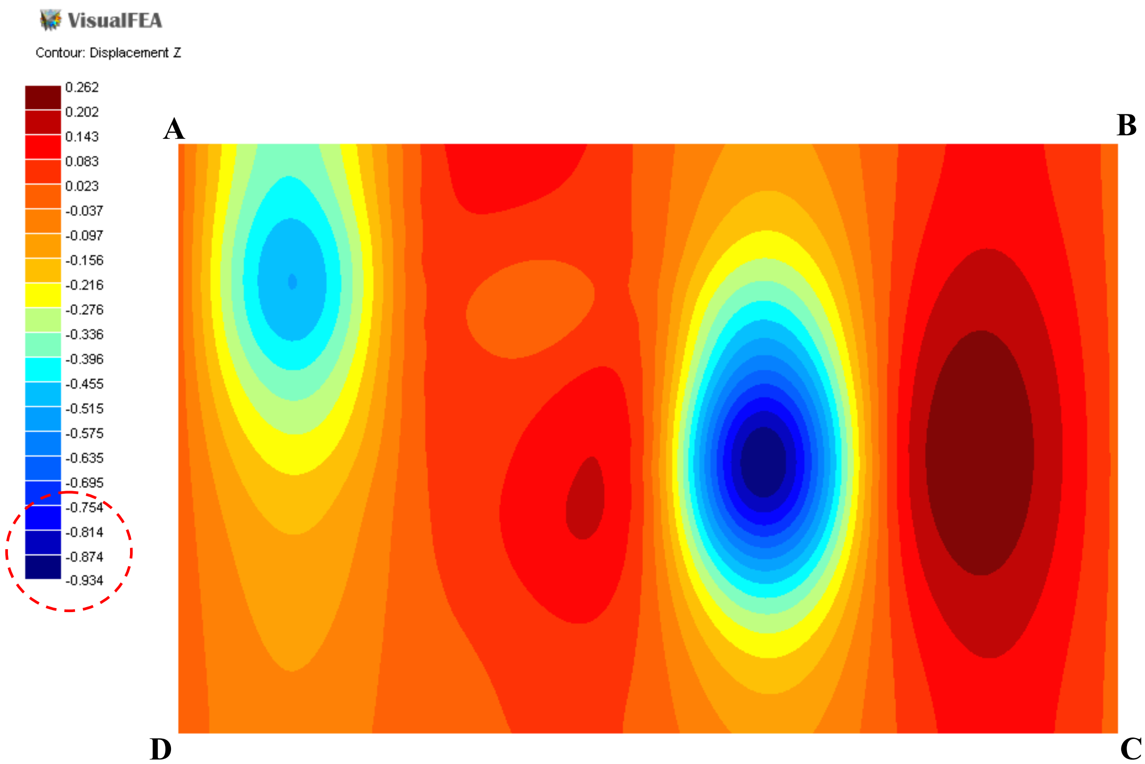


Figure 4-8. Module deformation [ft], (using only four piles per module)

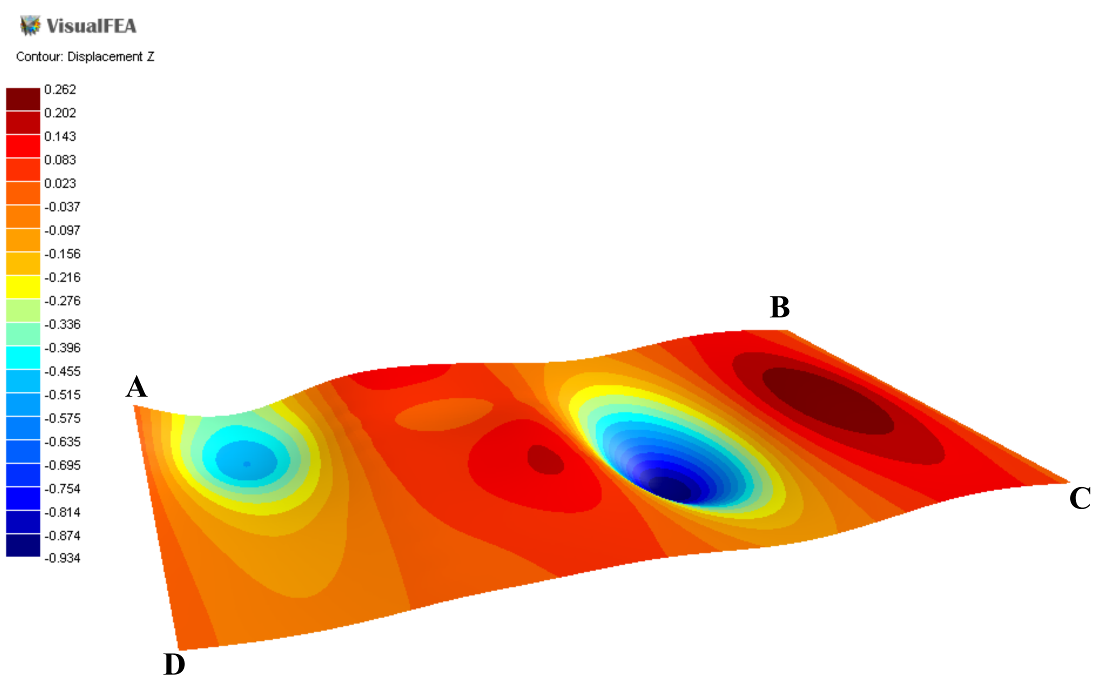


Figure 4-9. Module deformed shape (using only four piles per module)

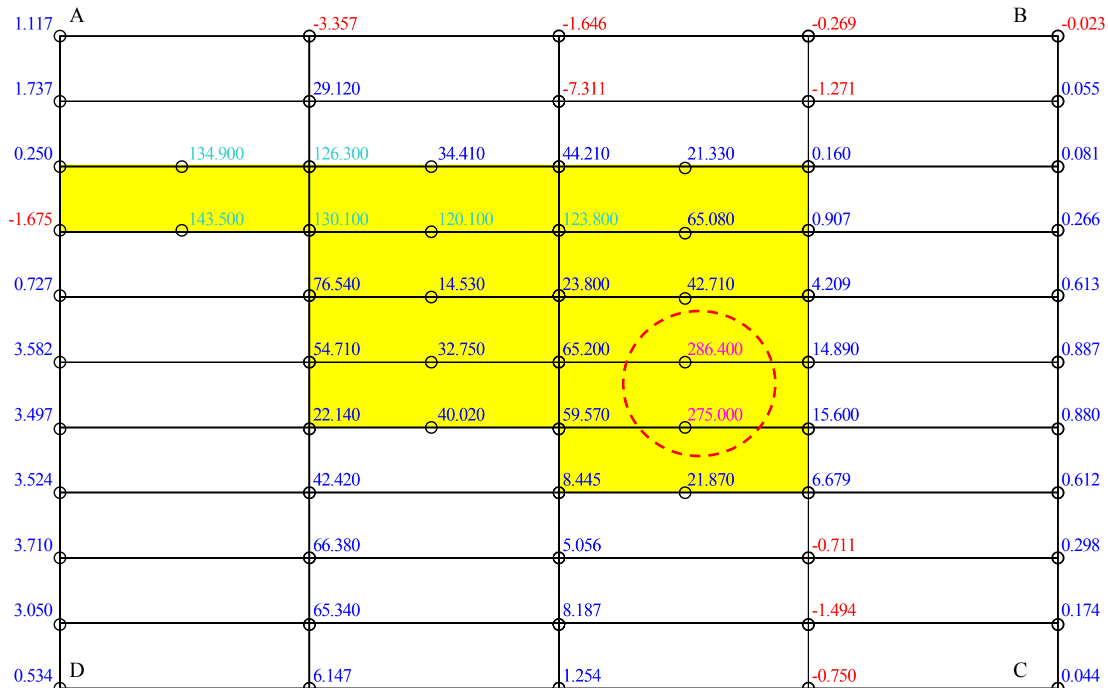


Figure 4-10. Pile reaction force [kips], (using six piles for critical modules)

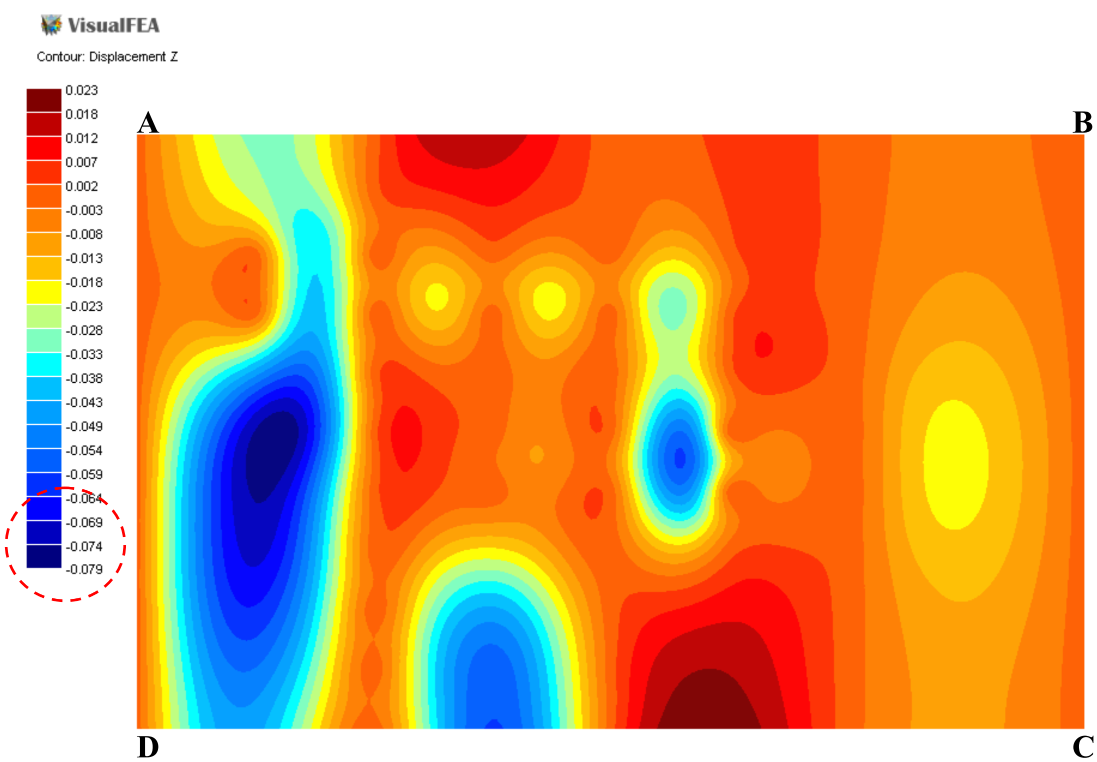


Figure 4-11. Module deformation [ft], (using six piles for critical modules)

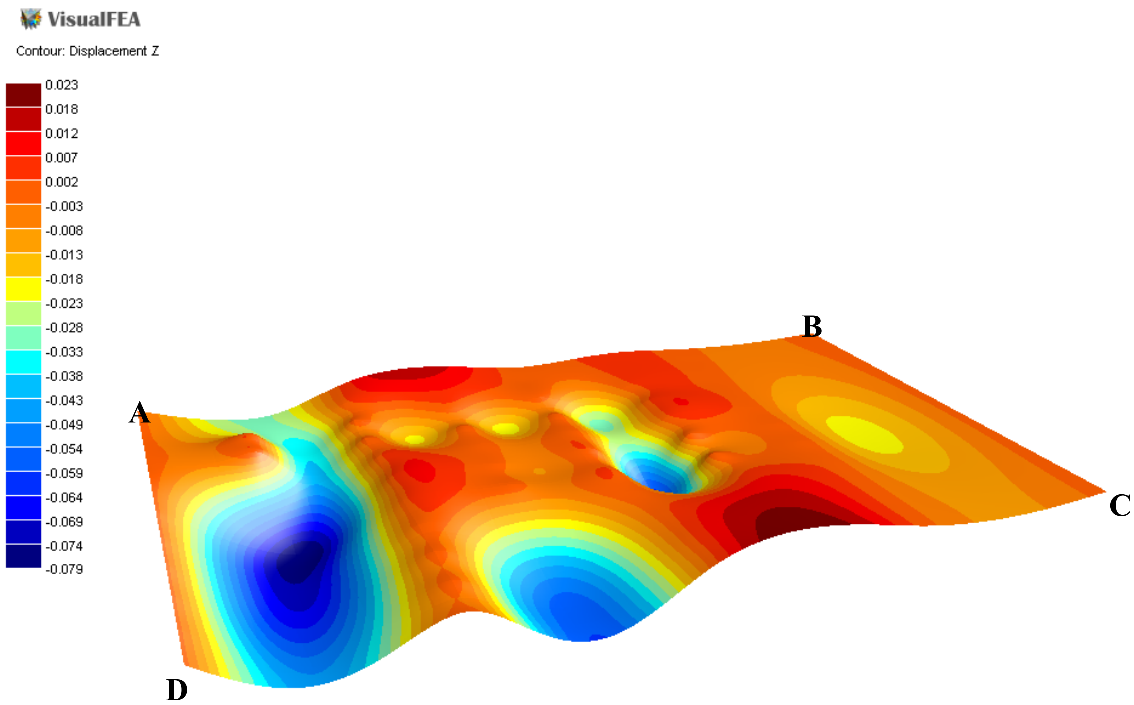


Figure 4-12. Module deformed shape (using six piles for critical modules)

4.2.2.3 LRFD Method

In the case of Rapid Rig, the pile capacity calculations are performed for the driven steel pipe piles and bored piles in accordance with the LRFD method. The maximum reaction force obtained from the Finite Element simulations as described in Section 4.2.2.2 is considered as an applied load for generating the recommended pile selection tables in the Rapid Rig case similar to the tables in the general case. Since this force is the maximum value over the platform, it is conservative to choose one size of pile based on the maximum force and to apply it for all other piles.

As can be seen in Figure 4-10, the reaction forces on most piles besides the two piles right underneath the mast are significantly lower than the maximum reaction value. Therefore, if a single size of pile is used for the whole area, it is not an economical design. Instead, Table 4-3 and 4-6 developed in the general case can be used to choose a proper size for those piles subjected to relatively low reaction forces.

4.2.2.4 Results Summary

Based on the pile capacity calculations in the case of Rapid Rig, two tables (Table 4-8 ~ 4-9) are developed to provide a simple way to choose an appropriate pile size for various soil conditions according to the LRFD method.

Table 4-8. Recommended size of driven piles in the Rapid Rig case (LRFD)

Weight of Rigs & Accessories (Unfactored)	Soil types / Factored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1594 kips	286.4 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 84 ft	L = 43 ft	L = 23 ft	L = 96 ft	L = 68 ft	L = 48 ft

Table 4-9. Recommended size of bored piles in the Rapid Rig case (LRFD)

Weight of Rigs & Accessories (Unfactored)	Soil types / Factored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1594 kips	286.4 kips	D = 24 in.	D = 24 in.	D = 20 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 75 ft	L = 40 ft	L = 36 ft	L = 137 ft	L = 103 ft	L = 62 ft

(where, P_o' = effective overburden pressure, G.W.L. = ground water depth measured from the ground surface,

4.2.3 Description of an Elevated Platform with Rapid Rig and a Wind Turbine

Generation of power for drilling and production operations by wind is a feasible approach in environmentally sensitive areas. The total vertical load of a wind turbine manufactured by Made, (a Spanish company with a specialty in wind and solar technology), is used for the foundation calculation of the proposed modular platform. Technical characteristics of the wind turbine chosen for this calculation are shown in Table 4-10. The load breakdown and the layout of Rapid Rig with the wind turbine are shown in Table 4-11, Table 4-12, Figure 4-13, and Figure 4-14, respectively. Since the wind load is considerably high for the wind turbine, the operating environmental condition and extreme environmental condition are both considered in this foundation calculation.

Table 4-10. Specification of the wind turbine

Rotor	Rated power	660 kW
	Rotor diameter	46 m
	Power control	1662 m^2
	Yaw system	Upwind, active
	Rotor swept area	1662 m 2
	Number of blades	3
	Blade type	LM 21
	Rotor speed	25,5 / 17 rpm
	Hub height	45 m
	Tilt angle	5º
Weights Estimation	Rotor	12.000 kg
	Nacelle (without rotor)	25.000 kg
	Tower	40.000 kg (43.5 m)
	Total weight	70.000 kg (43.5 tower)

[Source: http://www.made.es/06/english/html/ae_46.html]

Table 4-11. Load breakdown of Rapid Rig with the wind turbine in operating condition

No.	COMPONENTS	WEIGHTS [lbs] (DEAD)	WEIGHTS [lbs] (LIVE)	Factored Weights [lbs] D.L = 1.3 L.L = 1.5	Dimension W	Dimension L	Notes
1.	Substructure/Drillfloor package	80,000		104,000	10	58.5	
2.	Mast including installed equipment	100,000		130,000	18	25	
3.	Drawworks package includes Accumulator unit	70,000		91,000	10	29	
4.	Utilities Skid	25,000		32,500	10	28	
5.	Service Skid	20,000		26,000	10	38.75	
6.	Electrical Control House	30,000		39,000	10	42	
7.	Generator House #1	40,000		52,000	10	27.5	
8.	Generator House #2	40,000		52,000	10	27.5	
9.	Air Compressor House	30,000		39,000	10	27.5	
10.	Mud Pump #1	55,000		71,500	8.75	22	
11.	Mud Pump #2	55,000		71,500	8.75	22	
12.	Pipe Handling equipment	35,000		45,500	3	80	
13.	Control House skid including choke manifold	23,000		29,900	18	12.5	
	Choke Manifold hauled on same trailer	15,000		19,500	7.5	14	
14.	Mud Tank Skid #1 (Empty)	40,000		52,000	11.25	55	
	Mud Tank Skid #1 (Full)		204,750	307,125	11.25	55	375 barrels, 13 lbs/gal
15.	Mud Tank Skid #2 (Empty)	40,000		52,000	11.25	55	
	Mud Tank Skid #2 (Full)		204,750	307,125	11.25	55	375 barrels, 13 lbs/gal
16.	Water Tank (Empty)	20,000		26,000	7.5	45	
	Water Tank (Full)		139,440	209,160	7.5	45	400 barrels, 8.3 lbs/gal
17.	Work shop/Storage Skid	20,000		26,000	10	27.5	
18.	Fuel Tank Skid	10,000		13,000	8	30	
19.	Casing		530,000	795,000	18	25	53 lbs/ft, 10000 ft
20.	Pipes		234,000	351,000	18	25	19.5 lbs/ft, 12000 ft
21.	Collars		2,720	4,080	18	25	80 lbs/ft, 34 ft
22.	Drill collars		60,000	90,000	18	25	6000 lbs x 10
23.	Wind turbine (500 Kw)	154,000		200,200	36	36	
24.							
Total Weights without Casing		**902,000**	**845,660**	**2,441,090**			
Total Weights		**902,000**	**1,375,660**	**3,236,090**			

For the operating environmental condition, the load factors of dead load, live load, and wind load are 1.3, 1.5, and 1.2, respectively.

Table 4-12. Load breakdown of Rapid Rig with the wind turbine in extreme condition

No.	COMPONENTS	WEIGHTS [lbs] (DEAD)	WEIGHTS [lbs] (LIVE)	Factored Weights [lbs] D.L = 1.1 L.L = 1.1	Dimension W	Dimension L	Notes
1.	Substructure/Drillfloor package	80,000		88,000	10	58.5	
2.	Mast including installed equipment	100,000		110,000	18	25	
3.	Drawworks package includes Accumulator unit	70,000		77,000	10	29	
4.	Utilities Skid	25,000		27,500	10	28	
5.	Service Skid	20,000		22,000	10	38.75	
6.	Electrical Control House	30,000		33,000	10	42	
7.	Generator House #1	40,000		44,000	10	27.5	
8.	Generator House #2	40,000		44,000	10	27.5	
9.	Air Compressor House	30,000		33,000	10	27.5	
10.	Mud Pump #1	55,000		60,500	8.75	22	
11.	Mud Pump #2	55,000		60,500	8.75	22	
12.	Pipe Handling equipment	35,000		38,500	3	80	
13.	Control House skid including choke manifold	23,000		25,300	18	12.5	
	Choke Manifold hauled on same trailer	15,000		16,500	7.5	14	
14.	Mud Tank Skid #1 (Empty)	40,000		44,000	11.25	55	
	Mud Tank Skid #1 (Full)		204,750	225,225	11.25	55	375 barrels, 13 lbs/gal
15.	Mud Tank Skid #2 (Empty)	40,000		44,000	11.25	55	
	Mud Tank Skid #2 (Full)		204,750	225,225	11.25	55	375 barrels, 13 lbs/gal
16.	Water Tank (Empty)	20,000		22,000	7.5	45	
	Water Tank (Full)		139,440	153,384	7.5	45	400 barrels, 8.3 lbs/gal
17.	Work shop/Storage Skid	20,000		22,000	10	27.5	
18.	Fuel Tank Skid	10,000		11,000	8	30	
19.	Casing		530,000	583,000	18	25	53 lbs/ft, 10000 ft
20.	Pipes		234,000	257,400	18	25	19.5 lbs/ft, 12000 ft
21.	Collars		2,720	2,992	18	25	80 lbs/ft, 34 ft
22.	Drill collars		60,000	66,000	18	25	6000 lbs x 10
23.	Wind turbine (500 Kw)	154,000		169,400	36	36	
24.							
Total Weights without Casing		**902,000**	**845,660**	**1,922,426**			
Total Weights		**902,000**	**1,375,660**	**2,505,426**			

For the extreme environmental condition, the load factors of dead load, live load, and wind load are 1.1, 1.1, and 1.35, respectively.

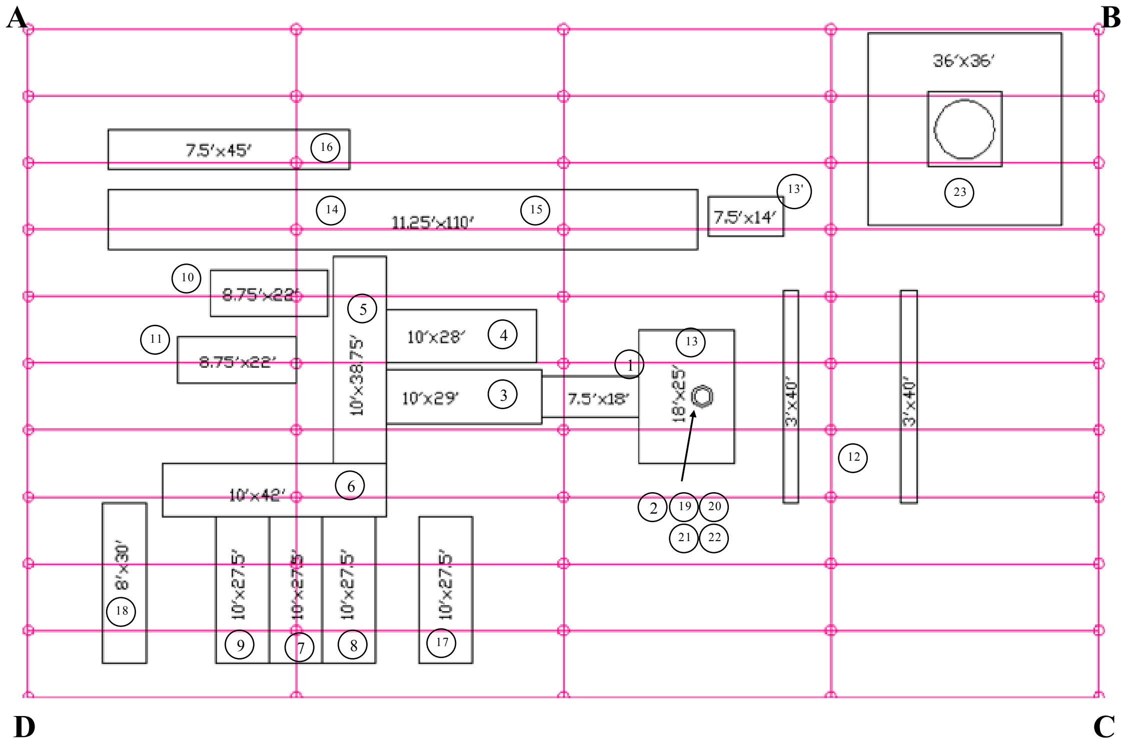


Figure 4-13. Layout of Rapid Rig and the wind turbine

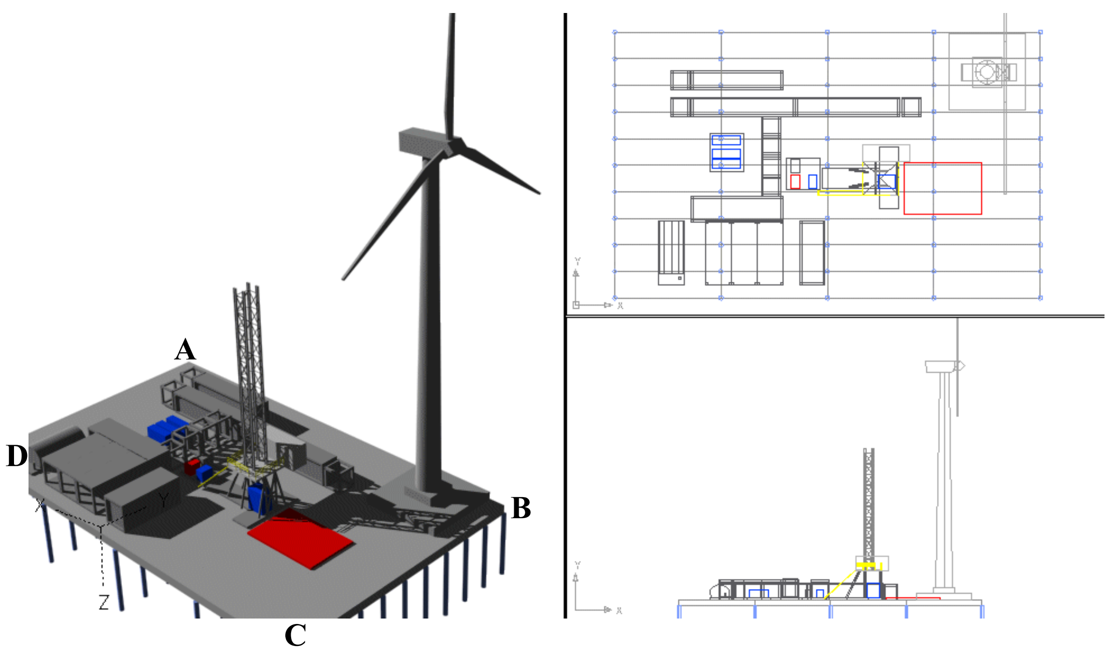


Figure 4-14. Three dimensional (3-D) layout of Rapid Rig and the wind turbine

4.2.3.1 Soil Conditions

The six soil conditions adopted for the general foundation calculations are used for this foundation calculation (i.e., very dense, medium, very loose for sand; hard, medium, soft for clay).

4.2.3.2 Weight Distribution on Platform

In order to calculate the load distribution of Rapid Rig with the wind turbine on the proposed modular platform, a numerical analysis program, VisualFEA, is used. Since the height of the wind turbine is around 150 ft, the wind load should be considered in this analysis. Following assumptions are made to perform the numerical analysis for this problem:

1. Young's modulus (E) for the aluminum material of each module is 1.44E + 09 psf.
2. The modules are represented by a 6 inches thick plate.
3. Self weight of modules is not considered in this analysis.
4. Rigid boundary conditions are adopted (The supports of the platform do not settle).

Four node quadrilateral elements are used in this analysis and the applied load layout of Rapid Rig with the wind turbine is shown in Figure 4-15.

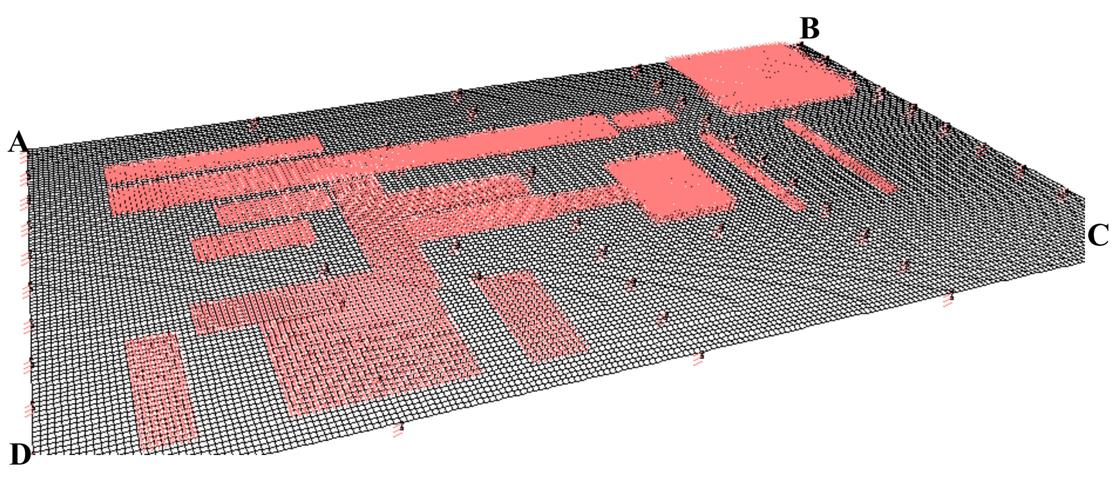


Figure 4-15. Applied load layout of Rapid Rig and the wind turbine

The pile reaction forces and the deformation of the deck on the modules are calculated by using only four piles for each module as shown in Figures 4-16 ~ 4-21. According to the results, the most critical pile reaction force and deformation for the operating environmental condition and the extreme environmental condition are 221.7 kips, 0.909 ft, 167.4 kips, and 1.054 ft, respectively. Since 1.0 ft is not an acceptable deformation, several critical modules are required to have six piles, each. The results of the analysis using six piles for critical modules are shown in Figure 4-22 ~ 4-27.

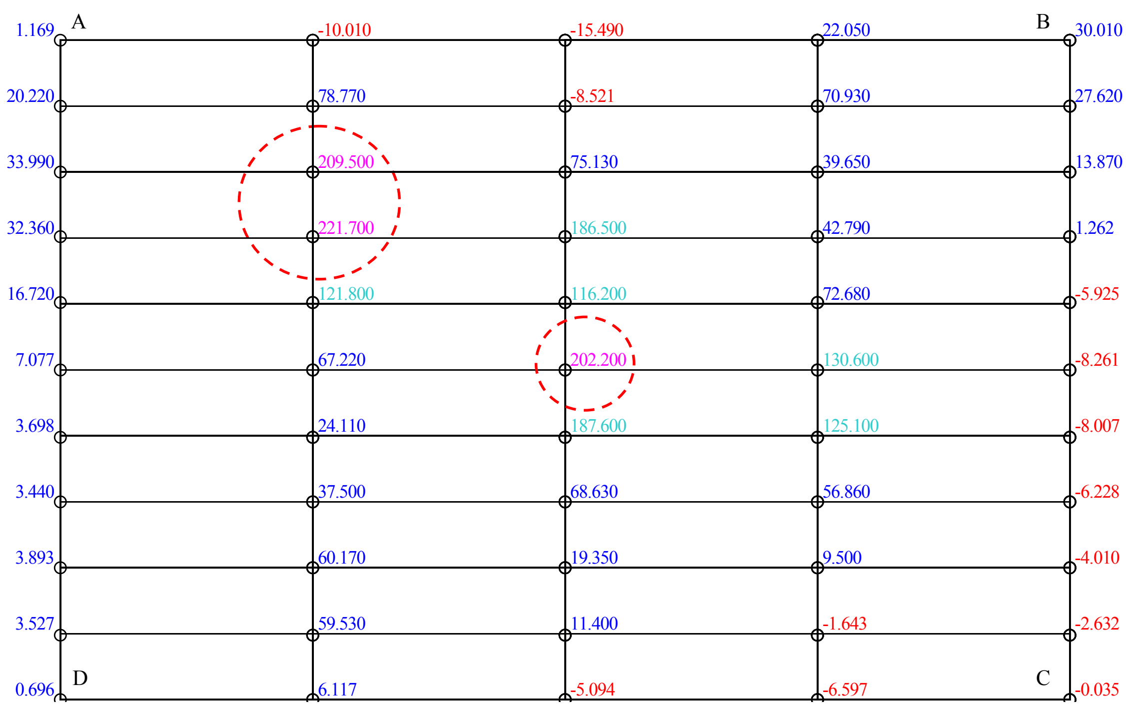


Figure 4-16. Pile reaction force [kips] in operating condition

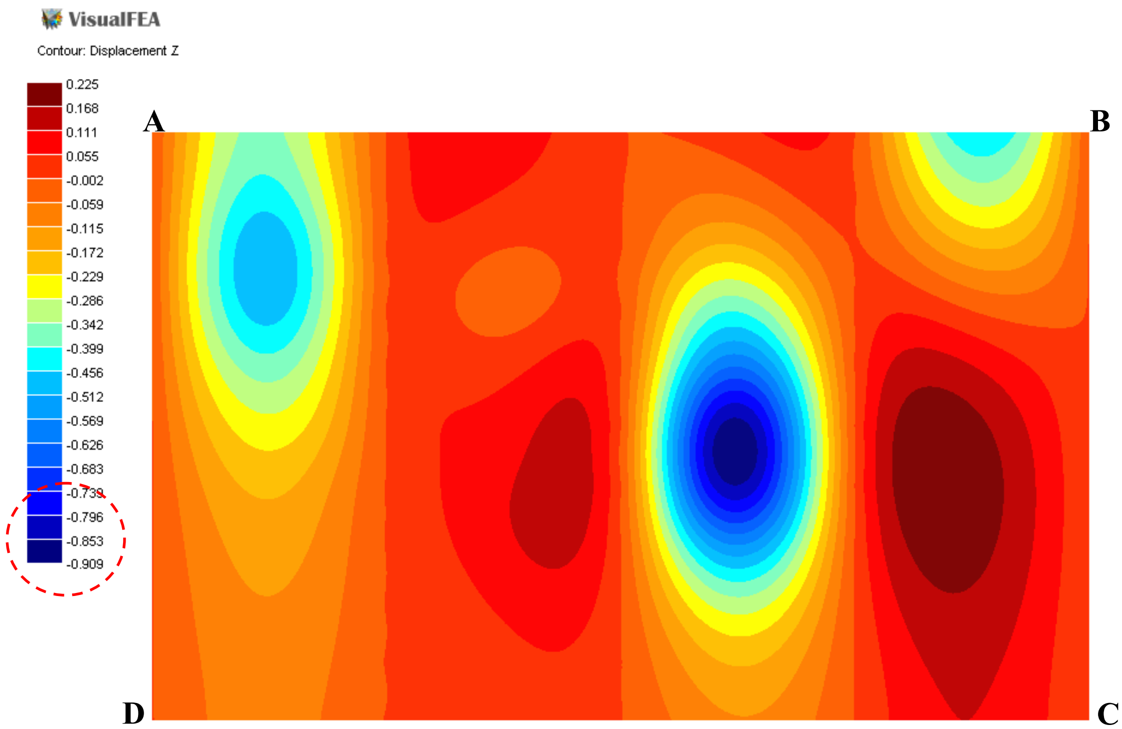


Figure 4-17. Module deformation [ft] in operating condition

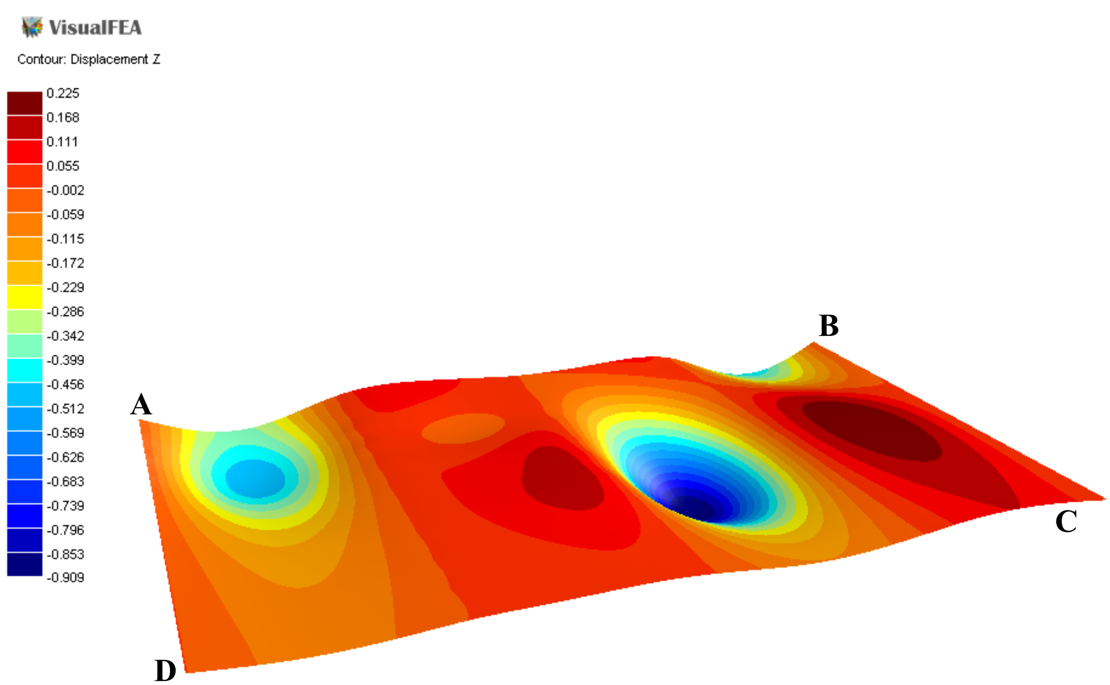


Figure 4-18. Module deformed shape in operating condition

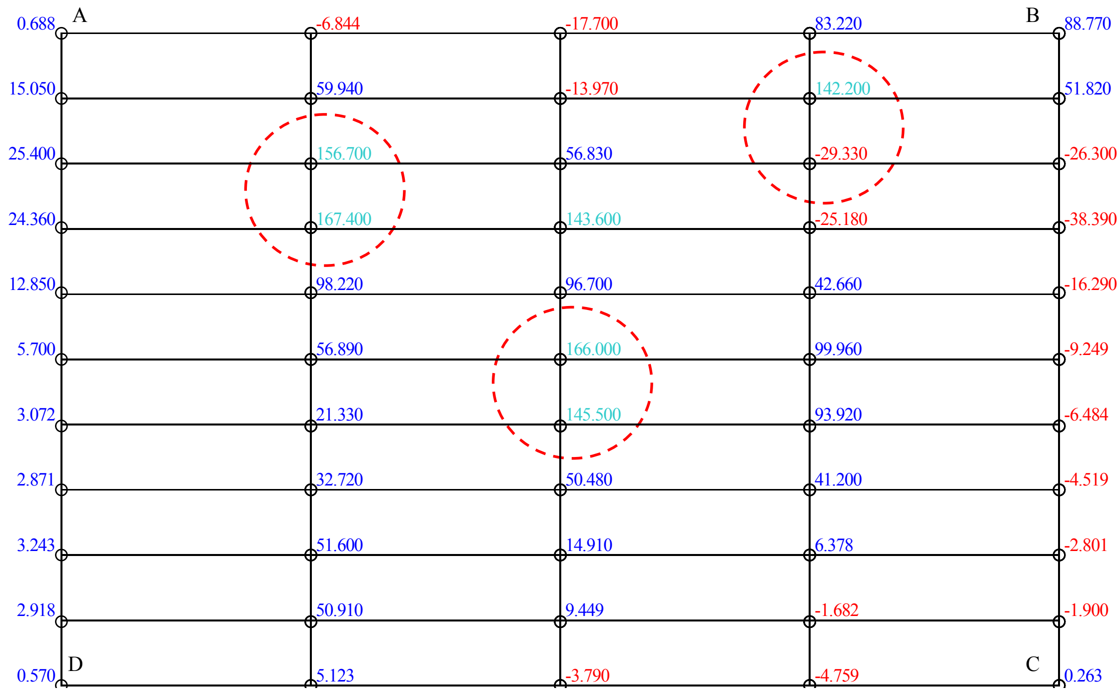


Figure 4-19. Pile reaction force [kips] in extreme condition

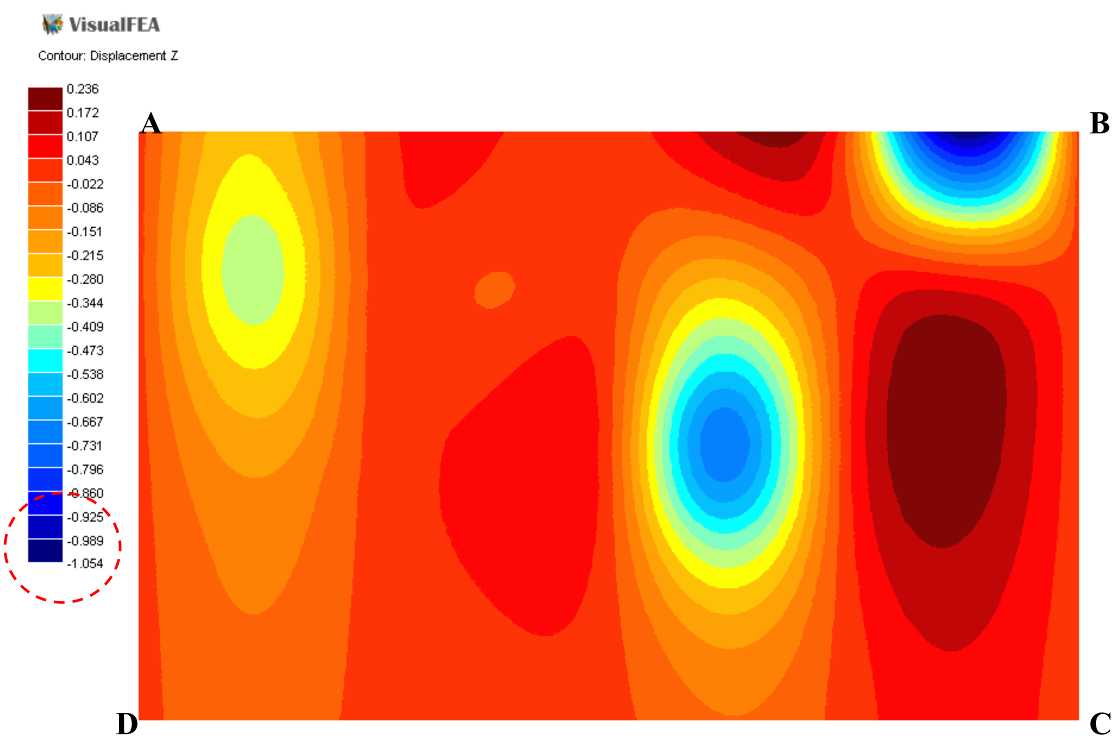


Figure 4-20. Module deformation [ft] in extreme condition

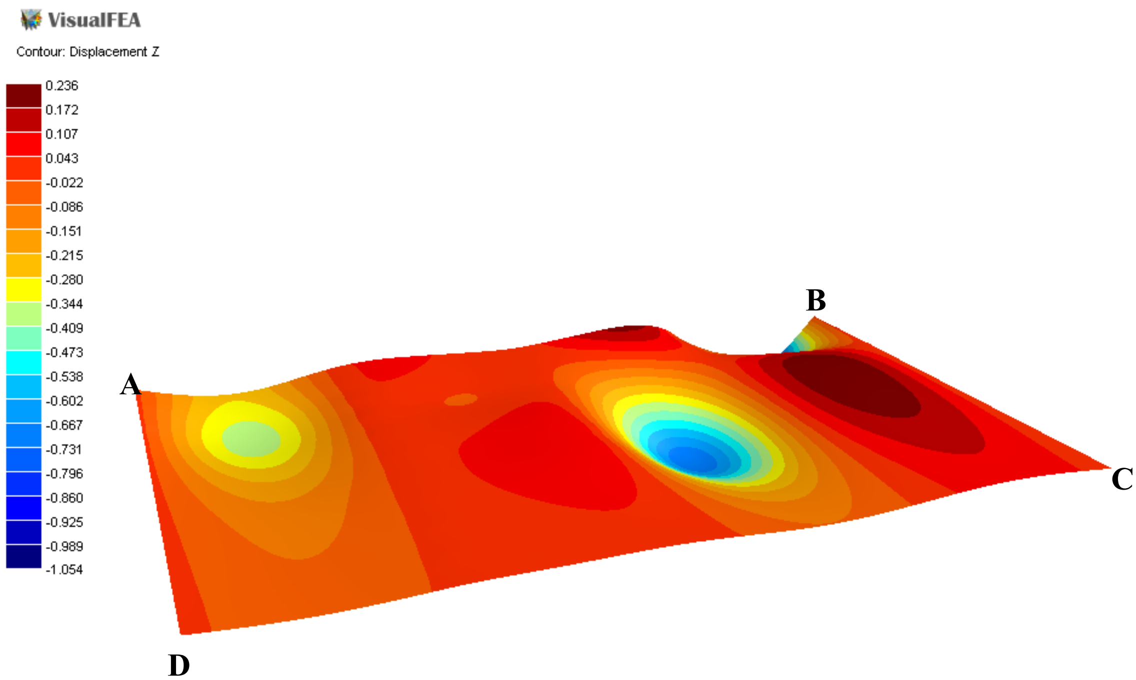


Figure 4-21. Module deformed shape in extreme condition

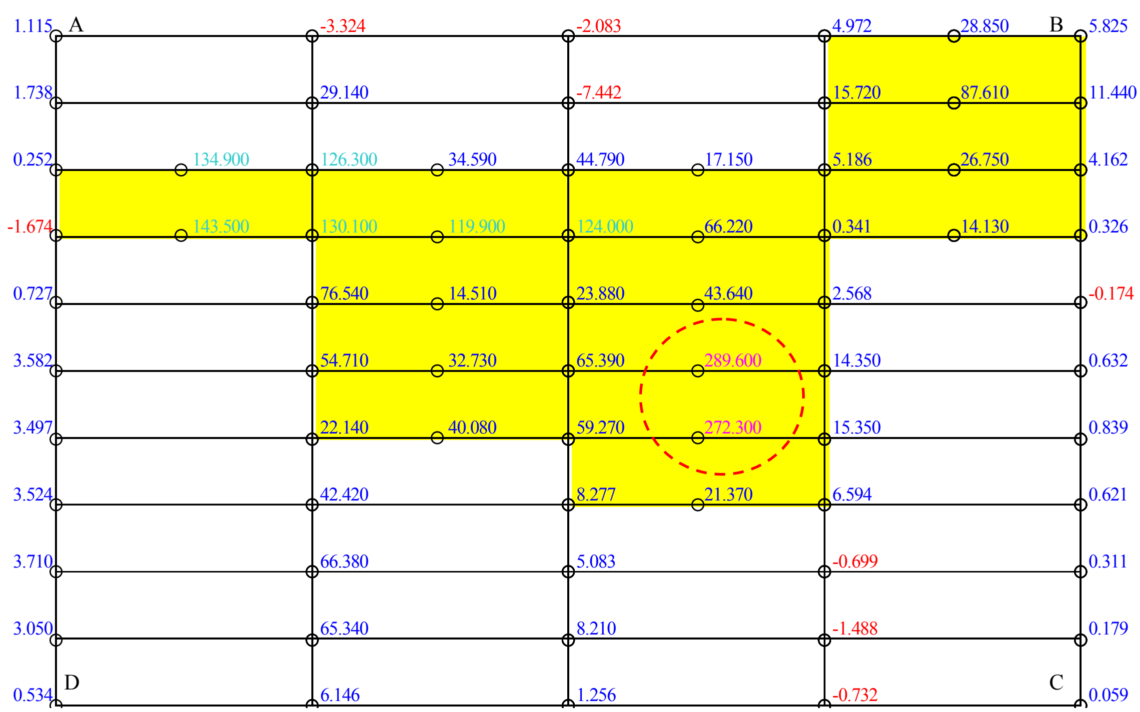


Figure 4-22. Pile reaction force [kips] in operating condition (using six piles)

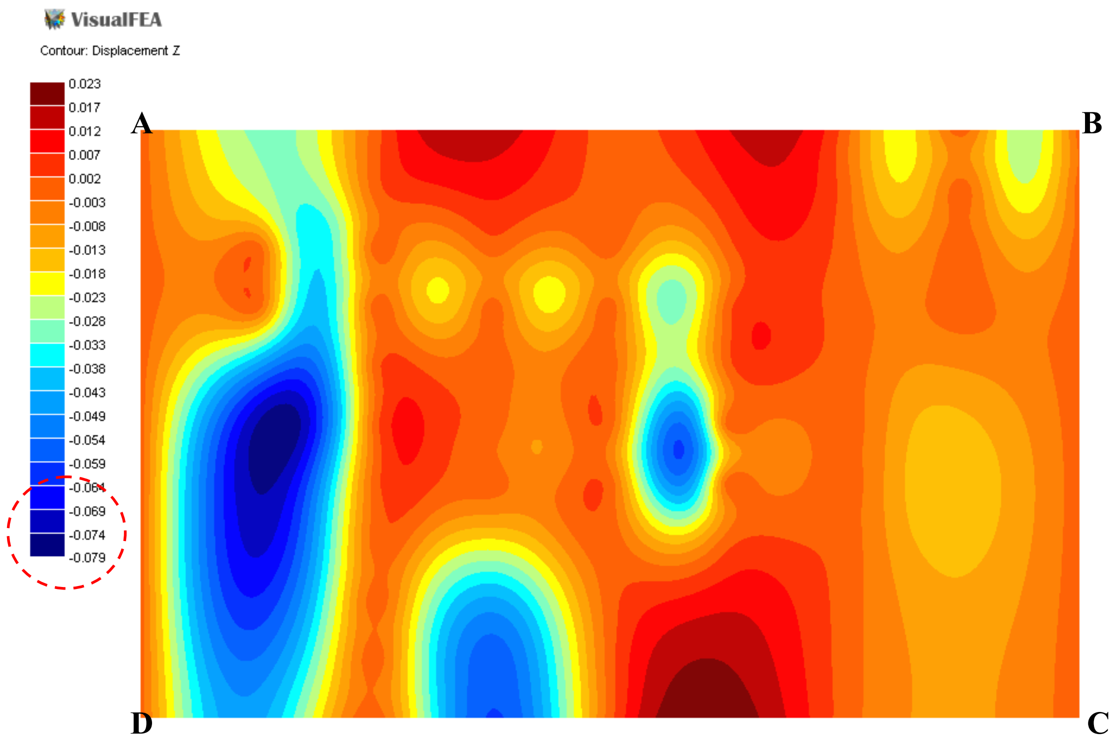


Figure 4-23. Module deformation [ft] in operating condition (using six piles)

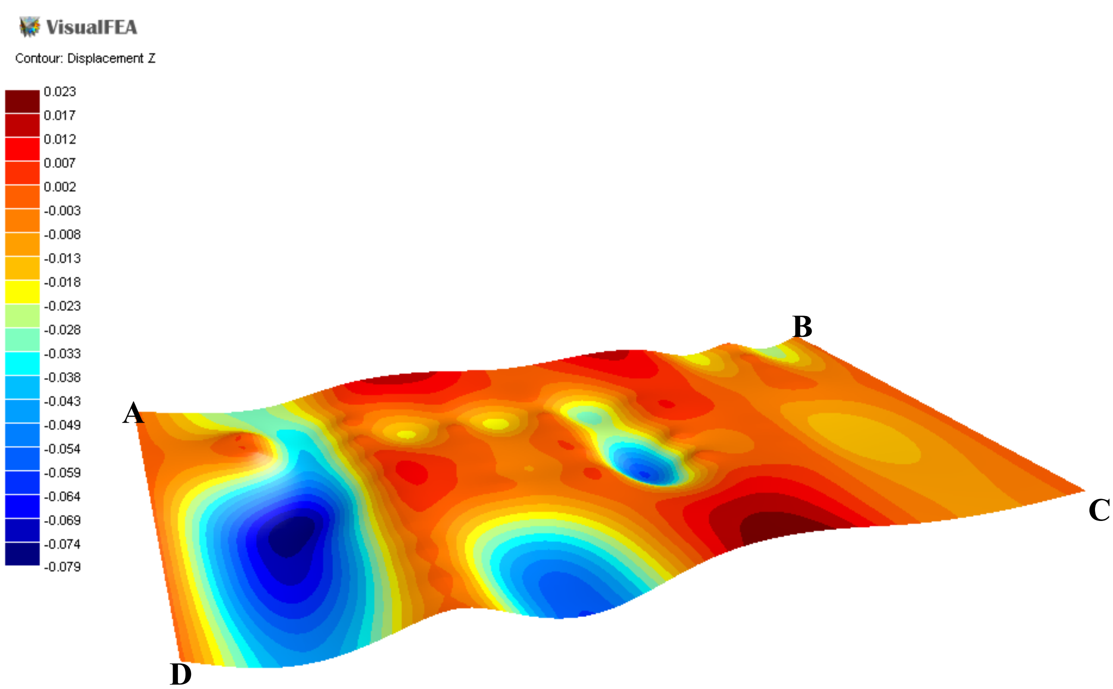


Figure 4-24. Module deformed shape in operating condition (using six piles)

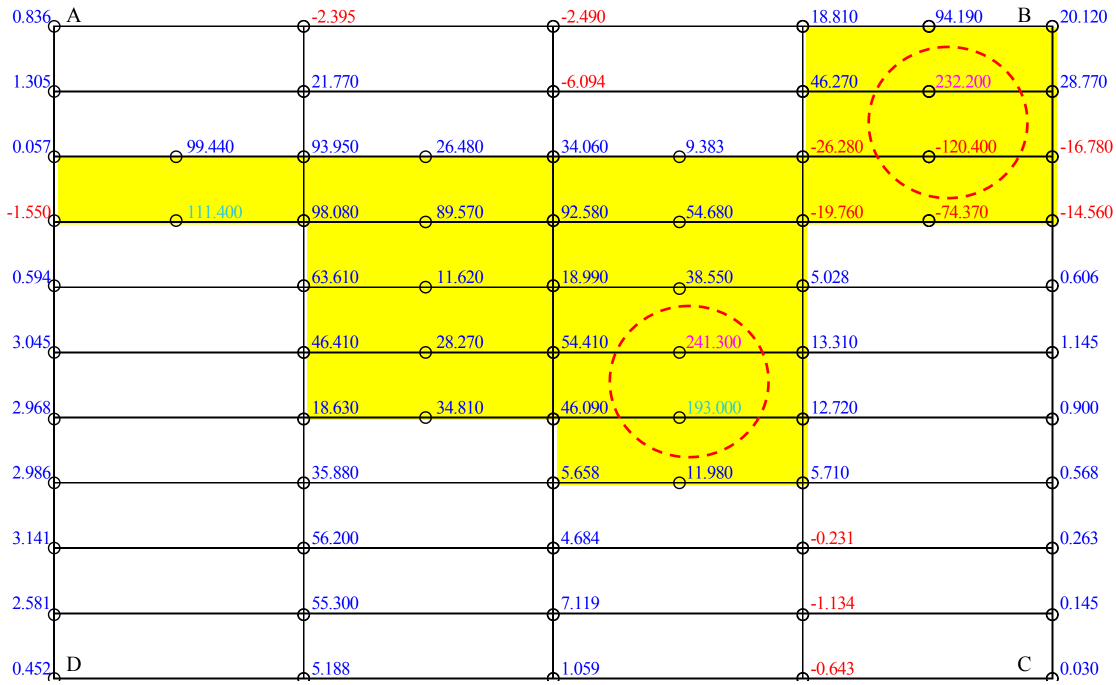


Figure 4-25. Pile reaction force [kips] in extreme condition (using six piles)

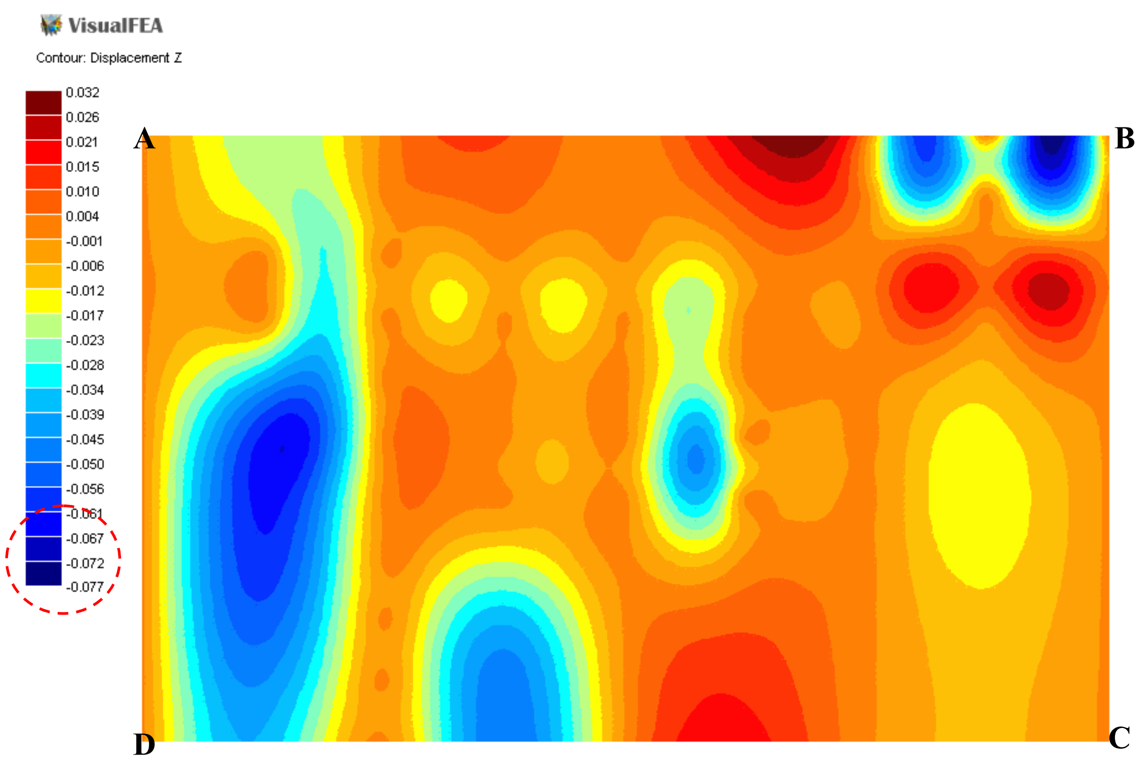


Figure 4-26. Module deformation [ft] in extreme condition (using six piles)

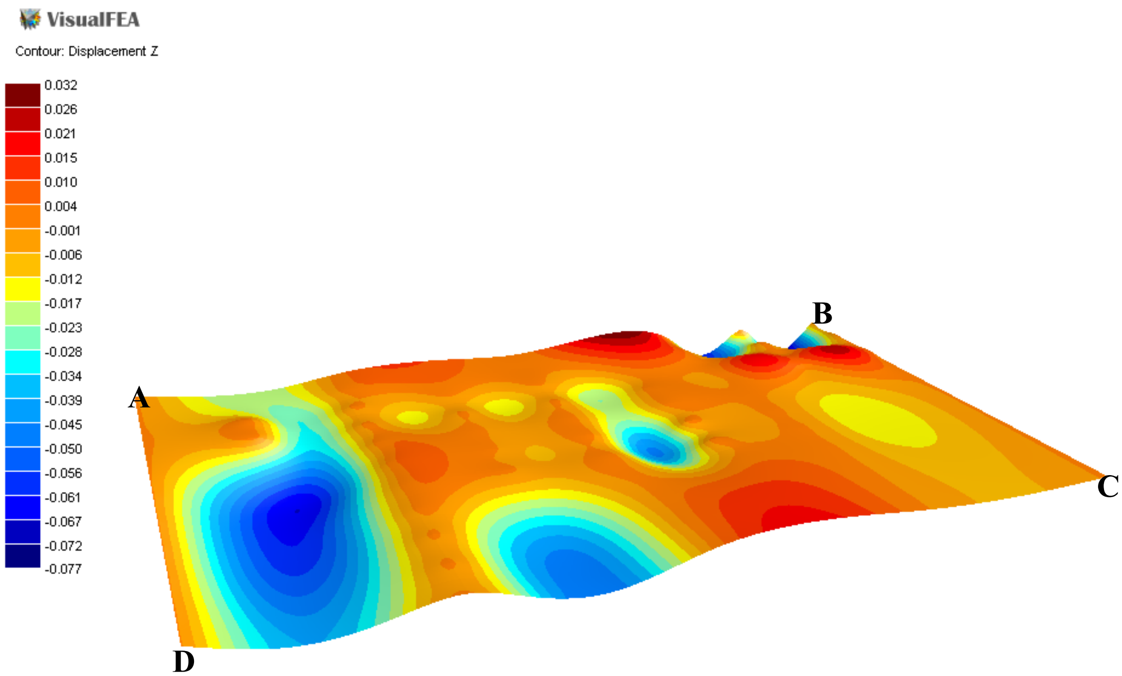


Figure 4-27. Module deformed shape in extreme condition (using six piles)

4.2.3.3 LRFD Method

In the case of Rapid Rig and the wind turbine, the pile capacity calculations are performed for the driven steel pipe piles and bored piles in accordance with the LRFD method. The maximum reaction force obtained from the 3-D simulations as described in Section 4.2.3.2 is considered as an applied load for generating the recommended pile selection tables in the Rapid Rig with wind turbine case similar to the tables in the general case. Since this force is the maximum value over the platform, it is conservative to choose one size of pile based on the maximum force and to apply it for all other piles.

As can be seen in Figure 4-22 and Figure 4-25, the reaction forces on most piles besides the four piles right underneath the mast and the wind turbine are significantly lower than the maximum reaction value. Therefore, if a single size of pile is used for the whole area, it is not an economical design. Instead, Table 4-3 and 4-6 developed in the general case can be used to choose a proper size for those piles subjected to relatively low reaction forces.

4.2.3.4 Results Summary

Based on the pile capacity calculations in the case of Rapid Rig with the wind turbine, two tables (Table 4-13 ~ 4-14) are developed to provide a simple way to choose an appropriate pile size for various soil conditions according to the LRFD method.

Table 4-13. Recommended size of driven piles in the Rapid Rig with wind turbine case

Weight of Rigs & Accessories (Unfactored)	Soil types / Factored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1748 kips	289.6 kips	D = 24 in.	D = 24 in.	D = 16 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 84 ft	L = 43 ft	L = 33 ft	L = 96 ft	L = 68 ft	L = 49 ft

(where, P_o' = effective overburden pressure, G.W.L. = ground water depth measured from the ground surface,

Table 4-14. Recommended size of bored piles in the Rapid Rig with wind turbine case

Weight of Rigs & Accessories (Unfactored)	Soil types / Factored max. vertical loads on one pile	Sand & Gravels			Silts & Clays		
		very loose	medium	very dense	soft	medium	hard
		γ_{sat} = 115 pcf G.W.L = 0 ft N_{SPT} = 10 bpf	γ_{sat} = 120 pcf G.W.L = 10 ft N_{SPT} = 30 bpf	γ_{sat} = 127 pcf G.W.L = 20 ft N_{SPT} = 50 bpf	γ_{sat} = 115 pcf G.W.L = 0 ft Su = 0.25 P_o'	γ_{sat} = 120 pcf G.W.L = 10 ft Su = 60 kPa	γ_{sat} = 127 pcf G.W.L = 20 ft Su = 100 kPa
1748 kips	289.6 kips	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.	D = 24 in.
		L = 76 ft	L = 40 ft	L = 29 ft	L = 137 ft	L = 104 ft	L = 62 ft

(where, P_o' = effective overburden pressure, G.W.L. = ground water depth measured from the ground surface,

4.2.4 Construction Strategies of Pile Foundation

In this section, four different construction methods of a driven steel pipe pile for an elevated platform with Rapid Rig are described for one specific soil condition with the LRFD method. The soil condition is assumed "Very dense sand" and the required soil parameters are shown in Figure 4-28.

Rapid Rig is placed on the platform as shown in Figure 4-29. It is noted that the layout shown in Figure 4-29 is not the same as the one shown in Figure 4-4. This is because EFD subject matter experts decided to reduce the number of modules being used in this study as many as possible since the cost of each module is very high. The refined platform consists of 24 aluminum modules (40 modules were initially used in Figure 4-4) and 45 piles as shown in Figure 4-30. Figure 4-30 also shows the reaction force on each pile and each pile is numbered as shown in Figure 4-31. The dimension of each component of Rapid Rig is provided by National Oilwell Varco.

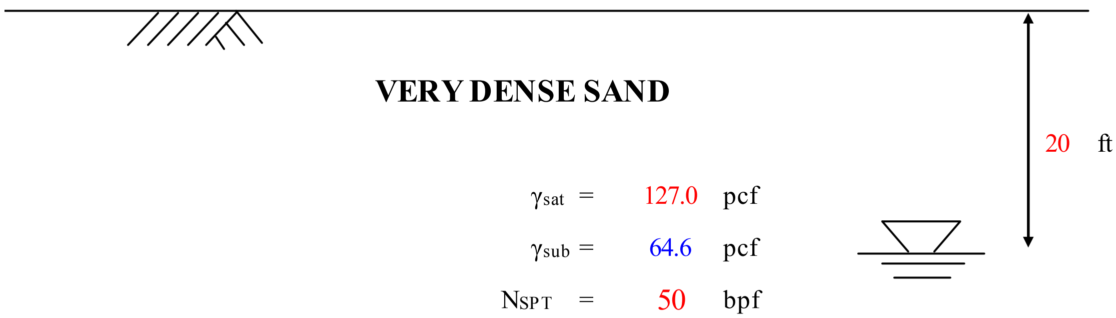


Figure 4-28. Assumed soil condition

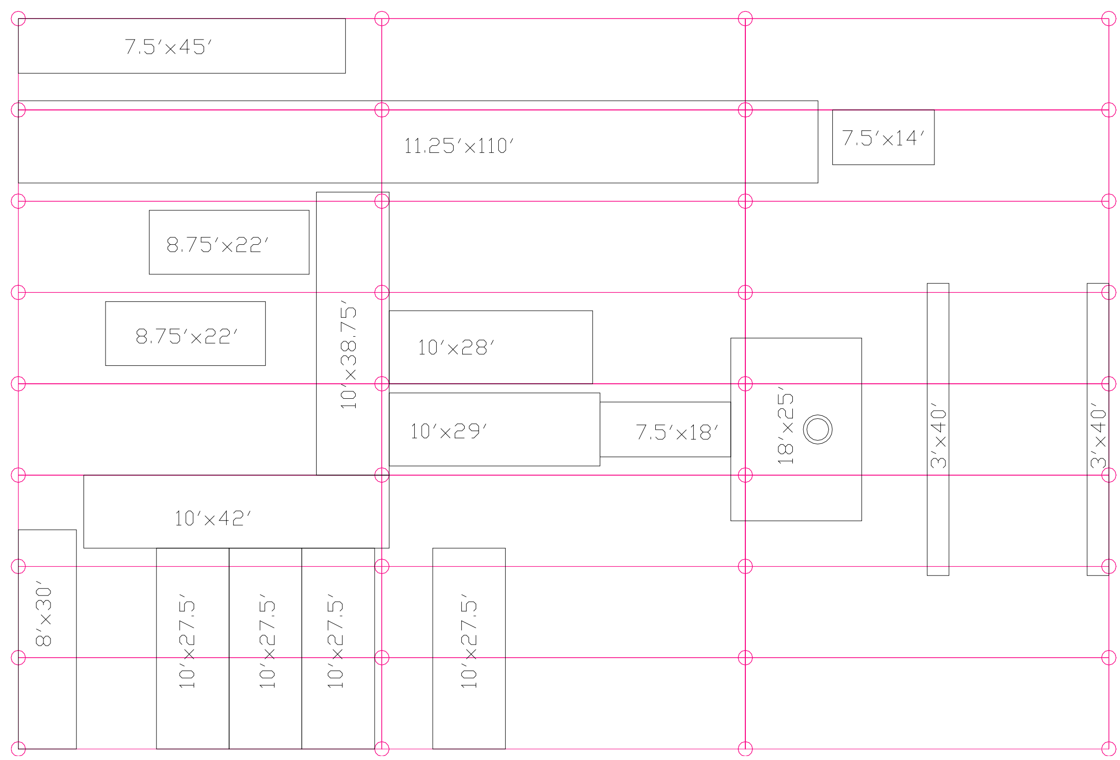


Figure 4-29. Layout of Rapid Rig on the elevated platform

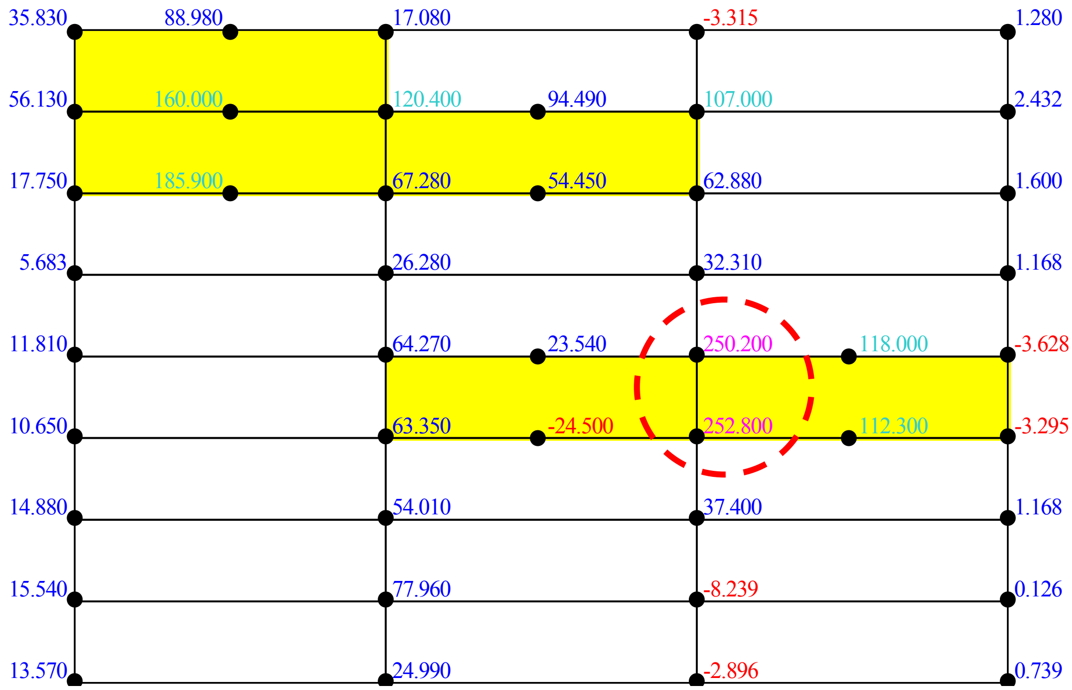


Figure 4-30. Reaction force on each pile [kips]

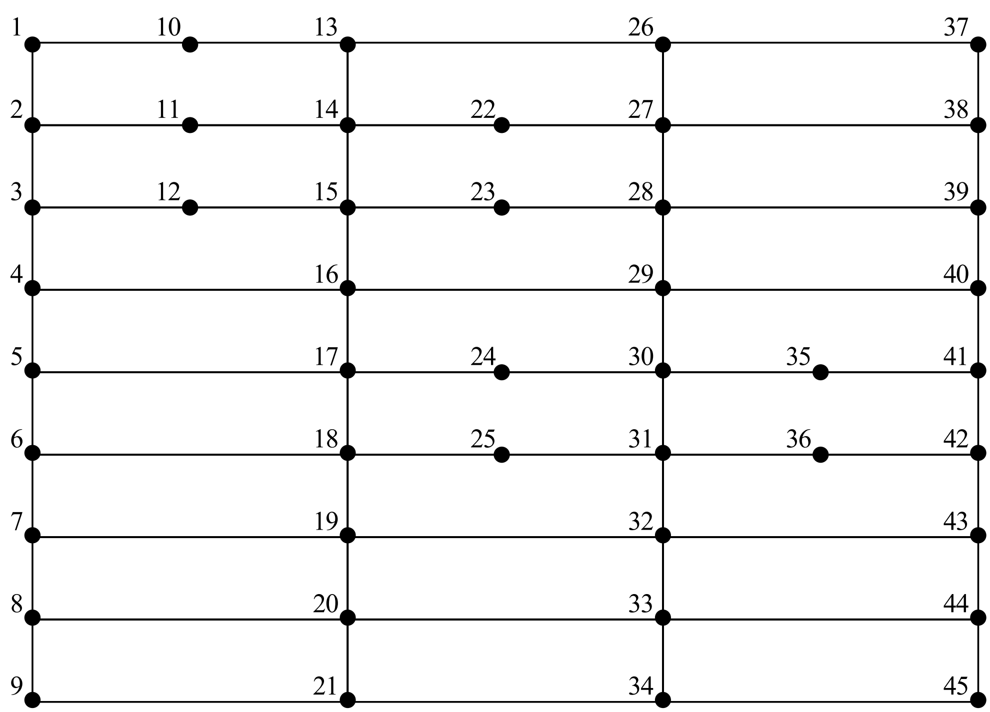


Figure 4-31. Numbers assigned to each pile

In order to estimate the cost of pile foundations, 'RSMeans (2006)', the reference book of construction cost information, and several EFD experts' inputs are used in this study. After gathering the cost information, Eq. (4-3) is developed to be used for the cost estimation of piles. Eq. (4-3) is the best fit for the piles, the range from 10 to 24 inches in diameter and from 10 to 100 feets in length.

$$\text{Cost} = [50 + (D - 10) \times 2.8] \times L \qquad (4\text{-}3)$$

where D is the diameter in inches and L is the length in feets.

Four different construction strategies of pile foundation are described as follows:

1. Optimal pile size for each pile: for each pile with its reaction force, an exhaustive search optimization routine is run to find the optimized pile size (i.e., diameter and length). Once all possible pile sizes, which satisfy the pile capacity design criteria described in Section 3.2, have been evaluated, the size with the lowest cost is the best pile size. Table 4-15 shows the optimized pile size and cost for each pile.
2. Using same piles for the entire platform area: This is the simplest method to construct piles. Since no. 31 and no. 32 piles shown in Figure 4-31 sustain the biggest applied load among all 45 piles, the pile size of no. 31 and no. 32 are used for the entire platform area. Table 4-16 shows the total cost of using this method.
3. Using two piles: Since the reaction forces on only two piles (no. 31 and 32) are significantly greater than other piles, two pile sizes are used. One is for those two piles (no. 31 and 32) and the other one is for the remaining piles. Table 4-17 shows the total cost of using this method.
4. Categorized by reaction forces: This method categorizes pile size by three different reaction forces: (1) the reaction force is greater than 200 kips; (2) the reaction force is greater than 100 kips and less than or equal to 200 kips; (3) the reaction force is less than or equal to 100 kips. Table 4-18 shows the total cost of using this method.

Table 4-15. Optimal pile size and cost for each pile

Pile no.	Diameter (in.)	Length (ft)	Quantities	Total	Pile no.	Diameter (in.)	Length (ft)	Quantities	Total
1	10	11	1	$550.00	24	10	10	1	$500.00
2	14	10	1	$612.00	25	12	16	1	$889.60
3	10	10	1	$500.00	26	10	10	1	$500.00
4	10	10	1	$500.00	27	20	10	1	$780.00
5	10	10	1	$500.00	28	16	10	1	$668.00
6	10	10	1	$500.00	29	10	10	1	$500.00
7	10	10	1	$500.00	30	24	15	1	$1,338.00
8	10	10	1	$500.00	31	24	15	1	$1,338.00
9	10	10	1	$500.00	32	12	10	1	$556.00
10	18	10	1	$724.00	33	10	11	1	$550.00
11	24	11	1	$981.20	34	10	10	1	$500.00
12	24	12	1	$1,070.40	35	22	10	1	$836.00
13	10	10	1	$500.00	36	20	10	1	$780.00
14	22	10	1	$836.00	37	10	10	1	$500.00
15	16	10	1	$668.00	38	10	10	1	$500.00
16	10	10	1	$500.00	39	10	10	1	$500.00
17	16	10	1	$668.00	40	10	10	1	$500.00
18	16	10	1	$668.00	41	10	10	1	$500.00
19	14	10	1	$612.00	42	10	10	1	$500.00
20	18	10	1	$724.00	43	10	10	1	$500.00
21	10	10	1	$500.00	44	10	10	1	$500.00
22	20	10	1	$780.00	45	10	10	1	$500.00
23	14	10	1	$612.00			∑	45	$28,741.20

Table 4-16. Pile size for "using same pile" method

Pile no.	Diameter (in.)	Length (ft)	Quantities	Total
all	24	15	45	$60,210.00
		∑	45	$60,210.00

Table 4-17. Pile size for "using two piles" method

Pile no.	Diameter (in.)	Length (ft)	Quantities	Total
30 & 31	24	15	2	$2,676.00
others	24	12	43	$46,027.00
		∑	45	$48,703.00

Table 4-18. Pile size for "categorized by reaction forces" method

Category	Diameter (in.)	Length (ft)	Quantities	Total
P > 200 kips	24	15	2	$2,676.00
100 < P ≤200	24	12	6	$6,422.00
P ≤ 100	20	10	37	$28,860.00
		∑	45	$37,958.00

4.2.5 Lessons Learned

Conventional onshore drilling for oil and gas consists of placing a gravel pad for leveling and carrying capacity purposes. The use of an elevated platform as an alternative to the gravel pad is less intrusive and leads to a more environmentally friendly approach to oil and gas drilling. Since elevated drilling platforms require the use of piles, many different cases of pile design are conducted through Section 4.2 to give site location engineers a basic idea about pile foundation designs of a platform for various platform weights and soil conditions. The four different construction strategies of pile foundation are also described in Section 4.2.4. "Using optimal pile size for each pile" method is the least expensive method while "using same pile size for the entire platform" method is the most expensive method. However, in real construction, some other construction factors such as pile set up time and possibility of wrong pile placement are also required to be considered. Therefore, site location engineers should select the appropriate pile construction strategy based on each site condition.

4.3 Feasibility of Using Composite Mat System in Drill Sites

Another alternative of environmentally friendly foundations for drill sites is composite mats. Since the total construction cost of an elevated platform is considerably high and the construction is time consuming, a composite mat system can be a good alternative to the gravel pad. DURA-BASE Composite Mat System from Newpark mats and Integrated Services is considered for the feasibility study in this section.

4.3.1 Specification of DURA-BASE Composite Mat System

The large size of DURA-BASE Composite Mat System is used in this feasibility study. Table 4-19 shows the specification of this mat. More specific information about this mat system can be found in the following website (http://www.newparkmats.com).

Table 4-19. Brief information about DURA-BASE Composite Mat System

Dimensions	8 ft wide, 14 ft long, and 4 inches depth (for one layer)
Weight	1,050 lbs
Material	High density polyethylene
Young's Modulus	1 GPa ≈ 2.09e+07 psf
Purchase rate	\$20.50/ft^2 (the rate was obtained in 2006)
Rent rate (90 days)	\$2.00/ft^2 (the rate subject to change)

4.3.2 Finite Element Analysis for the Composite Mat System

In order to conduct a parametric study of the composite mat, a finite element mesh (i.e., two-dimensional axisymmetric mesh and three node triangular elements) is generated using a numerical analysis program, VisualFEA as shown in Figure 4-32. For this parametric study, the applied load area is varied from 6 inches to 10 feets in diameter (i.e., D = 0.5, 1.0, 2.0, 4.0, 6.0, and 10 ft) and the ratio of Young's Modulus between the composite mat and the soil is varied from 1 to 100 (i.e., 1, 10, 20, and 100). The results of the analysis are summarized by ρ-values. The ρ-values are calculated by $P_{(max)}$ / $P_{(applied)}$. The $P_{(applied)}$ is the applied load on the mat system and the $P_{(max)}$ is the maximum pressure obtained from the ground. In this parametric analysis, the applied load is 1 psf and the result summary is shown in Table 4-20. In order to better display the results, result graphs are summarized as shown in Figure 4-33.

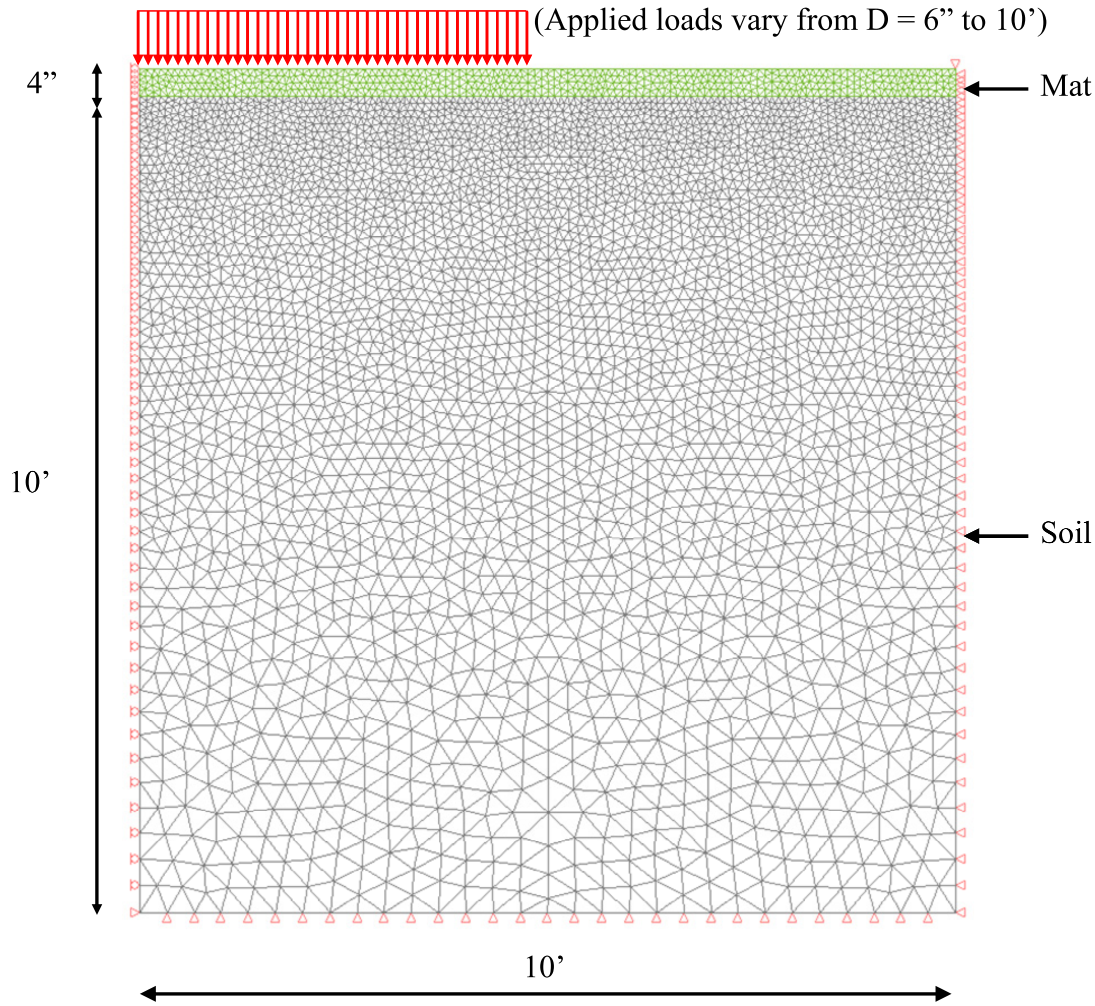


Figure 4-32. Actual mesh generated for this parametric analysis

Table 4-20. $\rho = P_{(max)} / P_{(applied)}$ values

Parameters		No Mat	One Mat	Two Mats
D = 0.5 ft	$E_{(mat)}/E_{(soil)} = 1$	1.000	0.437	0.175
	$E_{(mat)}/E_{(soil)} = 10$		0.218	0.077
	$E_{(mat)}/E_{(soil)} = 20$		0.158	0.053
	$E_{(mat)}/E_{(soil)} = 100$		0.064	0.020
D = 1 ft	$E_{(mat)}/E_{(soil)} = 1$	1.000	0.776	0.454
	$E_{(mat)}/E_{(soil)} = 10$		0.501	0.224
	$E_{(mat)}/E_{(soil)} = 20$		0.394	0.160
	$E_{(mat)}/E_{(soil)} = 100$		0.189	0.063
D = 2 ft	$E_{(mat)}/E_{(soil)} = 1$	1.000	0.955	0.807
	$E_{(mat)}/E_{(soil)} = 10$		0.853	0.519
	$E_{(mat)}/E_{(soil)} = 20$		0.771	0.409
	$E_{(mat)}/E_{(soil)} = 100$		0.486	0.193
D = 4 ft	$E_{(mat)}/E_{(soil)} = 1$	1.000	0.991	0.961
	$E_{(mat)}/E_{(soil)} = 10$		0.992	0.856
	$E_{(mat)}/E_{(soil)} = 20$		0.988	0.773
	$E_{(mat)}/E_{(soil)} = 100$		0.895	0.487
D = 6 ft	$E_{(mat)}/E_{(soil)} = 1$	1.000	0.995	0.985
	$E_{(mat)}/E_{(soil)} = 10$		0.993	0.962
	$E_{(mat)}/E_{(soil)} = 20$		1.000	0.936
	$E_{(mat)}/E_{(soil)} = 100$		1.000	0.729
D = 10 ft	$E_{(mat)}/E_{(soil)} = 1$	1.000	0.999	0.996
	$E_{(mat)}/E_{(soil)} = 10$		0.994	0.987
	$E_{(mat)}/E_{(soil)} = 20$		0.996	0.984
	$E_{(mat)}/E_{(soil)} = 100$		1.000	0.972

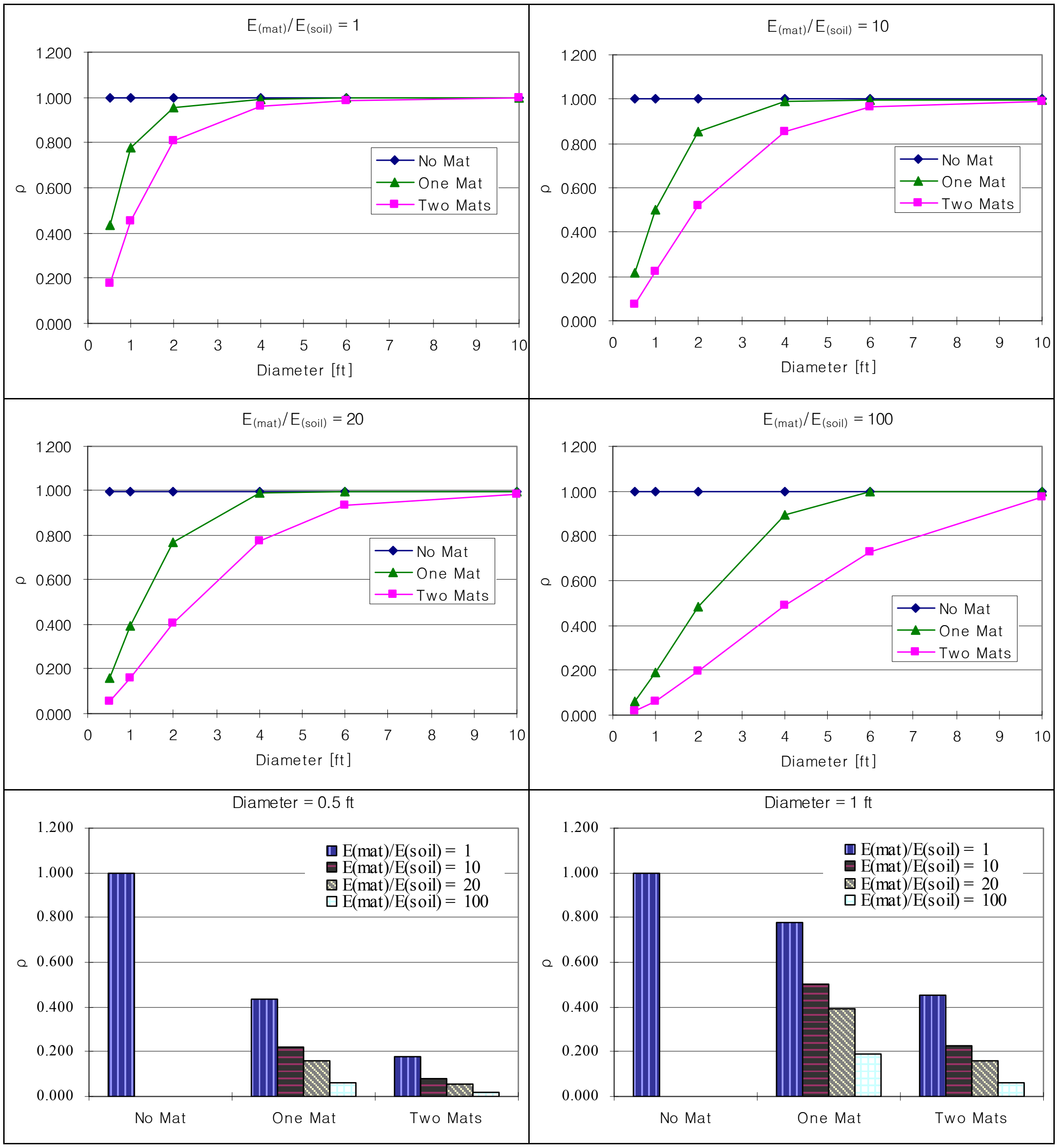


Figure 4-33. The result summary graphs

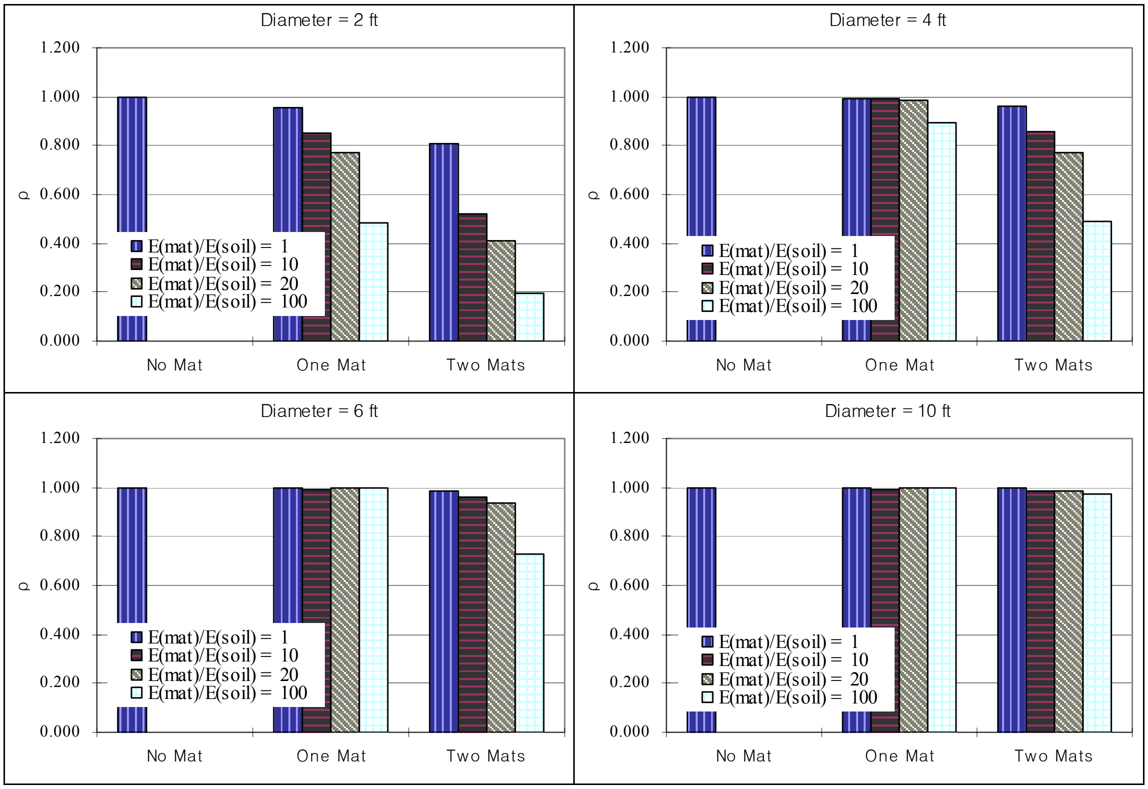


Figure 4-33. Continued

4.3.3 Lessons Learned

Throughout this parametric study, it is indicated that the single layer mat system (one mat) can decrease the pressure up to 95% for small loading areas (i.e., D = 6" such as car or truck tire areas) over soft soil (i.e., Young's Modulus is less than 10 MPa). Therefore, the mat system seems to be very beneficial for traffic areas such as small tires over soft soils. On the other hand, the single layer mat system does not provide significant decrease in pressure for large loading areas (i.e., D > 6') over stiff soil (i.e., Young's Modulus is greater than 50 MPa). Therefore, the mat system seems not to be significantly beneficial for large bins on desert soils. The double layer mat system (two mats) also looks beneficial for small loading areas but as applied load area increases, it seems to lose the benefit of using it especially on hard soils.

5. SYSTEMS APPROACH FOR TECHNOLOGY SELECTION

5.1 Research Methodology

The main purpose of this research is to help decision-makers select an optimal drilling system for a given site in order to minimize environmental impact and maximize profit at that specific site. A technology evaluation protocol has been developed by EFD project participants and then refined based on EFD experts' inputs and feedbacks. Further interaction with appropriate experts would be valuable in revising this evaluation protocol. The overall procedure is briefly illustrated as follows:

Step 1: Identify main subsystems, subsets, and technologies within each subset for the EFD operations.

Step 2: Define attributes and develop attribute scales to evaluate technologies.

Step 3: Assign scores to all technologies using the attribute scales.

Step 4: For each attribute, calculate the overall attribute score of a system by adding the technology scores or selecting the minimum technology score.

Step 5: For each attribute and in order to homogenize the scores, develop a "utility function (u_i)" to convert the overall dimensional score of a system (e.g., $, acres, and grades) into a non-dimensional utility value (between 0 and 1) of the system that reflects the decision-maker(s) value.

Step 6: Decide on a weight factor (k_i) for each attribute (i^{th}).

Step 7: Calculate the overall score of the system as "$\sum k_i u_i$" (multi-attribute utility function).

Step 8: Use optimization technique to evaluate all possible systems and to find the best system for a specific site. Once all possible systems have been evaluated, the system with the highest overall score is the best system.

Step 9: Conduct a sensitivity analysis to examine the impacts of possible changes in the attribute scores, weight factors, and utility functions on the optimal system.

Step 10: Suggest a small number of systems that should be attractive for a given site.

By performing the procedure illustrated above, this research provides a quantitative basis for suggesting appropriate drilling systems, explicitly evaluates alternatives against selected criteria, uses the best available information – both expert knowledge and data – in a coherent and logical way, and can help decision-makers with their choices of EFD technology for a given situation and best meet the goals of those involved. How to evaluate all possible systems with given information is fully described in Section 5.2 through Section 5.9.

5.2 Identify the Main Subsystems, Subsets, and Technologies within Each Subset for the EFD Operation

Four main subsystems and thirteen subsets including over hundred technologies have been identified for the EFD operation as shown in Figure 5-1 and Figure 5-2.

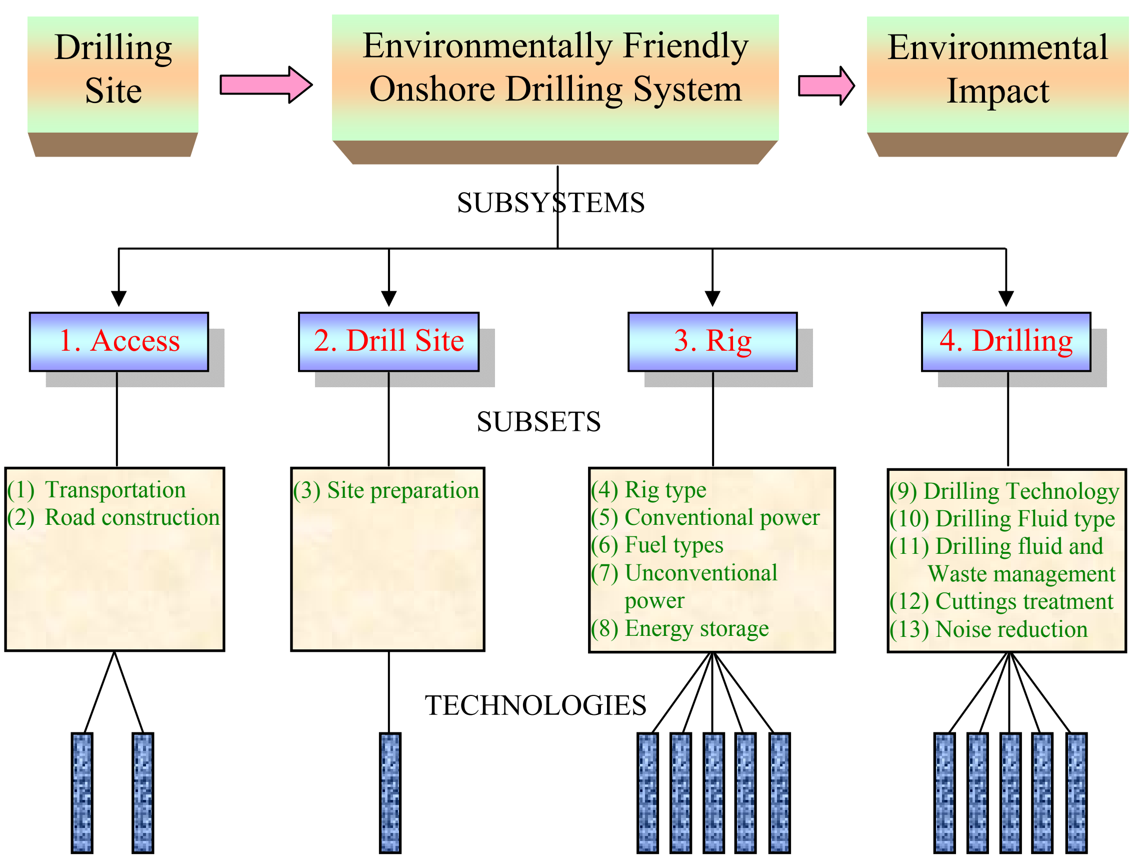


Figure 5-1. The structure of the EFD operation

(1) Transportation	(3) Site Preparation	(4) Rig Type	(9) Drilling Technology
Conventional diesel truck	Aluminum modules + bored piles	Barge rig	Overbalanced drilling
Conventional diesel truck w/noise suppressor	Aluminum modules + driven piles	Casing drilling rig	Overbalanced drilling w/noise suppressor
Low sulphur diesel truck w/tier III engine	Aluminum modules + spread footing	Coiled tubing rig	Underbalanced drilling
Low sulphur diesel truck w/tier III engine, w/noise suppressor	Board location	Flex rig	Underbalanced drilling w/noise suppressor
Helicopter	Caliche	Ideal rig	Managed pressure drilling
Helicopter w/noise suppressor	Cement pad	LOC250 (CWD)	Managed pressure drilling w/noise suppressor
Hovercraft	Compacted fill material	Rapid Rig	**(10) Drilling Fluid Type**
Hovercraft w/noise suppressor	Compacted native material	Traditional older vintage rig	Aerated muds (inject gas)
Mattracks	DURA-BASE Composite Mat	Trailer mounted rig	Dry gas and mist
Mattracks w/noise suppressor	Gravel pad	Truck mounted rig	Energized and foam
Rolligon	Ice pad (Arctic)	**(5) Conventional Power**	Oil-based muds
Rolligon w/noise suppressor	Just level out	Internal combustion engine	Synthetic-based muds
(2) Road Construction	Multiple well pad < 10 ft. well spacin	Internal combustion engine w/noise suppressor	Visco-elastic fluids
Board road	Multiple well pad 10-20 ft. well spaci	Internal combustion engine w/SCR	Water-based muds
Bridge decks (small wetland)	Piling	Internal combustion engine w/SCR, w/noise suppressor	**(11) Drilling Fluid and Waste Management**
Cable & wood	Recycle drill cuttings	Large scale utility turbines	Closed loop + containers + solid control equipment
Corduroy crossings		Large scale utility turbines w/noise suppressor	Lined reserve pit + solid control
DURA-BASE Composite Mat		Lean-burn natural gas engines	Open reserve pit + solid control
Expanded metal grating		Lean-burn natural gas engines w/noise suppressor	**(12) Cuttings Treatment**
Gravel roads		**(6) Fuel Type**	Bioremediation
Hexadeck		Bi-fuel system concept	Chemical fixation and solidification (CFS)
Pole rail crossings		Biodiesel	Co-composting
PVC or HDPE pipe mats		Conventional diesel	Composting
Recycled drill cutting road base		Low sulphur diesel	Cuttings injection
Roll-out road		Synthetic fuels	Evaporation and burial onsite
Roverdeck		Bio-gas	In-situ vitrification
Tire mats		Natural gas	Land-spreading
Wood mats		**(7) Unconv. Power**	Thermal desorption
Wood panels		Electric power from grid	Plasma arc
		Fuel cells	**(13) Noise Reduction**
		Photovoltaic	Construct buildings
		Wind turbines	Construct walls
		N/A	N/A
		(8) Energy Storage	
		Battery	
		Capacitor banks	
		Electrolysis to hydrogen	
		Flywheels	
		N/A	

Figure 5-2. List of technologies within each subset

Although the technology list shown in Figure 5-2 is not an exhaustive search, what it shows is the current and state of the art technologies for onshore operations. The following Figure 5-3 shows an example of the EFD technology selection. Each path through the subset tables represents one example of a possible EFD system.

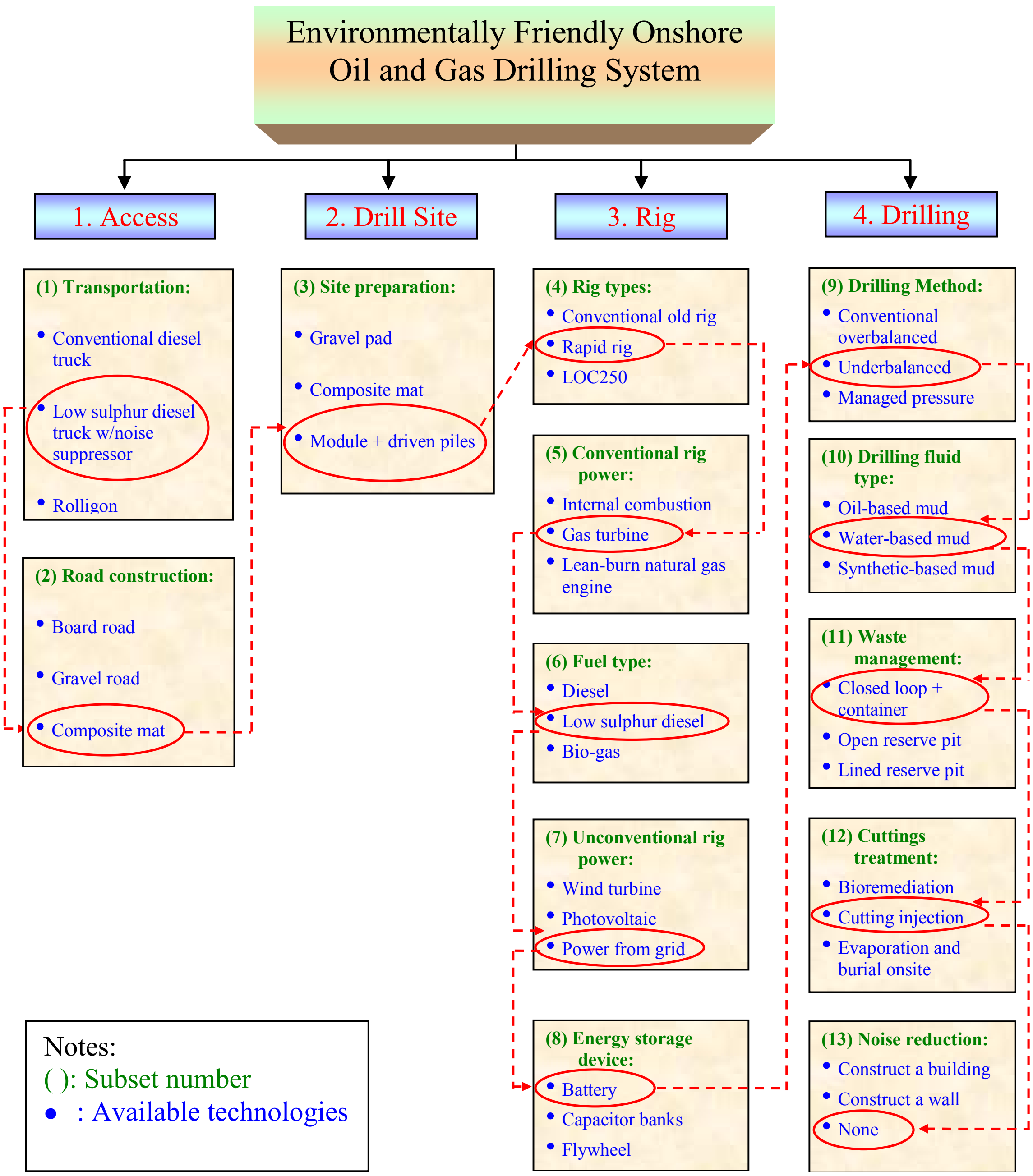


Figure 5-3. An example of the EFD technology selection

5.3 Develop Attributes and Attribute Scales

An attribute is one of the parameters considered in the evaluation of the system (e.g., cost, land area, emission, perception, and safety). Each attribute has an attribute scale used to score the technology on how well it meets the objective for this attribute (e.g., minimizes cost, footprint, and emission while maximizes positive perception and safety value).

In order to evaluate available technologies for onshore oil and gas drilling projects against each attribute, attribute scales that explicitly described their possible impacts on a project need to be specified (Keeney and Raiffa 1976). Nine attributes and their draft scales as defined by EFD subject matter experts are given in this section. These attributes should be both comprehensive and measurable (Keeney and Raiffa 1976) but it should be noted that the attributes do not need to be directly measurable entity (i.e., $ and acres). Constructed attributes (i.e., perception) can be, and often are, used instead (Keeney 1992). The attribute scales developed in this section are draft scales and thus further interaction with appropriate experts would be valuable in revising these scales.

1. Total cost (x_1) = if purchasing a technology, then it is suggested to assume the resale value of the technology so as to estimate the total expenditure for the technology during the drilling operation. In the case study described in Section 6, the resale value is assumed as 80% of the original technology cost. On the other hand, if renting a technology, then a daily rate of the technology is required to estimate the total expenditure during the drilling operation; minimizing cost is preferred.
2. Ecological footprint (x_2) = the total used land area in acres; minimizing ecological footprint is preferred.
3. Emissions of Environmental Protection Agency (EPA) and state regulated air pollutants (x_3) = it is suggested by an environmental expert to consider three air contaminants (i.e., CO, Nox, and PM) for this attribute. The relative importance of those contaminants is CO (20%), Nox (40%), and PM (40%) as shown in Table 5-1. Table 5-1 shows an example of how to calculate air emission score for each

technology. First, estimate three contaminants' real value for each technology in pounds per operating hour. Second, in order to get an overall air emission score for each technology, transform each contaminant's score into a non-dimensional score (U-value) between 0 and 1 using the proportional scoring approach, (x – worst score)/(best score – worst score). In this calculation, the best and worst scores should be obtained among all possible technologies being used. Finally, calculate the overall air emission score of a technology as $\sum k_i u_i$ (where k_i is a weight factor for each air contaminant, u_i is a non-dimensional score for each contaminant). This approach allows the decision-maker to make all air emission scores uniform and comparable; minimizing air emissions is preferred.

Table 5-1. An example of air emission score calculation

Technologies	Unit	0.2	0.4	0.4	Overall score
		CO	NO_x	PM	
Gravel road: Diesel truck + dust	(gram/hp-hr)	15.5	4	0.1	0.566
	(lb/hp-hr)	0.03418	0.00882	0.00022	
	(lb/hr)/unit	10.253	2.646	0.216	
	(lb/operating)	3250.280	838.782	68.520	
	U-value	0.000	0.822	0.593	
Composite mat: Low sulphur diesel truck w/tier III engine	(gram/hp-hr)	15.5	0.2	0.01	0.976
	(lb/hp-hr)	0.03418	0.00044	0.00002	
	(lb/hr)/unit	10.253	0.132	0.007	
	(lb/operating)	369.117	4.763	0.238	
	U-value	0.886	0.999	0.999	
Internal Combustion Engine	(lb/MWh)	6.2	21.8	0.78	0.118
	(lb/hr)/unit	6.200	21.800	0.780	
	(lb/hr)*portion	6.200	21.800	0.780	
	(lb/operating)	1339.200	4708.800	168.480	
	U-value	0.588	0.000	0.000	
Internal Combustion Engine with SCR	(lb/MWh)	6.2	4.7	0.78	0.431
	(lb/hr)/unit	6.200	4.700	0.780	
	(lb/hr)*portion	6.200	4.700	0.780	
	(lb/operating)	1339.200	1015.200	168.480	
	U-value	0.588	0.784	0.000	
Lean-burn natural gas engine	(lb/MWh)	5	2.2	0.03	0.878
	(lb/hr)/unit	5.000	2.200	0.030	
	(lb/hr)*portion	5.000	2.200	0.030	
	(lb/operating)	1080.000	475.200	6.480	
	U-value	0.668	0.899	0.962	
Power from grid	(lb/MWh)	0	0	0	1.000
	(lb/hr)/unit	0.000	0.000	0.000	
	(lb/hr)*portion	0.000	0.000	0.000	
	(lb/operating)	0.000	0.000	0.000	
	U-value	1.000	1.000	1.000	

It is noted that the linear transformation of emissions to utility is a placeholder and this needs to be reevaluated by experts, perhaps on a case-by-case basis.

4. Emissions of EPA and state regulated solid and liquid pollutants (x_4) = the ordinal draft scale was constructed by an EFD subject matter expert as shown in Table 5-2; minimizing solid and liquid emissions is preferred.

Table 5-2. Draft attribute scale for solid and liquid emission

Waste Management Technologies	Cuttings treatment	Solid/liquid emission score
Closed loop	Cutting injection	1.00
-	Bioremediation, Composting, In-situ vitrification, Land spreading, Plasma arc, Microwave technology	0.75
Lined reserve pit	Thermal desorption.	0.50
-	Chemical fixation and solidification	0.25
Open reserve pit	Evaporation and burial onsite	0.00

5. Emissions of EPA and state regulated noise pollutants (x_5) = according to Occupational Safety & health Administration (OSHA), the eight-hour time-weight average sound level (TWA), in decibels, is recommended as the noise emission's scale. TWA may be computed from the dose, in percent, by means of the formula: TWA = 16.61 log(D/100) + 90. D is the noise dose, in percent: D=100 C/T (where C is the total length of the work day, in hours, and T is the reference duration corresponding to the measured sound level, L in decibel). $T = 8/2^{(L-90)/5}$; minimizing noise emission is preferred.

6. Government, as regulators, perception (x_6) = the ordinal draft scale was constructed as shown in Table 5-3; maximizing government perception is preferred.

Table 5-3. Draft attribute scale for government perception

Description	**Perception score**
Strongly Support. All parties will encourage its use and are willing to appropriate funds for the cause.	1.00
Moderate Support. There is interest from a majority. Its use will be encouraged, but funds will not be appropriated.	0.75
Neutrality. All parties are indifferent. There is no resistance, but there is also no help.	0.50
Moderate opposition. Some resistance from the majority. Its use may be discouraged, but fines or restrictions won't be imposed.	0.25
Strong opposition. Strong resistance to its use from all parties. Restrictions or fines will be set up to eliminate this option.	0.00

7. Industry, as decision-makers, perception (x_7) = the ordinal draft scale was constructed as shown in Table 5-4; maximizing industry perception is preferred.

Table 5-4. Draft attribute scale for industry perception

Description	**Perception score**
Strongly Support. All parties are very interested and willing to invest for the facility.	1.00
Moderate Support. All parties are interested but somewhat hesitate to invest for the facility.	0.75
Neutrality. All parties are indifferent or uninterested.	0.50
Moderate opposition. Some parties have opposition. The other parties are indifferent or uninterested.	0.25
Strong opposition. No parties are willing to invest for the facility.	0.00

8. General public perception (x_8) = the ordinal draft scale was adapted from Keeney (1992) as shown in Table 5-5; maximizing public perception is preferred.

Table 5-5. Draft attribute scale for public perception

Description	Perception score
Support. No groups are opposed to the facility, and at least one group has organized support for the facility.	1.00
Neutrality. All groups are indifferent or uninterested.	0.75
Controversy. One or more groups have organized opposition, although no groups have action-oriented opposition (for example, letterwriting, protests, lawsuits). Other groups may either be neutral or support the facility.	0.50
Action-oriented opposition. Exactly one group has action-oriented opposition. The other groups have organized support, indifference, or organized opposition.	0.25
Strong action-oriented opposition. Two or more groups have action-oriented opposition.	0.00

9. Safety value (x_9) = the ordinal draft scale was constructed referring to OSHA's safety standards as shown in Table 5-6; maximizing safety value is preferred.

Table 5-6. Draft attribute scale for safety value

Description	Safety score
Very safe. No hazard associated with a technology.	1.00
Safe. It is recommended for workers constructing a technology be instructed on the hazards of the technology but it is not the mandatory. No hazard associated with the technology for other workers.	0.75
Neutrality. It is recommended for workers in a site be instructed on the hazards of a technology but it is not the mandatory.	0.50
Somewhat dangerous. Workers constructing a technology have to be instructed on the hazards associated with the technology, and it is recommended for other workers be instructed on the hazards of the technology, but it is not the mandatory.	0.25
Very dangerous. Every worker in a site has to be instructed on the hazards associated with a technology.	0.00

It is required that these attributes and their scales discussed above be revised and restructured, if necessary, through a series of meetings with EFD subject matter experts until the attributes are clearly and meaningfully defined and meet the independence assumptions implied by an additive utility function used in this research. A list of EFD experts contacted is available from the author. These nine attributes are assigned to each potential technology. In this research, it is explicitly assumed that the attributes are independent for each possible technology in conducting the technology evaluation over one attribute at a time. In discussion with subject matter experts to date, this assumption seems reasonable.

5.4 Assign Scores to All Technologies Using the Attribute Scales

In order to evaluate available technologies with respect to the nine attributes (i.e., x_1 through x_9), EFD subject matter experts' inputs, basic assumptions, and other references are used. Some examples of the cost estimation are shown in Figure 5-4 through Figure 5-9. Moreover, Table 5-7 and Table 5-8 are used to evaluate attribute scores of technologies within subset (5) and subset (7), rig power generation subsets.

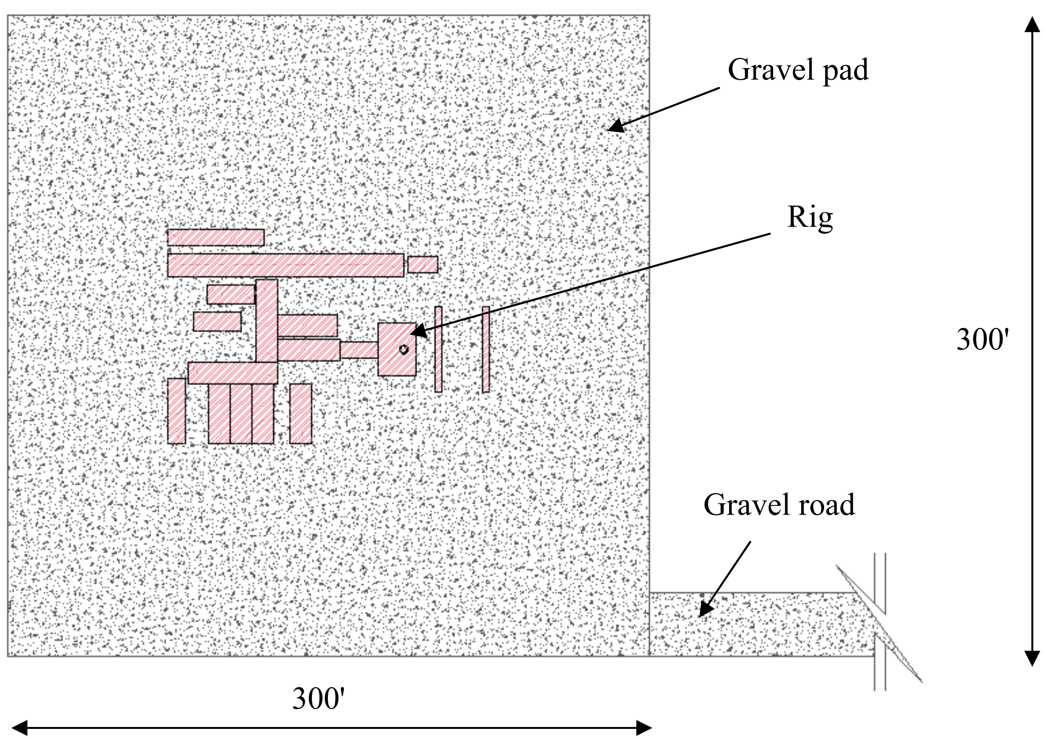


Figure 5-4. A typical layout of a conventional drilling site

Access Road ⇒ Gravel road

- Width = 25 ft (2 lanes)
- Length = 5280 ft (1 miles)
- Depth = 1.0 ft
- Unit weight = 120 pcf
- Material raw cost = \$3.00 / tons
- Mobilization cost = \$22.05 / tons (from Austin to College Station)

∴ Total cost = 25 × 5280 × 1.0 × 120 × \$25.05 / 2000 (lbs)

= \$198,396.00

Figure 5-5. Cost estimation of gravel road

Site preparation ⇒ Gravel pad with compact rig

- Width = 300 ft
- Length = 300 ft
- Depth = 1.0 ft
- Unit weight = 120 pcf
- Material raw cost = \$3.00 / tons
- Mobilization cost = \$22.05 / tons (from Austin to College Station)

∴ Total cost = 300 × 300 × 1 × 120 × \$25.05 / 2000 (lbs)

= \$135,270.00

Figure 5-6. Cost estimation of gravel pad

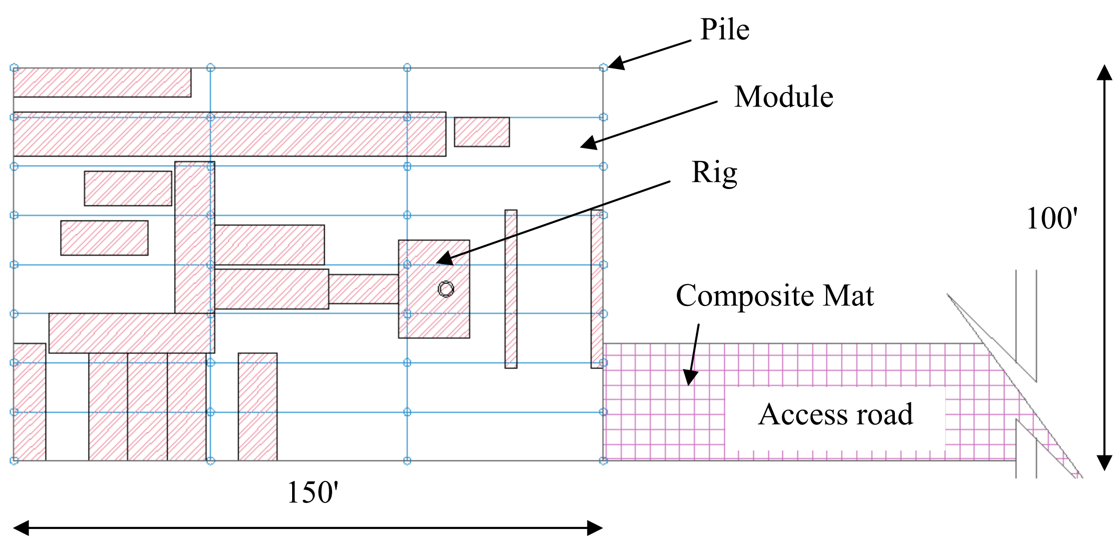


Figure 5-7. A layout of an EFD site

Access Road ⇒ DURA-BASE Composite Mat

- Width = 25 ft (2 lanes)
- Length = 5280 ft (1 miles)
- Purchase rate = \$20.62 / ft^2
- Rent (30 days) = \$1.12 / ft^2

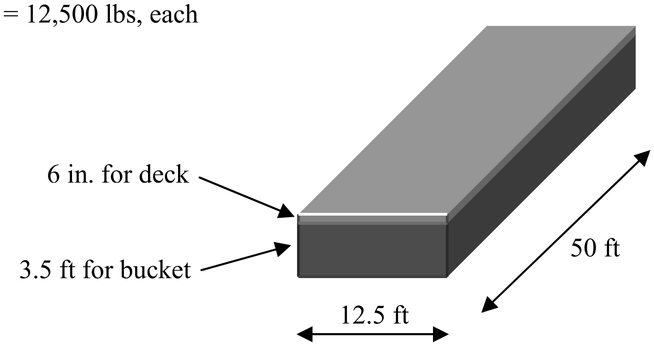
∴ Total cost when purchasing = 25 × 5280 × \$20.62 = \$2,721,840.00

Total cost when leasing = 25 × 5280 × \$1.12 = \$147,840.00

Figure 5-8. Cost estimation of Dura-Base Composite Mat

Site preparation ➔ Aluminum modules + Driven piles

- Aluminum modules:
  - Buckets:
    - ✓ Dimension = 12.5' (W) × 50' (L) × 3.5' (D)
    - ✓ Weight = 10,000 lbs, each
  - Decks:
    - ✓ 6" thick aluminum laminates filled with construction form (pre-fabricated)
    - ✓ Weight = 12,500 lbs, each



※ Raw material cost of aluminum: \$1.07 / lb

∴ Rough cost of a module:

① Raw material cost = 22500 × 1.07 = \$24,075.00

② Fabrication cost = \$10,000.00 (assumed)

③ Mobilization & Installation cost = \$10,000.00 (assumed)

Σ = **\$44,075.00**

- Module cost = \$44,075 / each
- The number of modules = 24 modules
- Pile cost = \$48,703 (for 45 piles when using two pile selections)

∴ Total cost = \$44,075 × 24 + \$48,703

= \$1,106,503.00

Figure 5-9. Cost estimation of an elevated platform

Table 5-7. Characteristic comparison of power generation technology.

Source: adapted from (Rogers et al. 2006)

Technology / Characteristic	Internal Combustion Engine			Combustion Gas Turbines	Micro turbines	wind	Photovoltaic	Fuel Cell
	Compression Ignition		Spark Ignition					
Technology Status	Commercial/Mature			Commercial/ Mature	Commercial/limited	Mature	Mature/ Developing	Commercial/ Developing
Add ons	W/O SCR	w/SCR						
Rated Power (Kw)	10-5,000			500 - 300,000	30-500†	1-5000	1-1000	100-3,000
Capacity factor	90-95%		92-97%	90-98%	95%(?)	24-40%	30%	>95%
Installed cost ($/Kw)	425-805	700-1000	600-1200	600-1400	1700-2600	1000-1600	>4500	550-5000
Fuel	Diesel, fuel oils, Synthetic liquid fuels		NG, biogas	NG, Distillate, biogas	Multi-fuel	wind	None	Multi-fuel, Hydrogen
O&M cost ($/kWh)	0.008-0.018		0.007-0.015	0.004-0.01	0.013-0.02	0.005	Negligible	0.020-0.04
Electrical Efficiency	30-40%		23-45%	21-40%	14-30%	20-46%	15-30%	36-50%
Noise	High			Moderate	Moderate	Low	None	Low
Foot Print (sq ft/kw)	0.22-0.7		0.15-0.31	0.02-0.61	0.15-0.35	5-100	200-600	0.9
NOx (lb.MWh)	21.8	4.7**	2.07*	1.15	0.44	0	0	0.03
SO2 (lb.MWh)	0.49	0.454**	0.006*	0.008	0.008	0	0	0.006
PM (lb.MWh)	0.78	0.78**	0.03*	0.08	0.09	0	0	0
CO2 (lb.MWh)	1432	1432**	1099*	1494	1596	0	0	1078

Sources: Distribute Energy Forum (www.deforum.org); Gas Fired Distributed Energy Resource Technology Characterizations November 2003 USDOE NREL/TP-620-34783; EPA Greenhouse Summer 2002 EPA-43-N-02-004;Bluestein, Joel et al,"The Impact of Air Quality Regul

SCR= Selected catalytic reactor

*Lean Burn Gas Fired Engine; ** Diesel with SCR; †Larger sizes under development

Table 5-8. Benefits of reduced use of diesel to generate electricity in annual base rate.

Source: adapted from (Rogers et al. 2006)

% power generated without diesel	10%	20%	65%
Power saved hp (kW)*	750 (560)	1500 (1120)	4875 (3637)
Diesel saved gals/hr	35	70	227
(gals/year)	245,000	490,000	1.6×10^6 gals
Savings /rig @$2.00/gal	$490k	$980k	$3.2MM
Emissions reduction tonnes/year			
NO_x	88	175	573
CO	13	26	85
SO_x	19	39	125
CO_2	2766	5531	17976

*Assumes 0.33 BSFC $GPH = \frac{BSFC * HP}{\rho}$; TE=40%; TE= $\frac{0.1335}{BSFC}$

$\rho = 7.1$ lbs/gal; HP= Power Saved BSCF = Brake Specific HP

Figure 5-10 briefly shows an influence diagram of each subset in a typical drilling site. As can be seen in Figure 5-10, attribute scores of a technology can be correlated with attribute scores of another technology in a different subset. For example, different rig type causes the variation of total drilling time and total drilling time varies total cost of technologies within many subsets. Moreover, selected technologies within subset (5) through subset (8) shown in Figure 5-1 are mutually related each other as shown in Figure 5-11. For example, the number of possible fuel types for a conventional power generation engine varies by what kind of engine is selected, and whether using an energy storage device or not should be dependent on whether an unconventional power generation method is used or not. If it is decided not to use an unconventional power generation method, an energy storage device is not necessarily considered as a subset in the "Rig" subsystem. An example of construction strategy and constraints for the "Rig" subsystem is specified as shown in Figure 5-11. Figure 5-12 shows an example of input spreadsheets used to score technologies in several subsets. The cost, footprint, and emission scores of a technology in subset (1), "Transportation", are not included in the input spreadsheet because those scores are already included as a mobilization part of technologies within other subsets. For example, the cost of gravel road shown in Figure 5-12 includes material, mobilization, and installation costs.

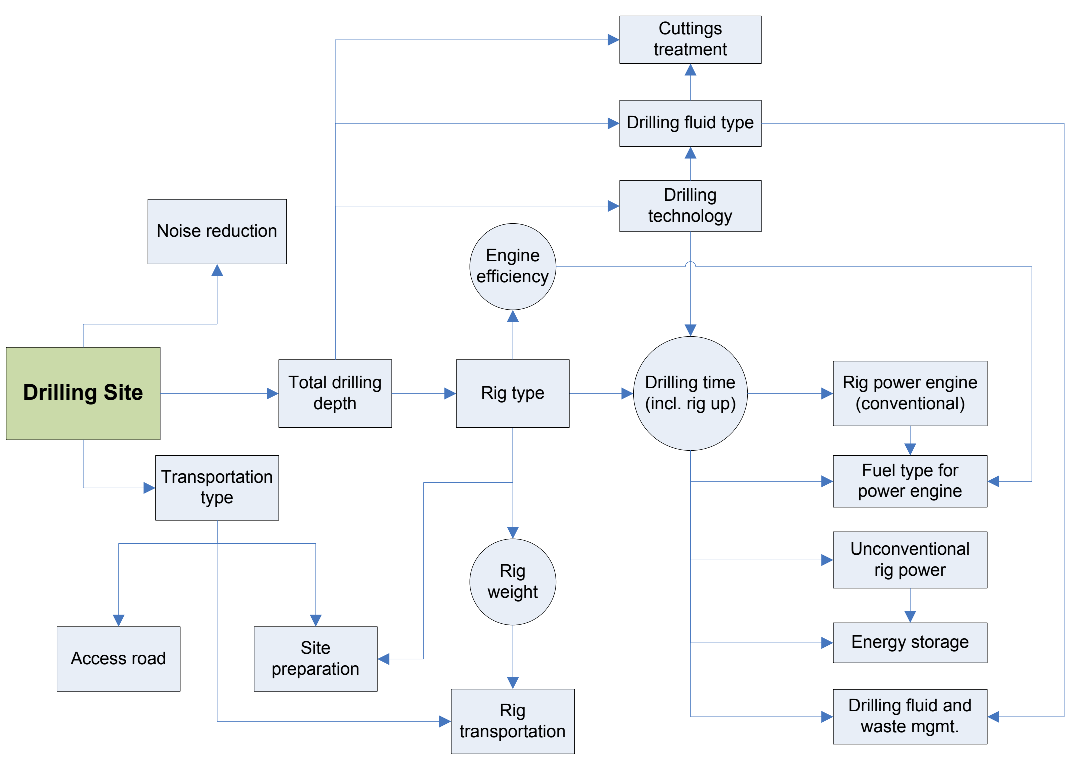


Figure 5-10. Brief influence diagram of a drilling project

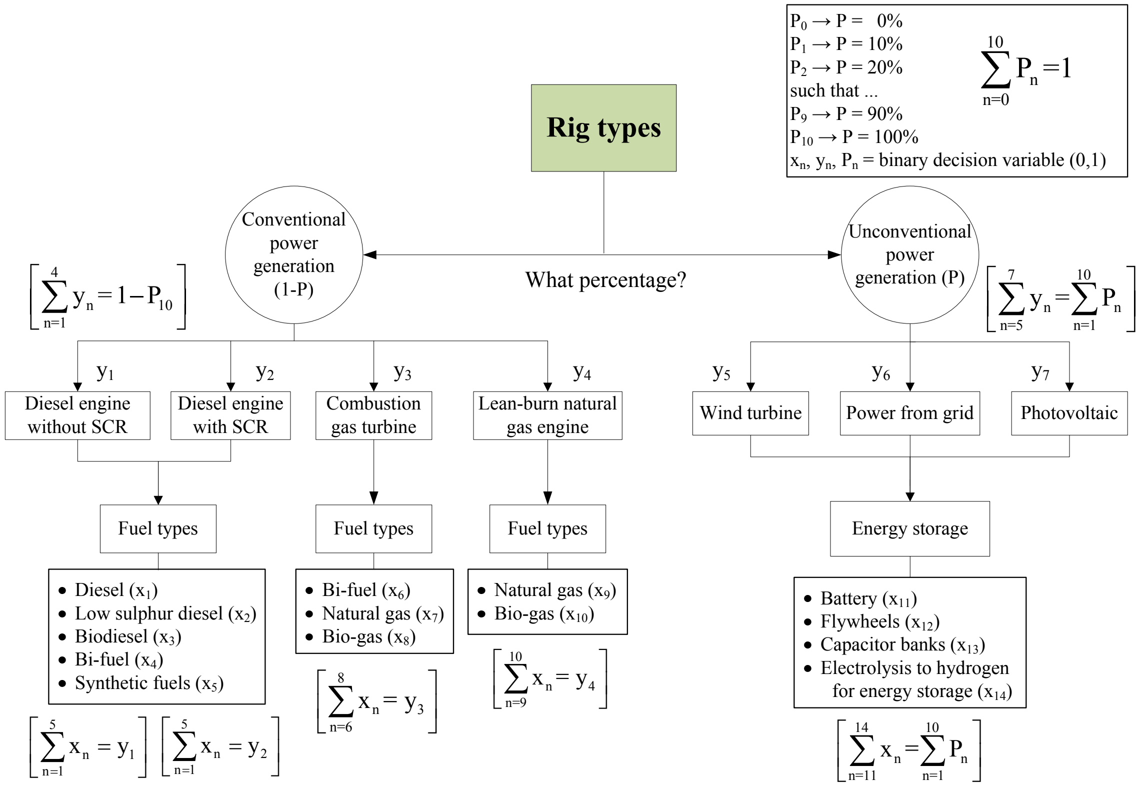


Figure 5-11. Selection procedure and constraints for the "Rig" subsystem

Sub-sets	Technologies	Total cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
				Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
1	Coventional diesel truck						0.250	1.000	0.250	0.750
	MAX						0.250	1.000	0.250	0.750
	MIN						0.250	1.000	0.250	0.750
2	Gravel roads	$148,500	3.030	0.566		98.562	0.250	1.000	0.250	0.500
	DURA-BASE from Composite Mat (buy)	$541,200	1.515	0.964		82.870	1.000	0.500	1.000	1.000
	DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
	MAX	$541,200	3.030	0.964		98.562	1.000	1.000	1.000	1.000
	MIN	$132,000	1.515	0.566		82.870	0.250	0.500	0.250	0.500
3	Gravel pad	$137,813	2.812	0.598		98.019	0.250	1.000	0.250	0.500
	DURA-BASE from Composite Mat (buy)	$502,250	1.406	0.967		82.242	0.750	0.750	0.750	1.000
	DURA-BASE from Composite Mat (rent)	$122,500	1.406	0.967		82.242	0.750	0.750	0.750	1.000
	Aluminum modules + driven piles	$372,408	0.007	0.973		97.614	1.000	0.500	1.000	0.500
	MAX	$502,250	2.812	0.973		98.019	1.000	1.000	1.000	1.000
	MIN	$122,500	0.007	0.598		82.242	0.250	0.500	0.250	0.500
4	Traditional older vintage rig	$220,000		0.973		78.630	0.500	1.000	0.500	0.500
	MAX	$220,000		0.973		78.630	0.500	1.000	0.500	0.500
	MIN	$220,000		0.973		78.630	0.500	1.000	0.500	0.500

Figure 5-12. An example of input scores

5.5 Calculate the Overall Attribute Score for Each Attribute

After each technology is evaluated with respect to the nine attributes (i.e., x_1 through x_9), for each attribute, the overall attribute score of a system is calculated by adding the technology scores of the system or selecting the minimum technology score of the system. The addition of individual scores is used for attributes such as cost, footprint, and emission as shown in Eq. (5-1) while the minimum score is used for attributes such as perception and safety as shown in Eq. (5-2). This section elaborates on how to calculate the overall attribute score for each attribute of a system. The overall score on the i^{th} attribute (X_i) is:

$$X_i = \sum_{n=1}^{N} x_{in} y_n \quad \text{for attribute } x_1 \text{ and } x_5 \text{ (i.e., i = 1 to 5)} \tag{5-1}$$

$$X_i = \text{Min}\left[x_{in} y_n\right] \quad \text{for attribute } x_6 \text{ through } x_9 \text{ (i.e., i = 3 to 9)} \tag{5-2}$$

where n is the index for possible technologies, N is the number of possible technologies, i is the index for the attributes, x_{in} is the score of the n^{th} technology on the i^{th} attribute, and y_n is a binary decision variable that is one if n^{th} technology is selected and zero if it is not.

The constraint required to consider is:

$$\sum_{n=1}^{M} y_n = 1 \quad \text{for each subset except subset (7), (8), and (13)} \tag{5-3}$$

where n is the index for possible technologies, M is the number of possible technologies within each subset, and y_n is a binary decision variable.

One technology should be selected within each subset except subset (7), (8), and (13) shown in Figure 5-1. Subset (7), (8), and (13) are optional. Figure 5-13 shows the overall attribute score for each attribute of a system. As can be seen in Figure 5-13, the overall scores of cost (x_1), footprint (x_2), and emissions (x_3 through x_5) are calculated by summing the scores of technologies selected within each subset. The overall scores of perceptions (x_6 through x_8), and safety (x_9), however, are calculated by choosing the worst score among technologies selected within each subset for a system because it is suggested that perception and safety values should be considered on the systems level not on the individual technology level.

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: Aluminum modules + driven piles	$372,408	0.007	0.973		97.614	1.000	0.500	1.000	0.500
(4) Rig type: Traditional older vintage rig	$220,000		0.973		78.630	0.500	1.000	0.500	0.500
(5) Rig power (Conventional): Internal combustion engine w/SCR, w/noise suppressor	$106,712		0.488		87.263	0.750	0.750	0.750	0.750
(6) Fuel type: Low sulphur diesel	$88,906					0.750	0.750	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$8,602	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Conventional overbalanced drilling	$204,000				116.700	1.000	0.500	0.500	0.500
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Lined reserve pit + solid control equip.*	$24,000	0.037		0.500		0.750	0.750	0.750	0.500
(12) Cuttings mgmt.: Cuttings injection	$60,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$1,294,568	1.559	4.398	1.500	463.077	0.250	0.500	0.250	0.500

Figure 5-13. Overall attribute score for each attribute of a system

5.6 Develop a Utility Function for Each Attribute

A utility function is a relationship between the dimensional attribute score (e.g., $, acres, and grades) and a non-dimensional number (between 0 and 1) that captures decision-maker preferences. The utility function is used to transform all scores into non-dimensional values between 0 and 1. This allows the decision-maker to make overall attribute score for each attribute uniform and comparable. Once the overall attribute score for each attribute of a system is calculated with respect to the nine attributes (i.e., x_1 through x_9), for each attribute (i) and in order to homogenize the scores, a utility function (u_i) needs to be developed to convert the overall dimensional score of a system into a non-dimensional utility value (between 0 and 1) of the system. This section elaborates on how to develop and apply utility functions for this research.

The proportional scoring approach (i.e., linear approach) is mainly suggested in this research to develop single-attribute utility functions because of a lack of expert assessment. This can be revisited as needed based on interactions with EFD subject matter experts. A general formula for the proportional scoring approach is given by:

$$u_i(X_i) = \frac{X_i - \text{Worst Score}}{\text{Best Score} - \text{Worst Score}} \tag{5-4}$$

where X_i is the overall score on the i[th] attribute of a system.

Figure 5-14 shows an example of the utility function curve for the cost attribute. As can be seen in this example, first maximum and minimum values for total cost are obtained. It is found that the range should go from \$0.78 million dollars to \$1.9 million dollars, where obviously less total costs are preferred to greater ones. Thus, to remain consistent with the scaling rule where the utility functions ranged from 0 to 1, it is defined u_1 (\$0.78 M) = 1 and u_1 (\$1.9 M) = 0. Procedures similar to those described above are also used to assess utility functions for attribute x_2 through x_9.

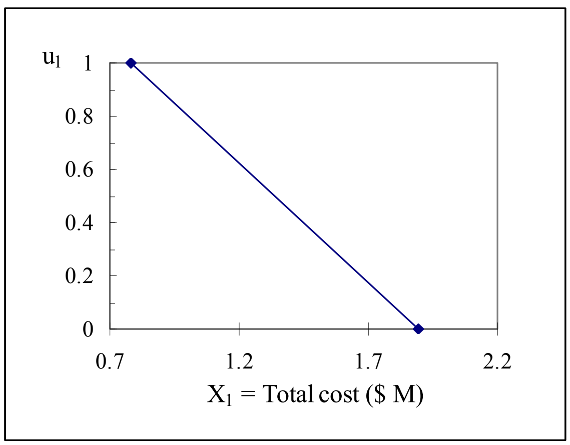


Figure 5-14. The single-attribute utility function curve for cost

In this research, the general shapes of the utility function for each attribute are linear. This implies risk neutrality, but it is very important, before proceeding, to do consistency checks on the reasonableness of the shape of the utility functions (i.e., exponential, linear, etc.) (Keeney and Raiffa 1976). This can be fulfilled by asking additional questions about the decision-maker's preferences, and comparing his/ her responses to the implications of the "fit" utility functions. When they are consistent with each other, the utility functions can be more confidence. When they are inconsistent, on the other hand, the inconsistencies are discussed, and part of all the assessment should be repeated (Keeney and Raiffa 1976). Figure 5-15 shows single-attribute utility values of a system.

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: Aluminum modules + driven piles	$372,408	0.007	0.973		97.614	1.000	0.500	1.000	0.500
(4) Rig type: Traditional older vintage rig	$220,000		0.973		78.630	0.500	1.000	0.500	0.500
(5) Rig power (Conventional): Internal combustion engine w/SCR, w/noise suppressor	$106,712		0.488		87.263	0.750	0.750	0.750	0.750
(6) Fuel type: Low sulphur diesel	$88,906					0.750	0.750	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$8,602	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Conventional overbalanced drilling	$204,000				116.700	1.000	0.500	0.500	0.500
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Lined reserve pit + solid control equip.*	$24,000	0.037		0.500		0.750	0.750	0.750	0.500
(12) Cuttings mgmt.: Cuttings injection	$60,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$1,294,568	1.559	4.398	1.500	463.077	0.250	0.500	0.250	0.500
Single Attribute Utility Values	0.539	0.991	0.701	0.600	0.677	0.250	0.500	0.250	0.500

Figure 5-15. Single-attribute utility values of a system

5.7 Combine Utility Values of Each Attribute into an Overall Utility

Once each single-attribute utility function $u_i(X_i)$ is derived for its attribute measure, these individual utility values are combined in some way into a final utility value. If mutual preferential and utility independence are satisfied, it is possible to define the multi-attribute utility function to the additive form:

$$U\left(X_1, X_2, \ldots, X_I\right) = U\left\{u_1\left(X_1\right), u_2\left(X_2\right), \ldots, u_I\left(X_I\right)\right. \\ = k_1 u_1\left(X_1\right) + \ldots + k_I u_I\left(X_I\right) = \sum_{i=1}^{I} k_i u_i\left(X_i\right) \quad (5\text{-}5)$$

where $u_i(X_i)$ is a single-attribute utility function scaled from 0 to 1, k_i is a weight factor for $u_i(X_i)$.

Since it is assumed that there is no interaction between each attribute, all of the weights are positive and they must sum to one (Hardaker 2004). In general, weight factors are decided by decision-makers. Table 5-9 shows an example of assigned weight factor for each attribute.

Table 5-9. An example of assigned weight factor for each attribute

Attributes	Weights
Total cost (x_1)	0.40
Footprint (x_2)	0.25
Air emission (x_3)	0.05
Solid/ liquid emission (x_4)	0.05
Noise emission (x_5)	0.05
Government perception (x_6)	0.05
Industry perception (x_7)	0.05
Public perception (x_8)	0.05
Safety (x_9)	0.05

A multi-attribute utility function of the additive form can be derived in two steps. First, single-attribute utility functions $u_i(X_i)$ of a system are derived for each attribute measure in turn, then these individual utility values are combined into an overall utility value of the system to simplify comparisons with other possible systems. Figure 5-16 shows an example of the multi-attribute utility value of a system with the weighting factors given in Table 5-9.

	Weights (Σ = 100% ∴ O.K!)								
	40%	25%	5%	5%	5%	5%	5%	5%	5%
Selected Technologies in Each Subset	**Total Cost ($)**	**Ecological Footprint (Acres)**	**Emissions**			**Perceptions**			**Safety Value**
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: Aluminum modules + driven piles	$372,408	0.007	0.973		97.614	1.000	0.500	1.000	0.500
(4) Rig type: Traditional older vintage rig	$220,000		0.973		78.630	0.500	1.000	0.500	0.500
(5) Rig power (Conventional): Internal combustion engine w/SCR, w/noise suppressor	$106,712		0.488		87.263	0.750	0.750	0.750	0.750
(6) Fuel type: Low sulphur diesel	$88,906					0.750	0.750	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$8,602	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Conventional overbalanced drilling	$204,000				116.700	1.000	0.500	0.500	0.500
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Lined reserve pit + solid control equip.*	$24,000	0.037		0.500		0.750	0.750	0.750	0.500
(12) Cuttings mgmt.: Cuttings injection	$60,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$1,294,568	1.559	4.398	1.500	463.077	0.250	0.500	0.250	0.500
Single Attribute Utility Values	0.539	0.991	0.701	0.600	0.677	0.250	0.500	0.250	0.500
∴ Multi-Attribute Utility Value =	**0.637**								

Figure 5-16. An example of the multi-attribute utility value of a system

5.8 Find the Best System

In this section, an optimization scheme is suggested based on a combination of multi-attribute utility theory and exhaustively enumerating all possible systems to provide a quantitative rationale and suggest the best set of systems according to a set of attributes, with the relative importance of the different attributes defined by the decision-maker. Since exhaustive search optimization is a simple, practical, and very robust method given the speed of modern computers (Cover et al. 2007), it is used to evaluate all possible systems and to find the 'best' available system that should be particularly attractive for a specific site. Larger problems would likely require more advanced optimization methods. Once all possible systems have been evaluated, the system with the highest overall utility score is the best system with given weighting factors.

After the optimization scheme has given the 'best' system, a sensitivity analysis can be conducted to examine the impact of possible changes in the attribute scores, weight factors, and utility functions on the best system. For example, the weight assigned to the cost attribute shown in Table 5-9 could be changed from the initially assigned value of 0.40. Since the weighting factors must sum to one in this research, the weights assigned to other attributes are known once a weight assigned to the cost attribute is decided. Conducting a sensitivity analysis for the technology selection process is an importance step because it can give an idea the range of weights over which certain systems should be selected for a specific site (Guikema and Milke 1999).

Note that the final answer needs not be a single system but that a few "optimal" systems which come close to best score can be selected. This may provide some flexibility for the person in charge of the drilling process.

5.9 Lessons Learned

Throughout this section, a system optimization approach is suggested based on a combination of multi-attribute utility theory and exhaustive search optimization. This methodology is designed to help decision-makers with their choices of EFD technology in onshore drilling operations. However, the approach used in this research does have some limitations. The crucial limitation is that the computational burden of the procedure may become prohibitive for problems with a large number of decision variables. One possible way to resolve this problem in this research is if the analyst can identify subsets that will always select the same technology for any weight combinations, the elimination of those subsets from the original thirteen subsets can significantly reduce computational burdens in future steps.

Moreover, estimating input values for available technologies are a very difficult step to proceed with the quantitative approach suggested in this research. The outcomes of the process should be brought into a question without having the adequate input values. Missing input information introduces additional errors into the analysis because the missing information represents another assumption that must be made to proceed with the analysis (Rehm et al. 2008). Even though many EFD subject matter experts have already participated in this research, more people's inputs and feedbacks are necessary to make the proposed technology selection process easier and quicker.

6. A CASE STUDY WITH PRE-SPECIFIED SYSTEMS

In order to test the technology evaluation protocol proposed in Section 5 in a real site and then to refine the protocol, a case study is conducted in Green Lake at McFaddin, TX. This section describes the results of the case study which provided a more logical and comprehensive approach that maximized the economic and environmental goals of both the landowner and the oil company leaseholder. How to arrive at the optimal drilling system for this site are fully described in this section.

6.1 Selected Site

It is assumed that an independent operator is to drill a well on their lease in South Texas in an environmentally sensitive wetland area. The lease extends to the center of Green Lake on the McFaddin Ranch as shown in Figure 6-1. The formation target is the upper Frio sand (Hovorka et al. 2001) at approximately 8500 ft in vertical depth. In order to protect the ranch as much as possible, low impact drilling and utilizing the very best drilling system is extremely important.

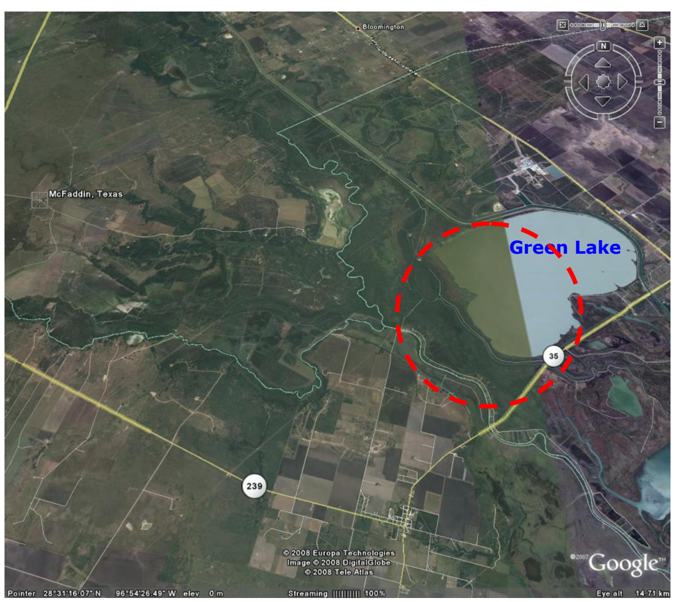


Figure 6-1. A satellite map of Green Lake at McFaddin, Texas

6.2 Description of the Pre-Specified Systems

Three different systems are pre-specified by an EFD expert in order to identify possible drilling technologies for Green Lake drilling site as shown in Table 6-1. A list of EFD experts contacted is available from the author. Although the technology list shown in Table 6-1 is not an exhaustive search, what it shows is the current and state of the art technologies for onshore oil and gas drilling operations.

Table 6-1. Pre-specified drilling systems

Subsets	1. Conventional Drilling	2. Moderately Improved Drilling	3. EFD in 5 years
(1) Transportation	Conventional diesel truck	Low sulphur diesel truck w/tier III engine, w/noise suppressor	Low sulphur diesel truck w/tier III engine, w/noise suppressor
(2) Road construction	Gravel road	DURA-BASE from Composite Mat (rent)	DURA-BASE from Composite Mat (rent)
(3) Site preparation	Gravel pad	DURA-BASE from Composite Mat (rent)	Aluminum modules + driven piles (elevated platform)
(4) Rig type	Traditional older vintage rig	Rapid Rig	LOC250 (CWD)
(5) Conventional rig power engine	Internal combustion engine	Internal combustion engine w/SCR, w/noise suppressor	Lean-burn natural gas engines w/noise suppressor
(6) Fuel type	Conventional diesel	Low sulphur diesel	Natural gas
(7) Unconventional rig power generation	None	Electric power from grid (10%)	Electric power from grid (30%)
(8) Energy storage	None	Flywheel	Flywheel
(9) Drilling technology	Conventional overbalanced drilling	Underbalanced drilling w/noise suppressor	Managed pressure drilling w/noise suppressor
(10) Fluid type	Water-based muds	Water-based muds	Water-based muds
(11) Drilling fluid and waste management	Lined reserve pit + solid control equipment	Closed loop + containers + solid control equipment	Closed loop + containers + solid control equipment
(12) Cuttings treatment	Cuttings injection	Cuttings injection	Chemical fixation and solidification (CFS)
(13) Noise reduction	None	None	None

6.3 Calculate Overall Utility Values of the Pre-Specified Systems

In order to calculate the overall utility score, the procedure described in Section 5 is required to be implemented. EFD subject matter experts' inputs, basic assumptions, and other references are used to evaluate available technologies with respect to the nine attributes (i.e., x_1 through x_9). Figure 6-2 shows the basic assumptions used in this case study and key input variables which are the most influence factors for input values of technologies.

Basic Assumptions

• Power consumption (peak):	1	MW
• Access road width:	25	ft (2 lanes)
• Access road length:	1	miles
• Width of drilling site:	350	ft (conventional rig + pad)
	300	ft (compact rig + pad)
	200	ft (conventional rig + modules + piles)
	150	ft (compact rig + modules + piles)
• Length of drilling site:	350	ft (conventional rig + pad)
	300	ft (compact rig + pad)
	125	ft (conventional rig + modules + piles)
	100	ft (compact rig + modules + piles)

Key Influence variables

• Transportation type:	Coventional diesel truck	
• Rig Type:	LOC250 (CWD)	
• Engine Type:	Internal combustion engine	
• Drilling Type:	Conventional overbalanced drilling	
• Noise reduction type:	N/A	
• Proportion of unconventional power:	30.0%	
• Resale value:	80.0%	
• Drilling Time:	9.0	days
• Move/Rig up:	1.0	days
• No. of wells:	1	wells

Figure 6-2. Basic assumptions and key influence variables

The influence diagram for this drilling site shown in Figure 6-3 should be considered before estimating attribute scores of technologies because attribute scores of a technology can be dependent on key influence variables described in Figure 6-2. For example, different rig type causes the variation of total drilling time and the total drilling time varies total cost of technologies within many subsets.

In this case study, the range of unconventional power usage is varied from 0% to 30% of total power usage. The construction strategy and constraints of the "Rig" subsystem are specified as shown in Figure 6-4. Figure 6-5 shows an example of input spreadsheets used to score technologies in several subsets. The cost, footprint, and emission scores of a technology in subset (1), "Transportation", are not included in the input spreadsheet because those scores are already included as a mobilization part of technologies within other subsets. For example, the cost of gravel road shown in Figure 6-5 includes material, mobilization, and installation costs. More detailed input values of available technologies can be found in APPENDIX B.

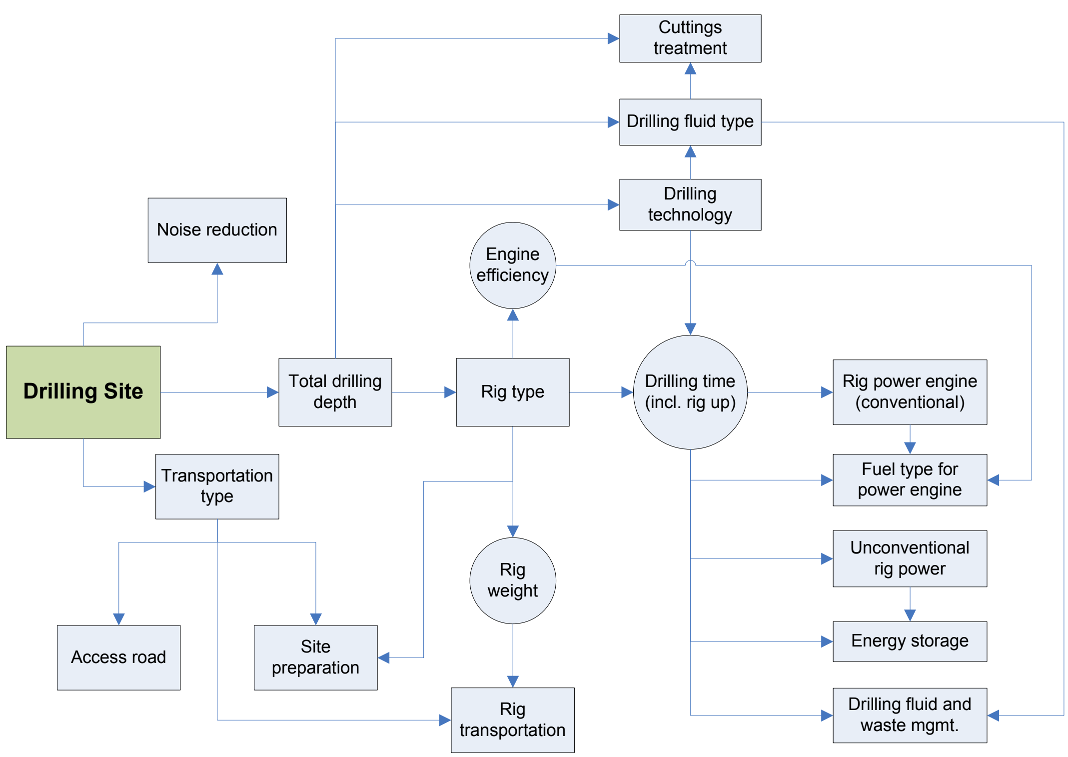


Figure 6-3. Influence diagram for the drilling site of the case study

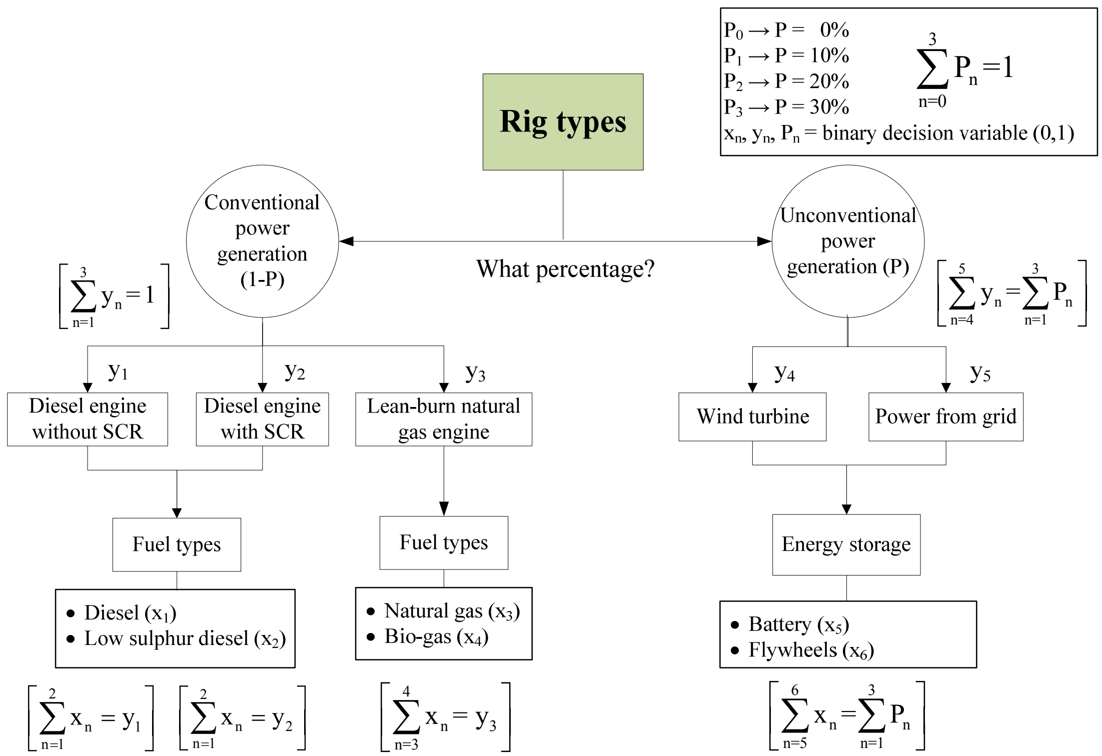


Figure 6-4. Selection procedure for the "Rig" subsystem of the case study

Sub-sets	Technologies	Buy($)	Resale Value ($)	Rent /day ($)	Daily Rate ($)	Total cost ($)	Ecological Footprint (Acres)
1	Low sulphur diesel truck w/tier III engine, w/noise suppressor						
2	Gravel roads	$198,396	$0		$19,840	$198,396	3.030
	DURA-BASE from Composite Mat (buy)	$2,721,840	$2,177,472		$54,437	$544,368	1.515
	DURA-BASE from Composite Mat (rent)					$147,840	1.515
3	Gravel pad	$135,270	$0		$13,527	$135,270	2.066
	DURA-BASE from Composite Mat (buy)	$1,855,800	$1,484,640		$37,116	$371,160	1.033
	DURA-BASE from Composite Mat (rent)					$100,800	1.033
	Aluminum modules + driven piles	$1,131,303	$905,042		$22,626	$226,261	0.005
4	LOC250 (CWD)			$15,000	$15,000	$173,800	
5	Lean-burn natural gas engines w/noise suppressor			$5,472	$5,472	$54,720	
6	Natural gas			$2,100	$2,100	$19,950	
7	Electric power from grid			$1,152	$1,152	$11,520	0.000
8	Flywheels	$450,000	$360,000		$9,000	$90,000	0.000
9	Managed pressure drilling w/noise suppressor			$21,500	$21,500	$193,500	
10	Water-based muds					$47,940	
11	Lined reserve pit + solid control equip.*			$2,000	$2,000	$18,000	0.037
	Closed loop + containers + solid control equip.*			$3,000	$3,000	$27,000	0.000

Figure 6-5. An example of input scores of the case study

Once each technology is evaluated with respect to the nine attributes (i.e., x_1 through x_9), for each attribute, the overall attribute score of a system is calculated by adding the technology scores of the system or selecting the minimum technology score of the system. In order to calculate the overall score of a system on the i^{th} attribute (X_i), Eq. (5-1), Eq. (5-2), and Eq. (5-3) should be considered.

As described in Section 5.6, A utility function is a relationship between the dimensional attribute score (e.g., $, acres, and grades) and a non-dimensional number (between 0 and 1) that captures decision-maker preferences. Once the overall attribute score for each attribute of a system is calculated with respect to the nine attributes (i.e., x_1 through x_9), for each attribute (i) and in order to homogenize the scores, a utility function (u_i) needs to be developed to convert the overall dimensional score of a system into a non-dimensional utility value (between 0 and 1) of the system. The proportional scoring approach given in Eq. (5-4) is mainly used in this case study to develop single-attribute utility functions except the noise attribute utility function.

According to Occupational Safety & health Administration (OSHA), the employer shall administer a continuing, effective hearing conservation program if employee noise exposures equal or exceed an 8-hour time-weighted average sound level (TWA) of 85 decibels. In this case study, therefore, it is assumed that if TWA of a technology does not exceed 85 decibels, the noise utility score of the technology would be closed to one while the noise utility score of the technology would be rapidly down to zero if TWA of the technology exceeds 85 decibels. There are five noise making subsets (2, 3, 4, 5, 9) in a system and thus it is considered that a utility value of the noise attribute (x_5) would be closed to one until a combined TWA does not exceed 425 (5 × 85) for a system. As a combined TWA exceeds 425, the utility value of the system rapidly goes down to zero. In order to satisfy these conditions, the noise attribute utility function is developed by the author as follows:

$$u_5(X_5) = a + b \times c^{X_5} \tag{6-1}$$

where X_5 is the noise attribute score, TWA in decibels, of a system and u_5 is the noise attribute utility value of the system. The constants (a, b, and c) are 1.02261, -8.5478E-07, and 1.028271, respectively. Figure 6-6 shows the utility function curves used in this case study.

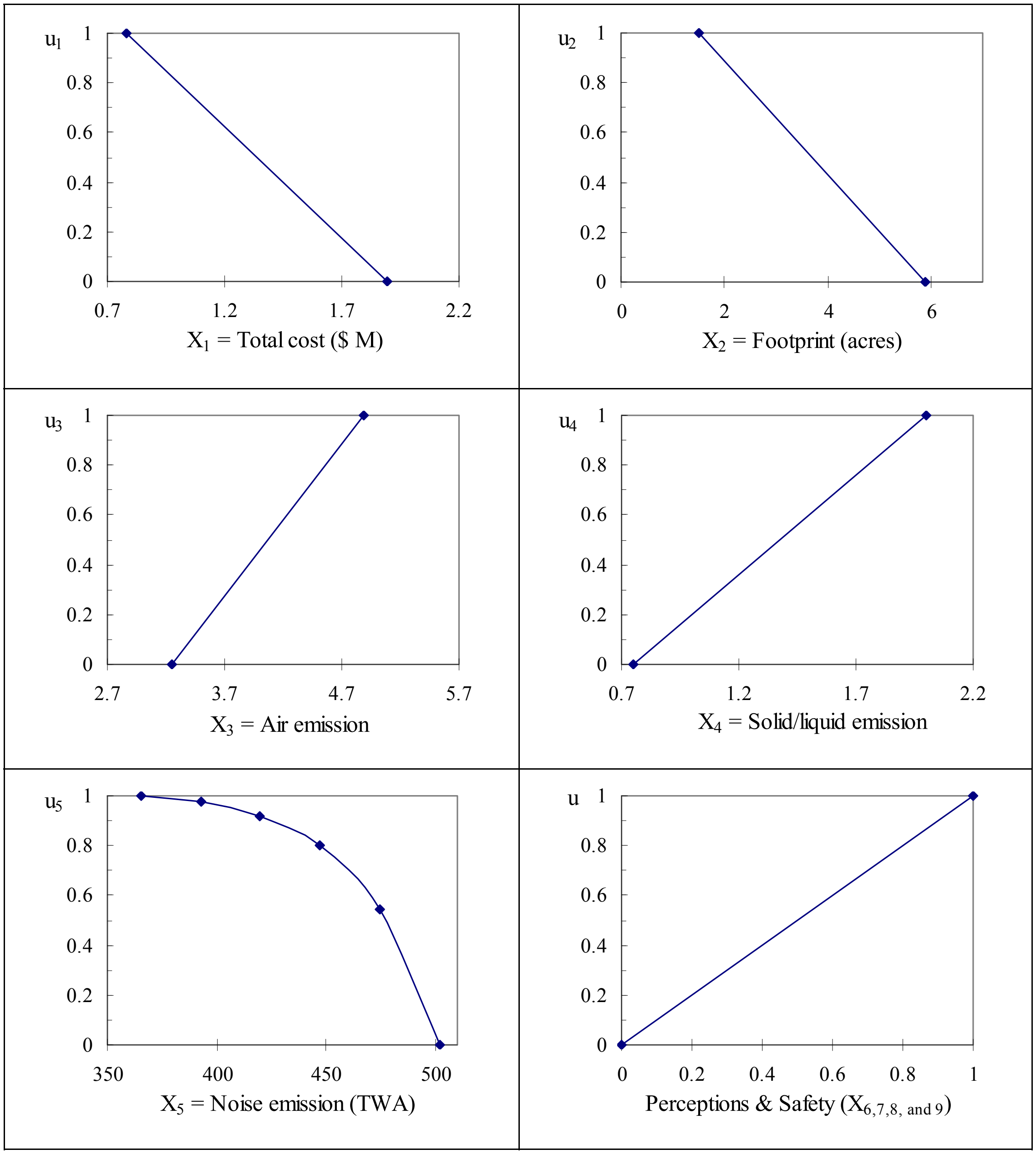


Figure 6-6. The single-attribute utility function curves

Once each single-attribute utility value is calculated, these individual utility values are combined into an overall utility value of a system described in Section 5.7.

The base case weight factors are decided by an EFD expert in this case study as shown in Table 6-2. Since it is assumed that there is no interaction between each attribute, all of the weights are positive and they must sum to one. Figure 6-7 through Figure 6-9 show the overall utility values of the pre-specified systems described in Table 6-1 with the weighting factors given in Table 6-2.

Table 6-2. The base case weight factor for the each attribute

Attributes	Weights
Total cost (x_1)	0.40
Footprint (x_2)	0.20
Air emission (x_3)	0.20/3
Solid/ liquid emission (x_4)	0.20/3
Noise emission (x_5)	0.20/3
Government perception (x_6)	0.05
Industry perception (x_7)	0.05
Public perception (x_8)	0.05
Safety (x_9)	0.05

	Weights (Σ = 100% ∴ O.K!)								
	40%	20%	6.667%	6.667%	6.667%	5%	5%	5%	5%
Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: Gravel roads	$148,500	3.030	0.566		98.562	0.250	1.000	0.250	0.500
(3) Site preparation: Gravel pad	$137,813	2.812	0.598		98.019	0.250	1.000	0.250	0.500
(4) Rig type: Traditional older vintage rig	$220,000		0.973		78.630	0.500	1.000	0.500	0.500
(5) Rig power (Conventional): Internal combustion engine	$80,000		0.118		110.073	0.500	1.000	0.500	0.750
(6) Fuel type: Conventional diesel	$94,080					0.500	1.000	0.500	0.500
(7) Rig power (Unconventional): N/A (0 %)	$0	0.000	1.000		0.000	0.250	1.000	0.250	1.000
(8) Energy storage: N/A	$0	0.000				0.250	1.000	0.250	1.000
(9) Drilling tech.: Conventional overbalanced drilling	$204,000				116.700	1.000	0.500	0.500	0.500
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Lined reserve pit + solid control equip.*	$24,000	0.037		0.500		0.750	0.750	0.750	0.500
(12) Cuttings mgmt.: Cuttings injection	$60,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$1,016,333	5.879	3.254	1.500	501.985	0.250	0.500	0.250	0.500
Single Attribute Utility Values	0.788	0.000	0.000	0.600	0.000	0.250	0.500	0.250	0.500
∴ **Multi-Attribute Utility Value =**	**0.430**								

Figure 6-7. Overall utility score of the conventional drilling system

	Weights (Σ = 100% ∴ O.K!)								
	40%	20%	6.667%	6.667%	6.667%	5%	5%	5%	5%
Selected Technologies in Each Subset	**Total Cost ($)**	**Ecological Footprint (Acres)**	**Emissions**			**Perceptions**			**Safety Value**
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: DURA-BASE from Composite Mat (rent)	$100,800	1.033	0.984		62.356	0.750	0.750	0.750	1.000
(4) Rig type: Rapid Rig	$168,000		0.986		60.016	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Internal combustion engine w/SCR, w/noise suppressor	$69,363		0.578		86.153	0.750	0.750	0.750	0.750
(6) Fuel type: Low sulphur diesel	$46,040					0.750	0.750	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$3,994	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	$202,950				96.250	0.750	0.750	0.750	0.750
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$29,700	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$49,500			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$896,127	2.548	4.524	2.000	369.471	0.500	0.500	0.750	0.750
Single Attribute Utility Values	0.896	0.764	0.778	1.000	0.997	0.500	0.500	0.750	0.750

∴ Multi-Attribute Utility Value = 0.821

Figure 6-8. Overall utility score of the moderately improved drilling system

	Weights (Σ = 100% ∴ O.K!)								
	40%	20%	6.667%	6.667%	6.667%	5%	5%	5%	5%
Selected Technologies in Each Subset	**Total Cost ($)**	**Ecological Footprint (Acres)**	**Emissions**			**Perceptions**			**Safety Value**
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: Aluminum modules + driven piles	$226,261	0.005	0.989		76.265	1.000	0.500	1.000	0.500
(4) Rig type: LOC250 (CWD)	$173,800		0.985		60.366	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	$54,720		0.936		83.742	1.000	0.500	1.000	0.750
(6) Fuel type: Natural gas	$19,950					1.000	0.500	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (30 %)	$11,520	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$90,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Managed pressure drilling w/noise suppressor	$193,500				94.100	0.750	0.750	1.000	1.000
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Chemical fixation and solidification (CFS)	$61,710			0.250		0.750	0.750	1.000	0.500
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$1,054,240	1.520	4.886	1.250	379.169	0.500	0.500	1.000	0.500
Single Attribute Utility Values	0.754	1.000	1.000	0.400	0.989	0.500	0.500	1.000	0.500

∴ Multi-Attribute Utility Value = 0.786

Figure 6-9. Overall utility score of the EFD system in five years

In this case study, since an exhaustive search optimization is a simple, practical, and very robust method given the speed of modern computers (Cover et al. 2007), it is used to evaluate all possible systems and to find the 'best' available system that should be particularly attractive for Green Lake drilling site. Larger problems would likely require more advanced optimization methods. Figure 6-10 briefly illustrates the total possible number of systems used in this case study. Once all possible systems have been evaluated, the system with the highest overall utility score is the best system with given weighting factors. Figure 6-11 shows the overall utility value of the best system with the weighting factors given in Table 6-2.

1. When "Diesel engine" is selected as a conventional power generation,

Subsets	Subsystems				∏
	1. Access	2. Drill Site	3. Rig	4. Drilling	
(1)	2	4	3	3	72
(2)	3		2*	1	6
(3)			2	2	4
(4)			1	2	2
(5)			1	1	1
				∏	3,456

2. When "Natural gas engine" is selected as a conventional power generation,

Subsets	Subsystems				∏
	1. Access	2. Drill Site	3. Rig	4. Drilling	
(1)	2	4	3	3	72
(2)	3		1	1	3
(3)			1	2	2
(4)			1	2	2
(5)			1	1	1
				∏	864

∴ Total number of possible systems within 1 conventional power generation scenario = 3,456 + 864

Σ 4,320

4 different portions of unconventional power usage (0, 10, 20, 30%) were considere

∴ Total number of iterations = 4 × 4320 = 17280

*: 2 types of diesel engine

Figure 6-10. Total number of possible systems used in this cast study

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions: Air	Emissions: Solid& Liquid	Emissions: Noise (TWA)	Perceptions: Gov.	Perceptions: Ind.	Perceptions: Public	Safety Value
Weights (Σ = 100% ∴ O.K!)	40%	20%	6.667%	6.667%	6.667%	5%	5%	5%	5%
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: DURA-BASE from Composite Mat (rent)	$100,800	1.033	0.984		62.356	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	$173,800		0.985		60.366	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	$70,354		0.918		85.603	1.000	0.500	1.000	0.750
(6) Fuel type: Natural gas	$25,650					1.000	0.500	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$3,840	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	$184,500				95.700	0.750	0.750	0.750	0.750
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$856,724	2.548	4.863	2.000	368.721	0.500	0.500	0.750	0.750
Single Attribute Utility Values	0.931	0.764	0.986	1.000	0.998	0.500	0.500	0.750	0.750

∴ Multi-Attribute Utility Value = 0.849

Figure 6-11. Overall utility score of the best system

Figure 6-12 shows the comparison of the single-attribute utility values of the pre-specified systems given in Table 6-1 and the best system with the weighting factors given in Table 6-2. It is indicated that the overall utility score of the System 2, "Moderately improved drilling system", is greater than the utility score of the system 3, "EFD system in five years."

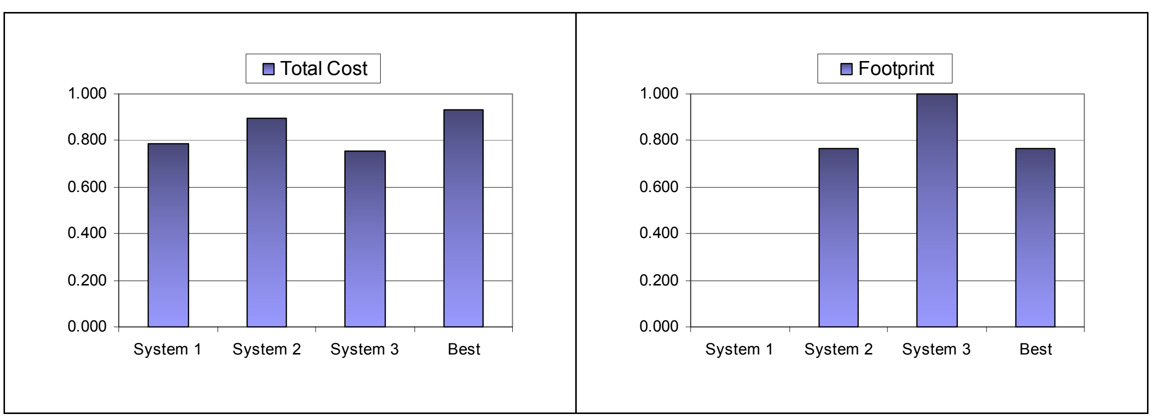


Figure 6-12. Comparison of single-attribute utility scores and overall utility scores

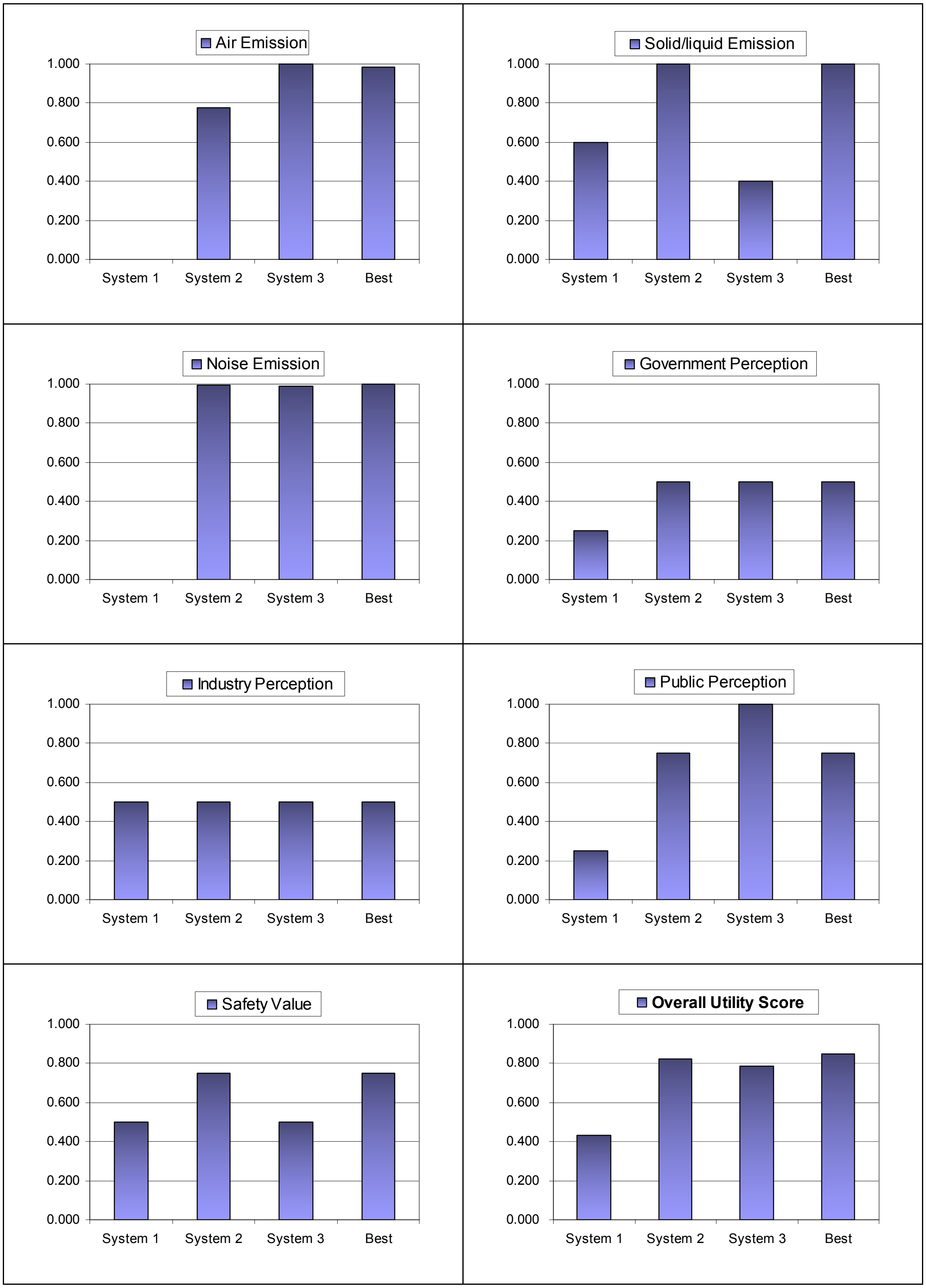


Figure 6-12. Continued

6.4 Conduct a Sensitivity Analysis

After the optimization scheme has given the 'best' system, a sensitivity analysis can be conducted to examine the impact of possible changes in the attribute scores, weight factors, and utility functions on the best system. For example, the weights assigned to cost attribute could be changed from the initially assigned value of 0.40 given in Table 6-2. Since the weighting factors must sum to one in this case study, the weights assigned to other attributes are known once a weight assigned to cost attribute is decided. Conducting a sensitivity analysis for the technology selection process is an importance step because it can give an idea the range of weights over which certain systems should be selected for a specific site (Guikema and Milke 1999). This step contains two sections. One is a sensitivity analysis for weighting factors of each attribute and the other one is a sensitivity analysis for uncertainty of overall attribute scores.

6.4.1 Sensitivity Analysis for Weighting Factors of Each Attribute

In order to demonstrate how a sensitivity analysis can be conducted, four different weight scenarios are defined by an EFD expert as shown in Table 6-3, the optimization routine is run for each weight combination, and then the results are compared as shown in Table 6-4. Each of those weight combinations represents a different point of view for the EFD technology selection problem. In this step, the change in the overall utility score of the optimal system is not a good sensitivity measure because the overall utility score directly depends on the input parameters being used and there are also many uncertainties in those input values. Instead, it is suggested to look at the changes in the technologies selected for the optimal system because this is the decision that is the most interest to the decision-makers.

Table 6-3. Weight combinations used in the sensitivity analysis

Weight no.	Cost (W_1)	Footprint (W_2)	Emissions (W_3)			Perception (W_4)			Safety (W_5)	Note
			Air	S/L	Noise	Gov.	Ind.	Public		
1	0.60	0.25	0.05/3	0.05/3	0.05/3	0.05/3	0.05/3	0.05/3	0.05	Conventional
2	0.40	0.20	0.20/3	0.20/3	0.20/3	0.05	0.05	0.05	0.05	Base case
3	0.27	0.25	0.08	0.08	0.08	0.05	0.05	0.07	0.07	EFD
4	0.12	0.30	0.10	0.10	0.10	0.05	0.05	0.09	0.09	More EFD

Table 6-4. Results of the sensitivity analysis

Subsets	For weight no. 1	For weight no. 2	For weight no. 3 and no. 4
(1) Transportation	Conventional diesel truck	Low sulphur diesel truck w/tier III engine, w/noise suppressor	Low sulphur diesel truck w/tier III engine, w/noise suppressor
(2) Road construction	DURA-BASE from Composite Mat (rent)	DURA-BASE from Composite Mat (rent)	DURA-BASE from Composite Mat (rent)
(3) Site preparation	DURA-BASE from Composite Mat (rent)	DURA-BASE from Composite Mat (rent)	Aluminum modules + driven piles (elevated platform)
(4) Rig type	LOC250 (CWD)	LOC250 (CWD)	LOC250 (CWD)
(5) Conventional rig power engine	Lean-burn natural gas engines w/noise suppressor	Lean-burn natural gas engines w/noise suppressor	Lean-burn natural gas engines w/noise suppressor
(6) Fuel type	Natural gas	Natural gas	Natural gas
(7) Unconventional rig power generation	None	Electric power from grid (10%)	Electric power from grid (10%)
(8) Energy storage	None	Flywheel	Flywheel
(9) Drilling technology	Underbalanced drilling w/noise suppressor	Underbalanced drilling w/noise suppressor	Managed pressure drilling w/noise suppressor
(10) Fluid type	Water-based muds	Water-based muds	Water-based muds
(11) Drilling fluid and waste management	Closed loop + containers + solid control equipment	Closed loop + containers + solid control equipment	Closed loop + containers + solid control equipment
(12) Cuttings treatment	Cuttings injection	Cuttings injection	Cuttings injection
(13) Noise reduction	None	None	None

In order to generate the combinations of weights required to conduct this sensitivity analysis method, upper and lower bounds on the parameters need to be assessed. This can be done by asking to real project staffs or decision-makers. In this case study, the upper and lower bounds of each attribute weight are decided as shown in Table 6-5.

Table 6-5. Range of the allowable weight factor for each attribute

Weights	Cost (W_1)	Footprint (W_2)	Emissions (W_3)			Perception (W_4)			Safety (W_5)
			Air	S/L	Noise	Gov.	Ind.	Public	
Maximum	1.00	1.00	1/3	1/3	1/3	1/3	1/3	1/3	1.00
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Based on the ranges given in Table 6-5, this study enumerates all possible weight combinations within these bounds that summed to one in increments of roughly 0.1. Since the weights must sum to one, as one weight increases, others must decrease. In this case study, for example, as w_1 increases, other weights (i.e., w_2, w_3, w_4, and w_5) decrease by the ratio of the weight combination shown in Table 6-3. For example, the weights assigned to cost attribute could be changed from the initially assigned value of 0.60, 'Conventional case (weight no.1)', given in Table 6-2. Since the weighting factors must sum to one, the weights assigned to other attributes are known once a weight assigned to cost attribute is decided. It is noted that since the ratio of an assigned weight for each attribute is different from each weight combination, even if weights assigned to the same attribute are identical and increase by equal percentage for two different weight combinations, the weights assigned to other attributes decrease by the different ratio for the two weight combinations. The total number of weight combinations for further consideration is about 410 in this sensitivity analysis.

Deciding on the number of combinations of weights being used in a sensitivity analysis usually involves a trade-off between increased computational time for the analysis and the potential for increased modeling accuracy. This trade-off needs to be made on a case-specific basis (Guikema and Milke 2003). Once the combinations of input parameters are defined, the optimization routine is performed for each combination. This has the potential to consume significant time in the process, especially for problems where a large number of technologies are considered.

In this sensitivity analysis where weights are varied, twelve different drilling systems are selected as the optimal systems for at least one of the weight combinations being considered. Table 6-6 shows the proportion of each of twelve systems selected for this sensitivity analysis. The fact that SET 1, the most selected optimal solution, is selected for 42% of the weight combinations emphasizes the need for a sensitivity analysis.

Table 6-6. Proportion of the optimal systems for this case study

	SET NUMBER											
	1	2	3	4	5	6	7	8	9	10	11	12
Proportion (%)	41.6	35.0	9.1	4.7	2.0	1.5	1.5	1.5	1.5	0.7	0.5	0.5

Throughout the sensitivity analysis conducted in this case study, six different drilling systems are suggested for Green Lake drilling site as shown in Figure 6-13. Figure 6-13 shows which technologies are selected for each suggested system.

SET 1 (41.6%)	SET 2 (35%)
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor	(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor
(2) Road construction: DURA-BASE from Composite Mat (rent)	(2) Road construction: DURA-BASE from Composite Mat (rent)
(3) Site preparation: Aluminum modules + driven piles	(3) Site preparation: DURA-BASE from Composite Mat (rent)
(4) Rig type: LOC250 (CWD)	(4) Rig type: LOC250 (CWD)
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor
(6) Fuel type: Natural gas	(6) Fuel type: Natural gas
(7) Rig power (Unconventional): Electric power from grid (10 %)	(7) Rig power (Unconventional): Electric power from grid (10 %)
(8) Energy storage: Flywheels	(8) Energy storage: Flywheels
(9) Drilling tech.: Managed pressure drilling w/noise suppressor	(9) Drilling tech.: Underbalanced drilling w/noise suppressor
(10) Fluid type: Water-based muds	(10) Fluid type: Water-based muds
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	(11) Waste mgmt.: Closed loop + containers + solid control equip.*
(12) Cuttings mgmt.: Cuttings injection	(12) Cuttings mgmt.: Cuttings injection
(13) Noise reduction: N/A	(13) Noise reduction: N/A

SET 3 (9.1%)	SET 4 (4.7%)
(1) Transportation: Coventional diesel truck	(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor
(2) Road construction: DURA-BASE from Composite Mat (rent)	(2) Road construction: DURA-BASE from Composite Mat (rent)
(3) Site preparation: DURA-BASE from Composite Mat (rent)	(3) Site preparation: Aluminum modules + driven piles
(4) Rig type: LOC250 (CWD)	(4) Rig type: LOC250 (CWD)
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor
(6) Fuel type: Natural gas	(6) Fuel type: Natural gas
(7) Rig power (Unconventional): N/A (0 %)	(7) Rig power (Unconventional): Electric power from grid (30 %)
(8) Energy storage: N/A	(8) Energy storage: Flywheels
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	(9) Drilling tech.: Managed pressure drilling w/noise suppressor
(10) Fluid type: Water-based muds	(10) Fluid type: Water-based muds
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	(11) Waste mgmt.: Closed loop + containers + solid control equip.*
(12) Cuttings mgmt.: Cuttings injection	(12) Cuttings mgmt.: Cuttings injection
(13) Noise reduction: N/A	(13) Noise reduction: N/A

SET 5 (2%)	SET 6 (1.5%)
(1) Transportation: Coventional diesel truck	(1) Transportation: Coventional diesel truck
(2) Road construction: DURA-BASE from Composite Mat (rent)	(2) Road construction: DURA-BASE from Composite Mat (rent)
(3) Site preparation: DURA-BASE from Composite Mat (rent)	(3) Site preparation: DURA-BASE from Composite Mat (rent)
(4) Rig type: LOC250 (CWD)	(4) Rig type: LOC250 (CWD)
(5) Rig power (Conventional): Internal combustion engine	(5) Rig power (Conventional): Internal combustion engine
(6) Fuel type: Low sulphur diesel	(6) Fuel type: Conventional diesel
(7) Rig power (Unconventional): N/A (0 %)	(7) Rig power (Unconventional): N/A (0 %)
(8) Energy storage: N/A	(8) Energy storage: N/A
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	(9) Drilling tech.: Underbalanced drilling w/noise suppressor
(10) Fluid type: Water-based muds	(10) Fluid type: Water-based muds
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	(11) Waste mgmt.: Lined reserve pit + solid control equip.*
(12) Cuttings mgmt.: Cuttings injection	(12) Cuttings mgmt.: Cuttings injection
(13) Noise reduction: N/A	(13) Noise reduction: N/A

Figure 6-13. Six systems suggested for Green Lake drilling site

As can be seen in Figure 6-13, the results of six systems can indicate the potential for further simplification of a technology selection problem. In this case, the technologies selected for five subsets (i.e., (2), (4), (10), (12), and (13)) are always same in all suggested systems. Therefore, if sensitivity to weights is the only concern, the optimal decision would revolve around the technologies for only eight subsets of the original thirteen subsets.

Figure 6-14 shows the comparison of the single-attribute utility values of six suggested drilling systems given in Figure 6-13. Input values used in those suggested drilling systems can be found in APPENDIX B.

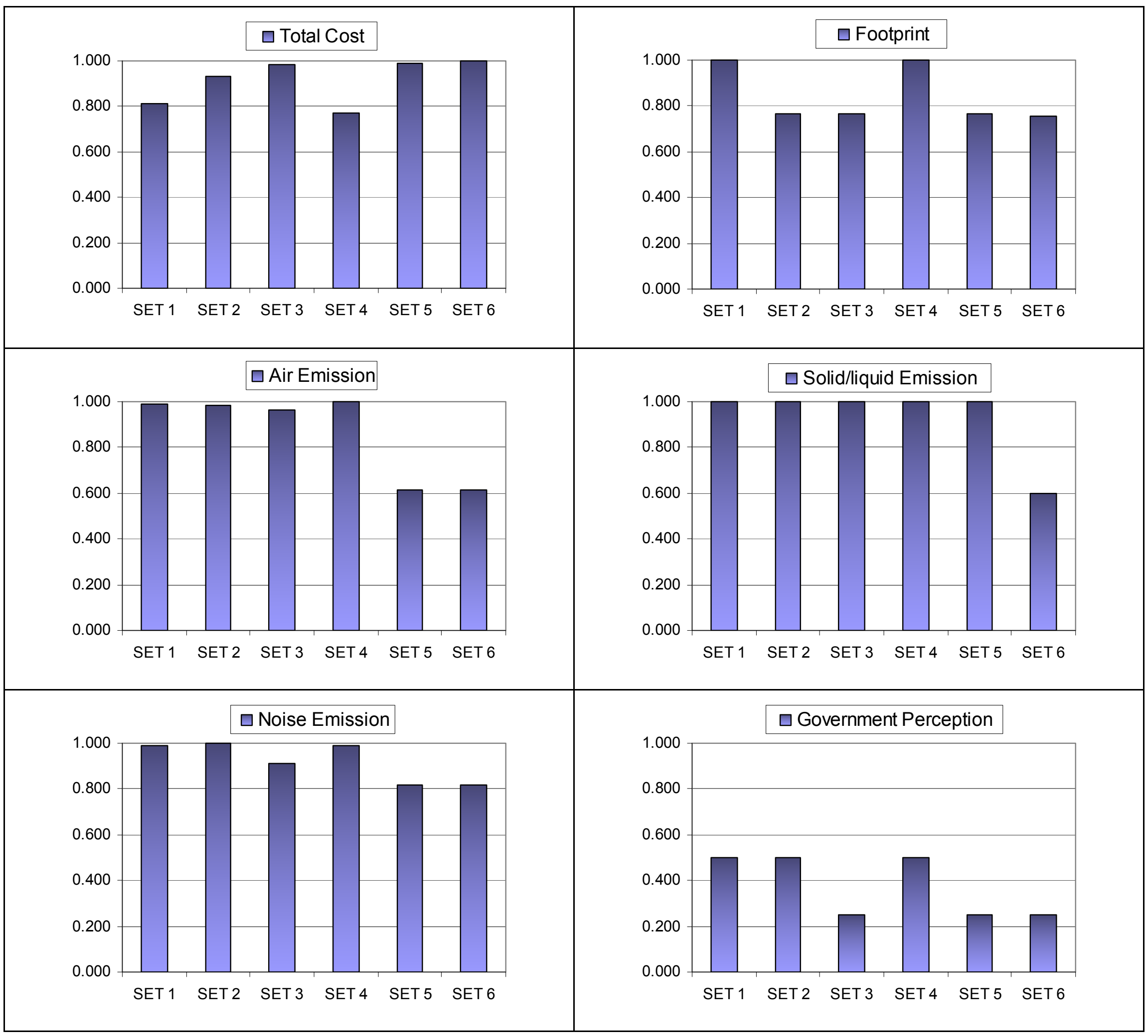


Figure 6-14. Comparison of the single-attribute utility scores

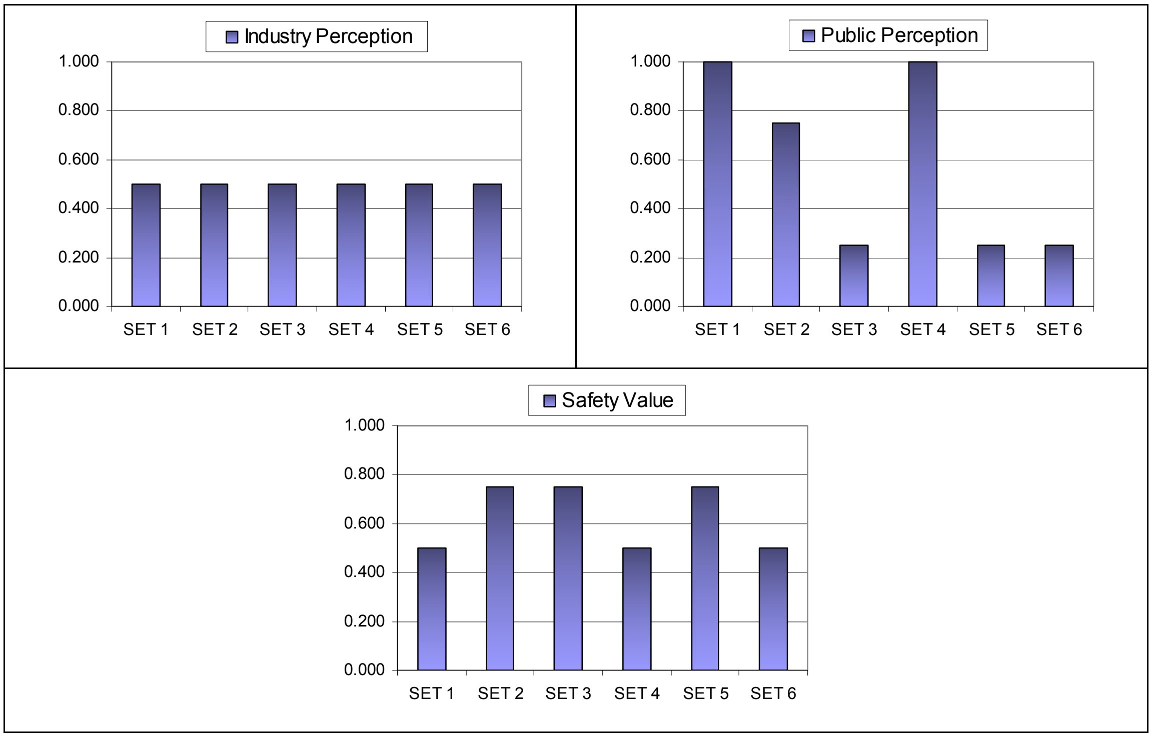


Figure 6-14. Continued

Figure 6-15 through Figure 6-19 show which system should be selected as weight 1 through weight 5 ($w_1 \sim w_5$) are varied respectively by the ratio of the base-case weight combination described in Table 6-3. Since the weights must sum to one, as one weight increases, others must decrease. In Figure 6-15, for example, as w_1 increases, other weights (i.e., w_2 through w_5) decrease by the ratio of the base-case weight combination shown in Table 6-3. Figure 6-15 shows that SET 2 is preferred over SET 1 as w_1 increases and SET 4, containing 30% of unconventional power usage, is only selected as the optimal system when the cost attribute is not considered ($w_1 = 0$). This is simply because currently developed unconventional power generation methods and energy storage devices are usually costly even though they significantly decrease emission rates. Figure 6-16 shows that an increase in w_2 has little effect on the overall utility score of SET 6.

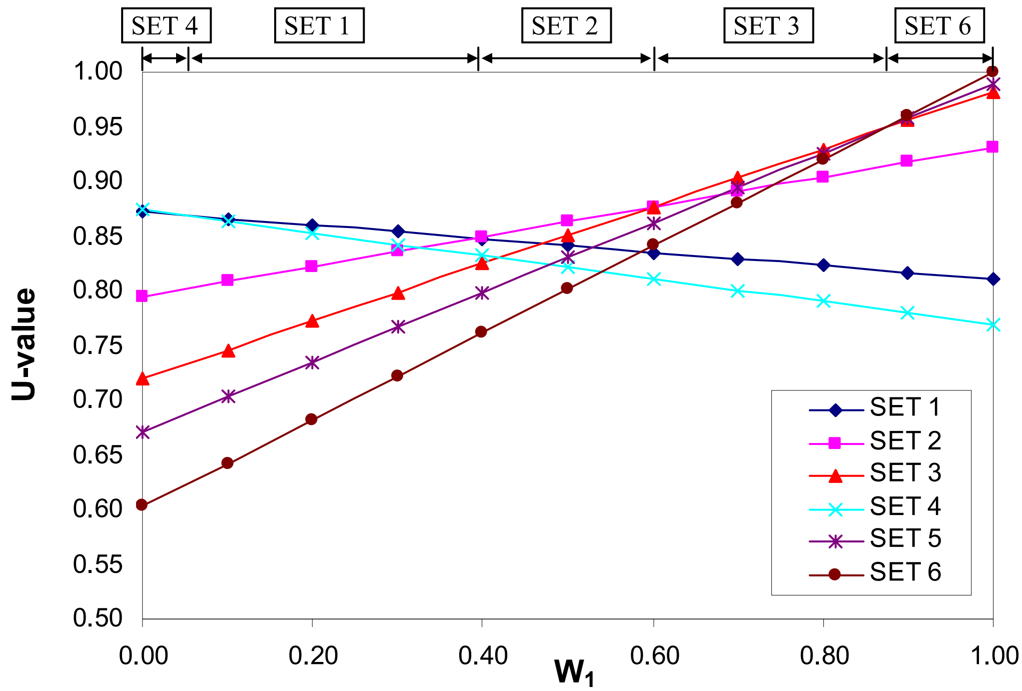


Figure 6-15. Optimal utility scores of the suggested systems when W_1 is varied

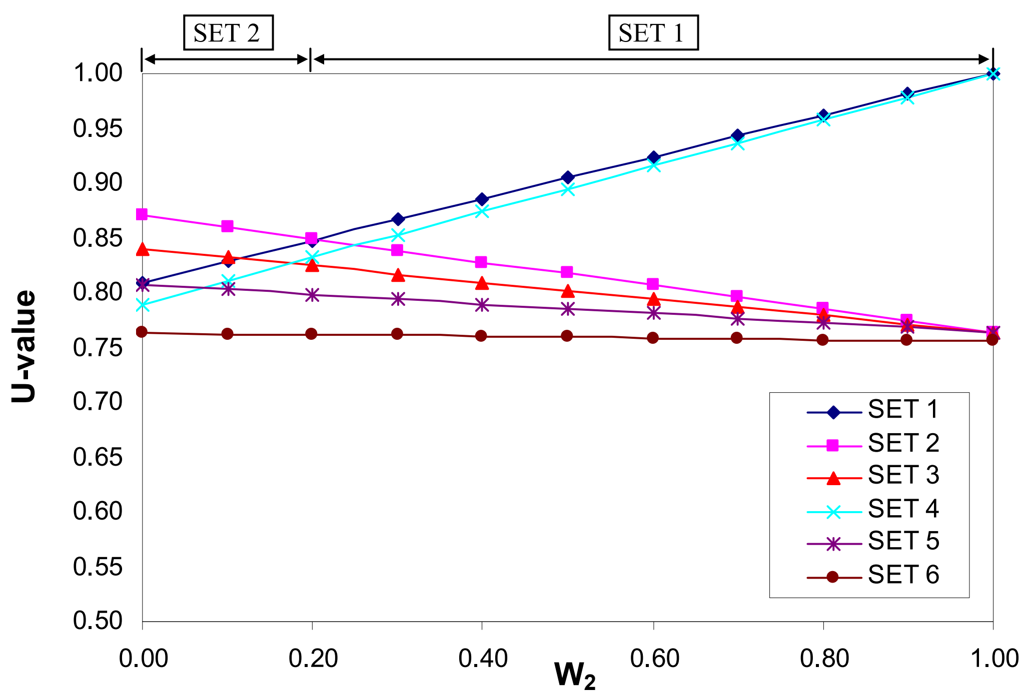


Figure 6-16. Optimal utility scores of the suggested systems when W_2 is varied

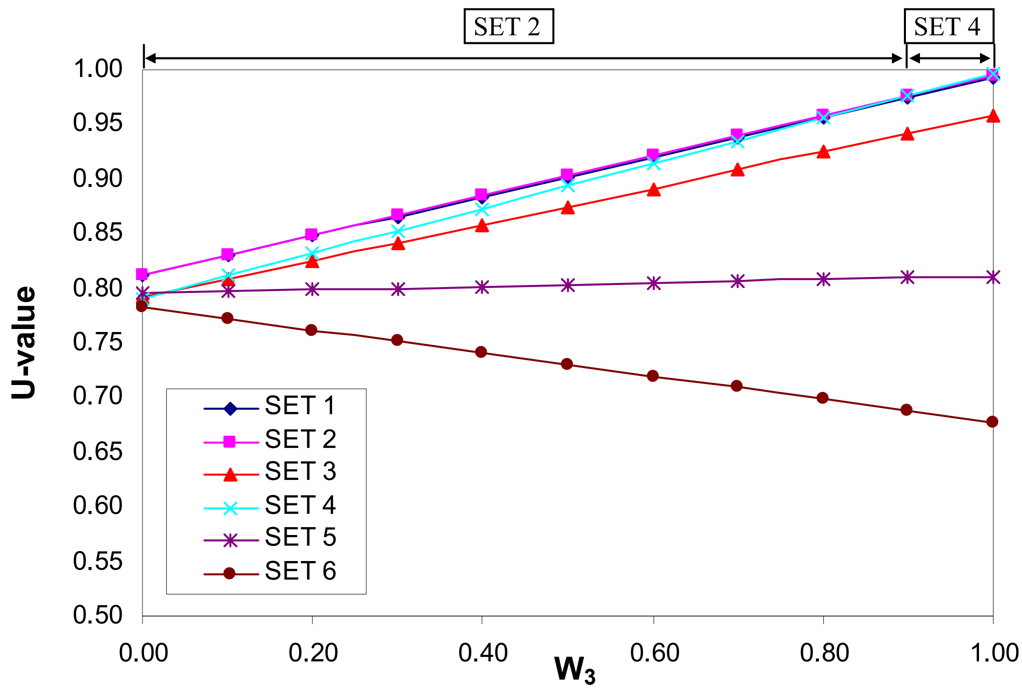


Figure 6-17. Optimal utility scores of the suggested systems when W_3 is varied

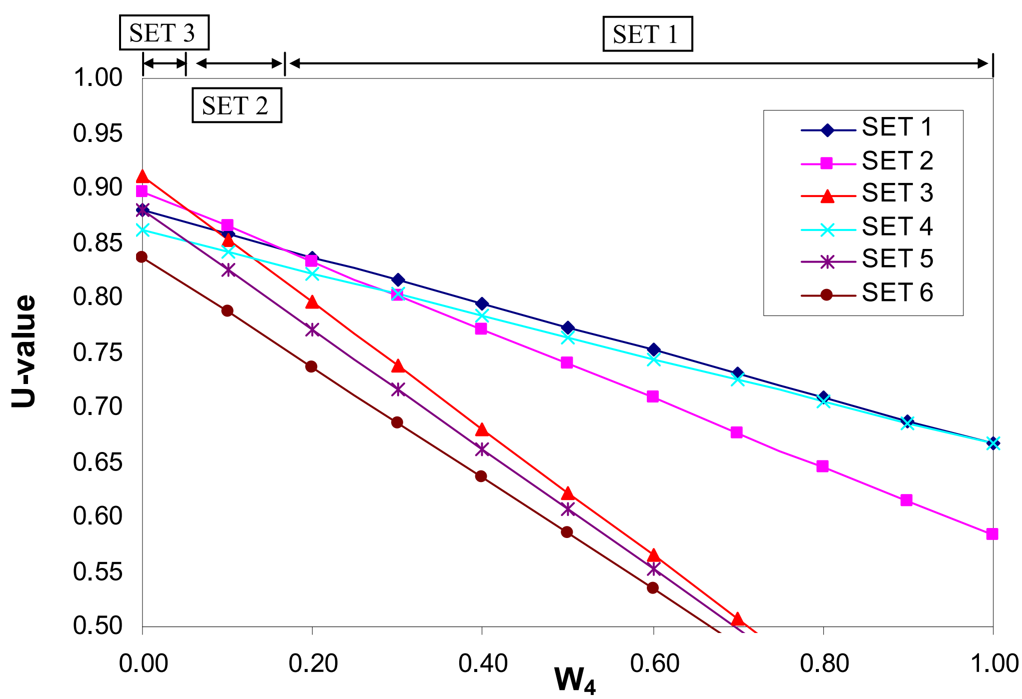


Figure 6-18. Optimal utility scores of the suggested systems when W_4 is varied

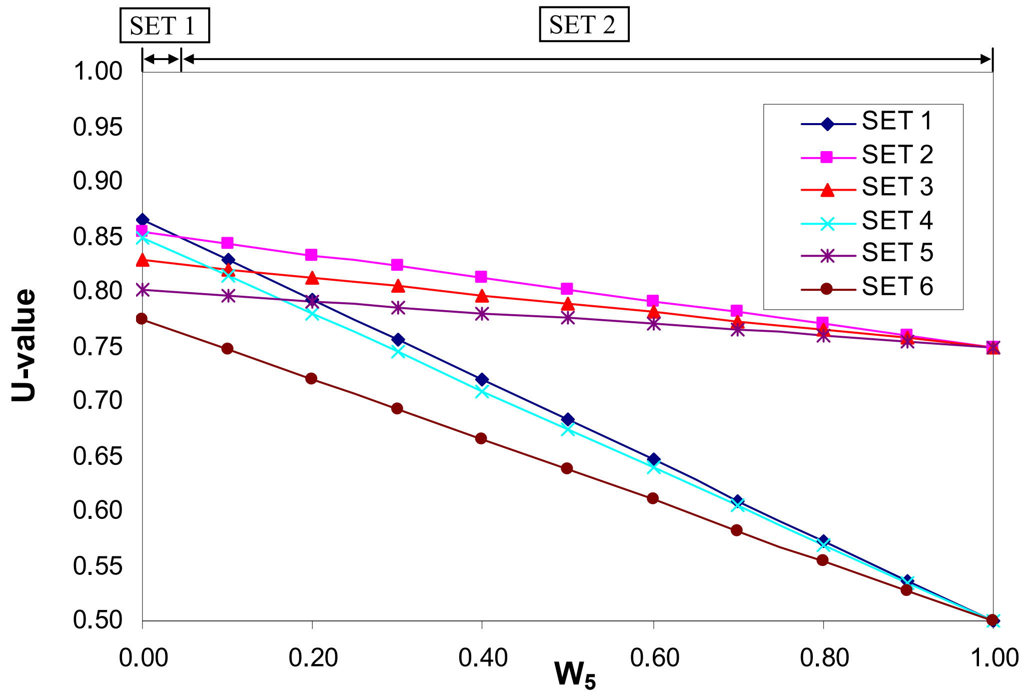


Figure 6-19. Optimal utility scores of the suggested systems when W_5 is varied

Another way of displaying the results of the sensitivity analysis is shown in Figure 6-20 through Figure 6-29. These figures focus not on the relative overall utility score of the different systems but on the system selections themselves. This displaying method is more useful and intuitive when people want to know which system should be selected with a given weight combination. However, the drawback of using this method is these are only three-dimensional plots so two remaining weights should be fixed at zero.

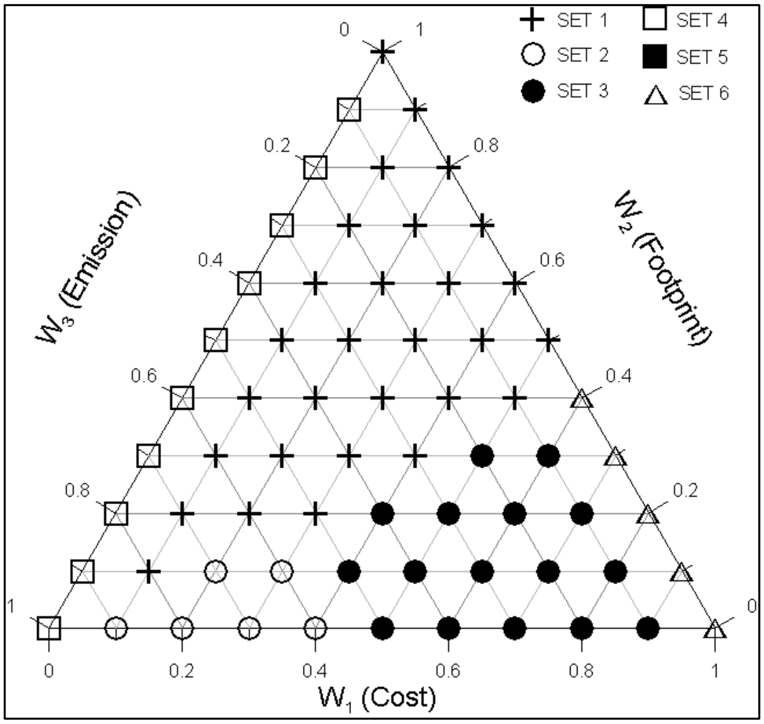


Figure 6-20. Optimal system selection as a function of W_1, W_2, and W_3

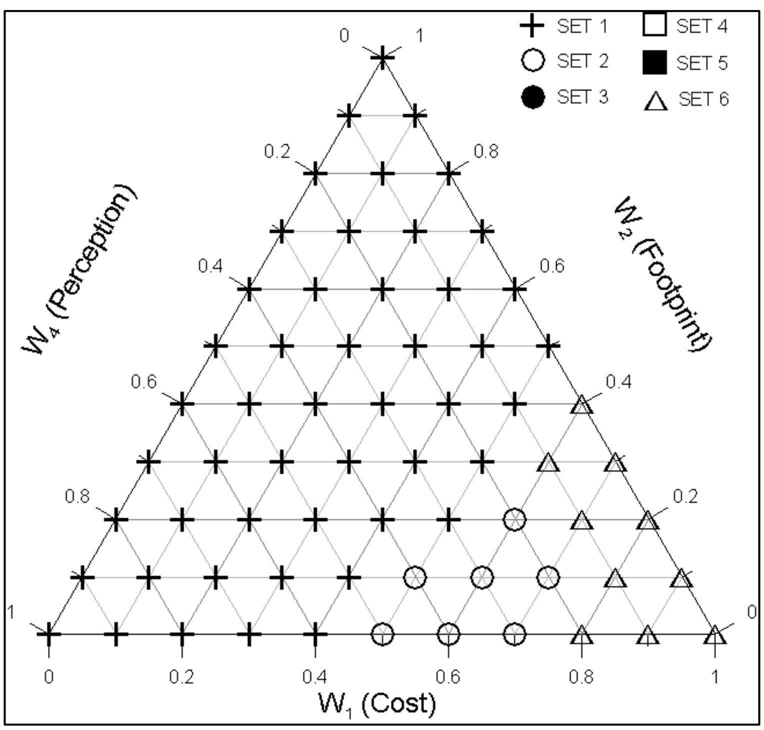


Figure 6-21. Optimal system selection as a function of W_1, W_2, and W_4

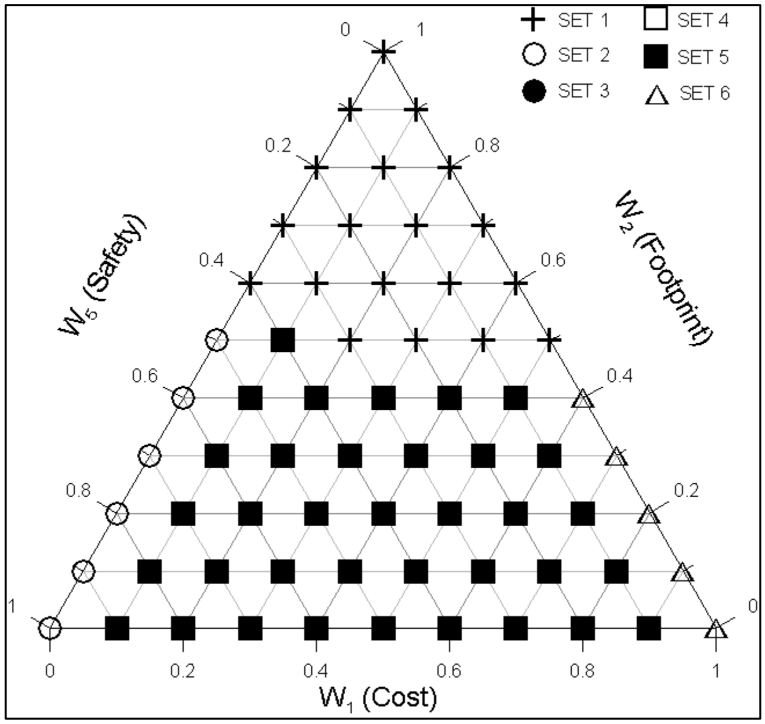


Figure 6-22. Optimal system selection as a function of W_1, W_2, and W_5

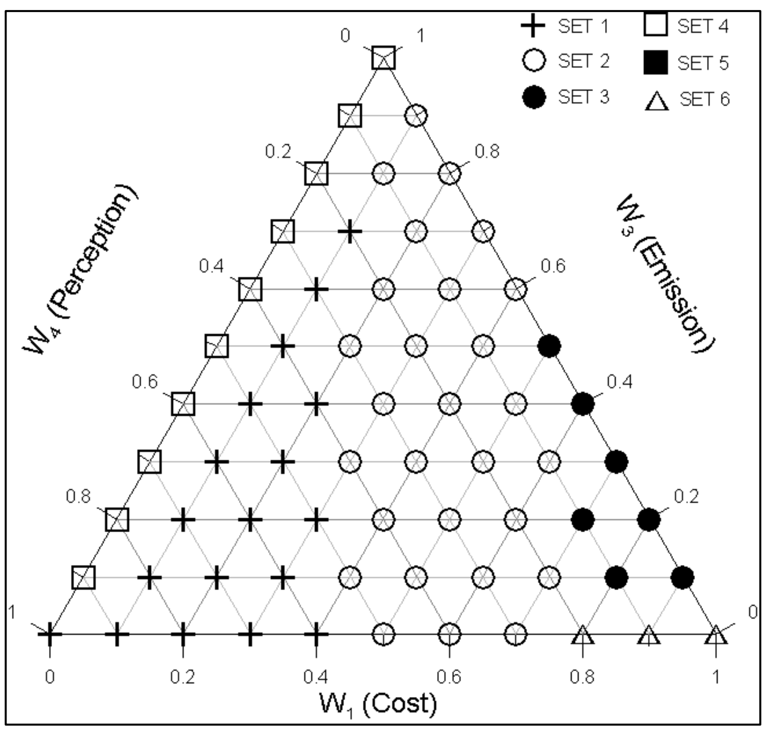


Figure 6-23. Optimal system selection as a function of W_1, W_3, and W_4

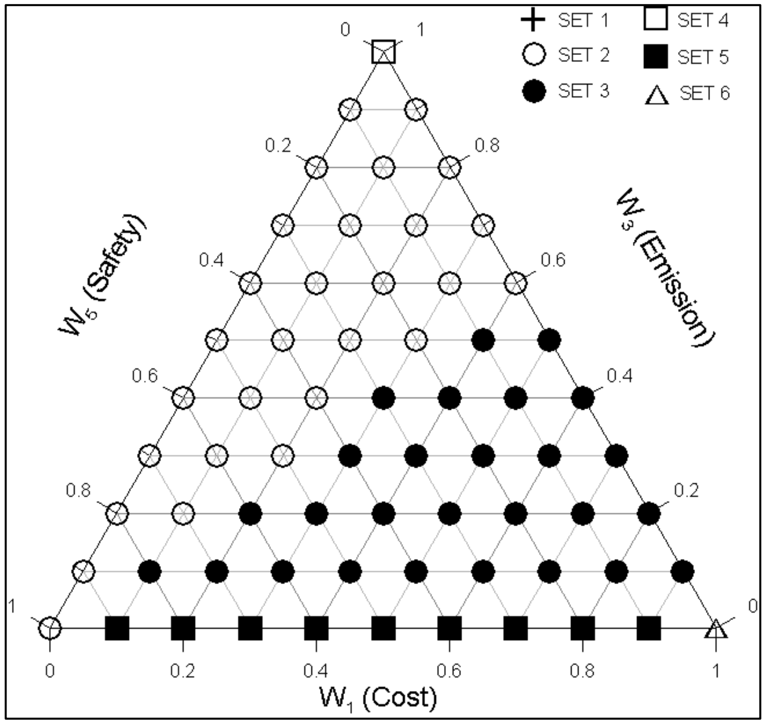


Figure 6-24. Optimal system selection as a function of W_1, W_3, and W_5

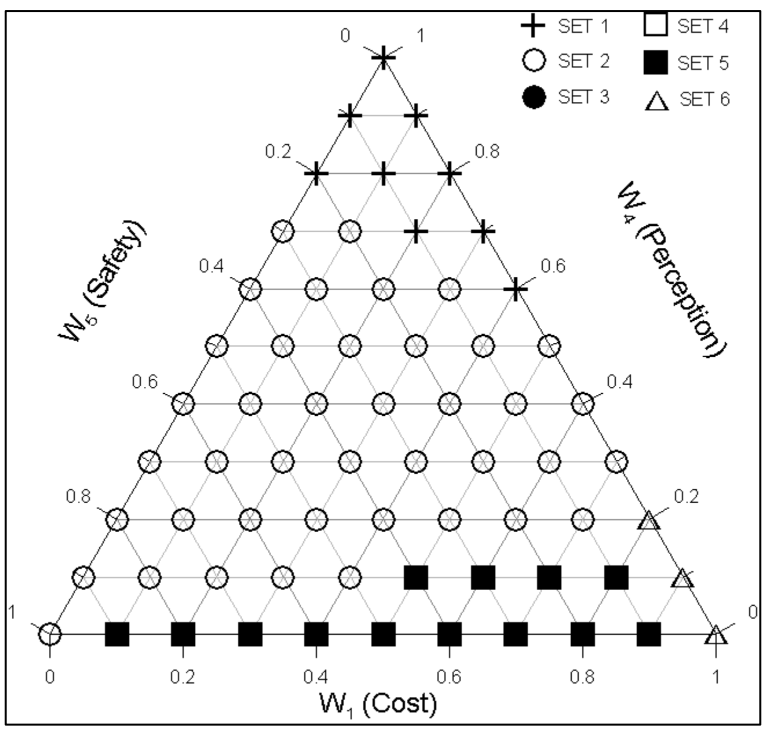


Figure 6-25. Optimal system selection as a function of W_1, W_4, and W_5

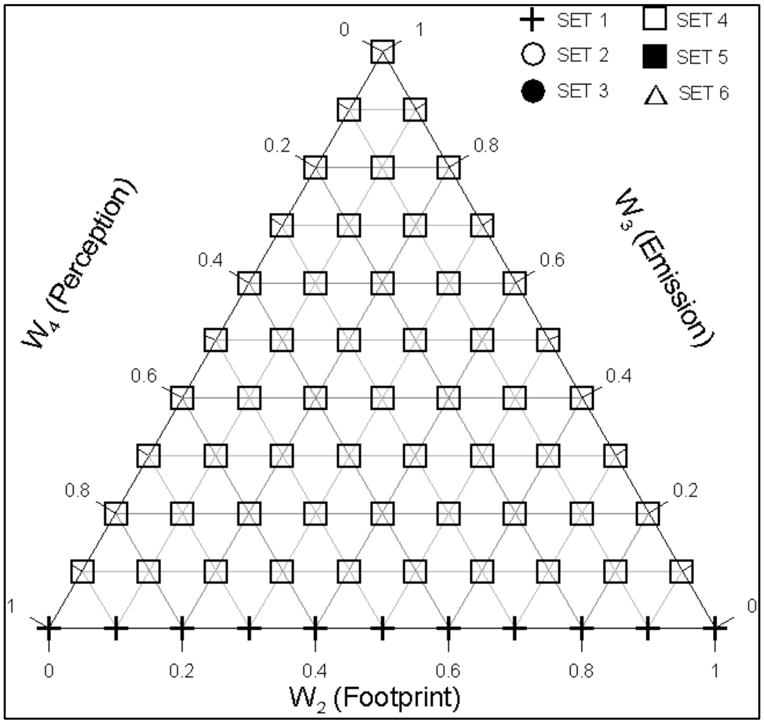


Figure 6-26. Optimal system selection as a function of W_2, W_3, and W_4

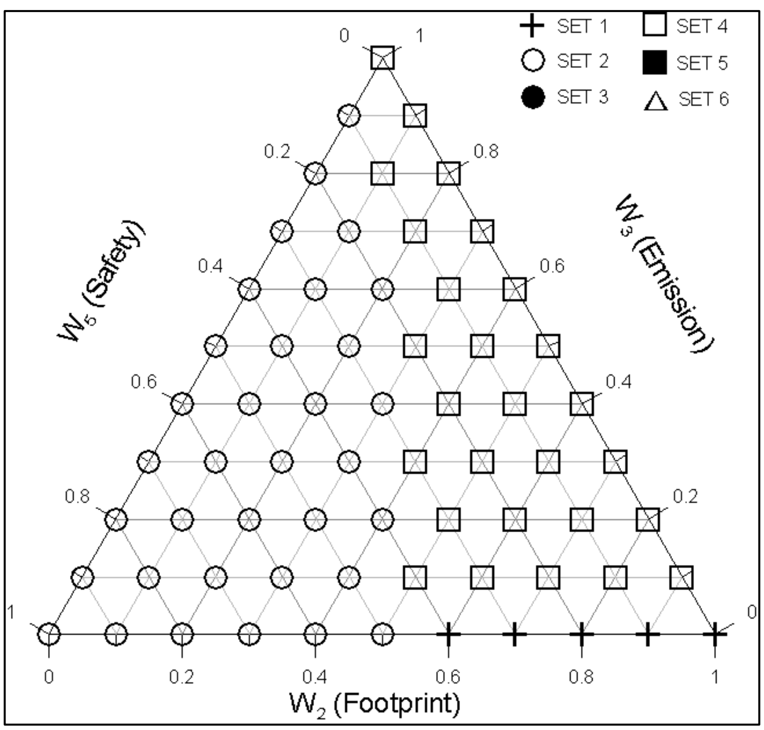


Figure 6-27. Optimal system selection as a function of W_2, W_3, and W_5

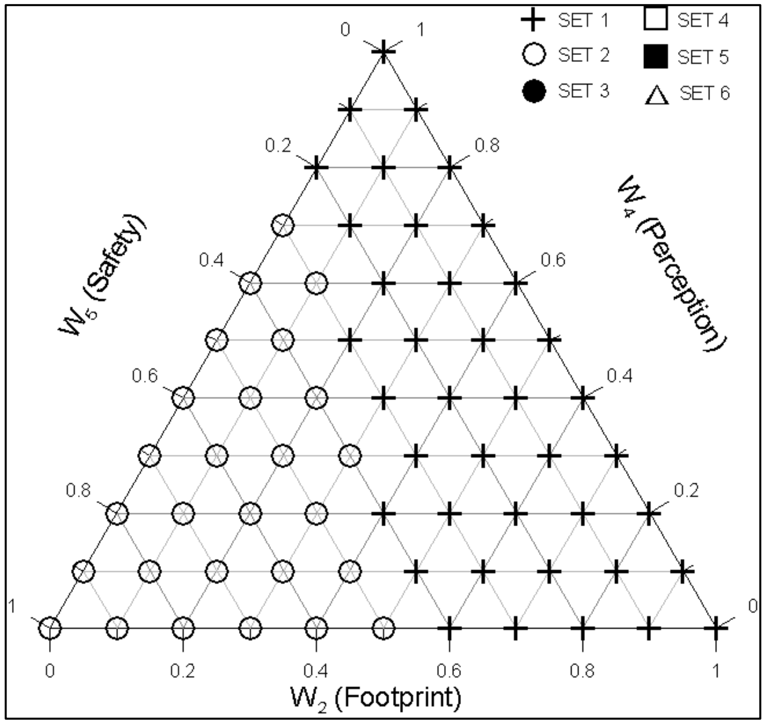


Figure 6-28. Optimal system selection as a function of W_2, W_4, and W_5

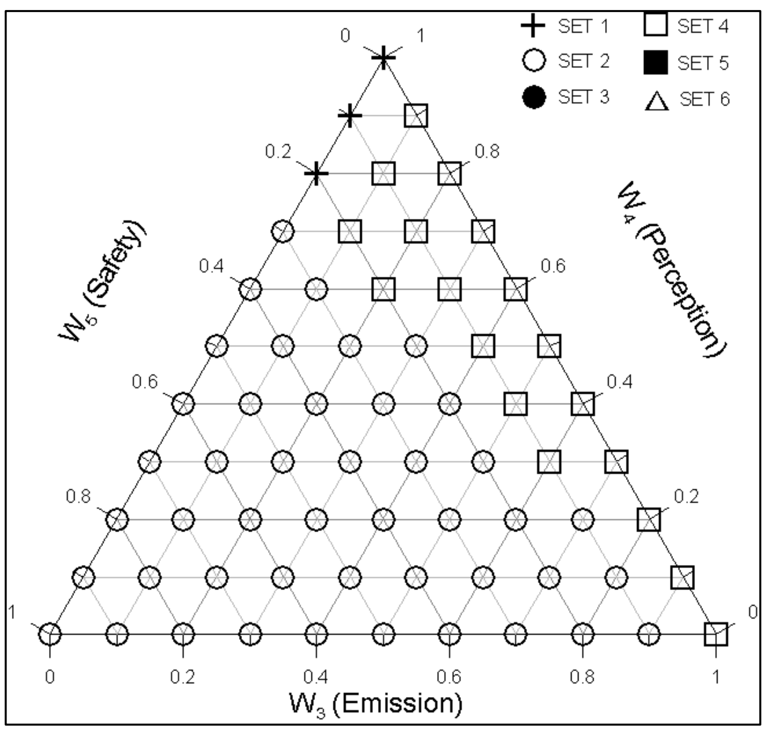


Figure 6-29. Optimal system selection as a function of W_3, W_4, and W_5

6.4.2 Sensitivity Analysis for Uncertainty of Overall Attribute Scores

In order to identify how much sensitive the overall utility score is to changes in the input attribute scores, overall attribute scores of two different systems (i.e., SET 1 and SET 6, which are the most and the least suggested optimal system) are varied from the original values with two different discrete weight combinations shown in Table 6-7. The variation of the cost, footprint, and emission attribute scores are ± 10% from the original values and the variation of other attribute scores (i.e., perception and safety) are upper and lower grade score from the original values. The input scores and the variation of the overall attribute scores being used in this sensitivity analysis are shown in Figure 6-30 and Figure 6-31. It is noted that the overall public perception score of SET 1 can't be varied to the upper grade score because the original score of this attribute is one, which is the possible maximum score can be assigned to this attribute. The possible maximum and minimum score should be considered for attributes using the ordinal scales such as solid/liquid emission, three perceptions, and safety.

Table 6-7. Weight combinations used in the sensitivity analysis

Weight no.	Cost (W_1)	Footprint (W_2)	Emissions (W_3)			Perception (W_4)			Safety (W_5)	Note
			Air	S/L	Noise	Gov.	Ind.	Public		
1	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	Even
2	0.40	0.20	0.20/3	0.20/3	0.20/3	0.05	0.05	0.05	0.05	Base case

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: Aluminum modules + driven piles	$226,261	0.005	0.989		76.265	1.000	0.500	1.000	0.500
(4) Rig type: LOC250 (CWD)	$173,800		0.985		60.366	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	$70,354		0.918		85.603	1.000	0.500	1.000	0.750
(6) Fuel type: Natural gas	$25,650					1.000	0.500	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$3,840	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Managed pressure drilling w/noise suppressor	$193,500				94.100	0.750	0.750	1.000	1.000
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$991,184	1.520	4.868	2.000	381.030	0.500	0.500	1.000	0.500
Single Attribute Utility Values (Original)	0.811	0.966	0.768	1.000	0.988	0.500	0.500	1.000	0.500
Used Upper Bound Scores	$1,090,302.68	1.67	5.35	2.00	419.13	0.75	0.75	1.00	0.75
Used Lower Bound Scores	$892,065.83	1.37	4.38	1.80	342.93	0.25	0.25	0.75	0.25

Figure 6-30. Input values and variation of the overall attribute scores of SET 1

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	Solid& Liquid	Noise (TWA)	Gov.	Ind.	Public	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: DURA-BASE from Composite Mat (rent)	$90,000	1.033	0.976		79.945	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	$167,000		0.977		77.458	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Internal combustion engine	$50,000		0.338		107.998	0.500	1.000	0.500	0.750
(6) Fuel type: Conventional diesel	$45,600					0.500	1.000	0.500	0.500
(7) Rig power (Unconventional): N/A (0 %)	$0	0.000	1.000		0.000	0.250	1.000	0.250	1.000
(8) Energy storage: N/A	$0	0.000				0.250	1.000	0.250	1.000
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	$184,500				95.700	0.750	0.750	0.750	0.750
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Lined reserve pit + solid control equip.*	$18,000	0.037		0.500		0.750	0.750	0.750	0.500
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$780,040	2.585	4.254	1.500	443.971	0.250	0.500	0.250	0.500
Single Attribute Utility Values	0.935	0.756	0.613	0.600	0.820	0.250	0.500	0.250	0.500
Used Upper Bound Scores	$858,044.00	2.84	4.68	1.65	488.37	0.50	0.75	0.50	0.75
Used Lower Bound Scores	$702,036.00	2.33	3.83	1.35	399.57	0.00	0.25	0.00	0.25

Figure 6-31. Input values and variation of the overall attribute scores of SET 6

Figure 6-32 through Figure 6-39 show the sensitiveness of the input attribute scores of the two systems with two discrete weight combinations given in Table 6-7. In Figure 6-32, for example, since steeper slope indicates more sensitive attribute, the air emission attribute seems to be the most sensitive attribute among the nine attributes. In Figure 6-33, however, perception and safety attributes seem to change the overall utility score of SET 1 more than other attributes. This is because the cost, footprint, and emission attributes vary by only ± 10% from the original values while perception and safety attributes vary by about 20% ~ 100% from the original values due to the grade score scale (i.e., 0, 0.25, 0.50, 0.75, 1.00).

The weight factor assigned to each attribute is very important element when identifying the sensitiveness of input attribute scores. In Figure 6-34, for example, the cost attribute seems to be the most sensitive attribute for SET 1, which is not the same result shown in Figure 6-32. This is simply because the weight assigned to each attribute is different between these two figures. The weight assigned to the cost attribute is 1/9 in Figure 6-32 while the weight is 0.40 in Figure 6-34. The noise emission attribute seems to be the most sensitive attribute for SET 6 with 'Even' weight combination as shown in Figure 6-36. It is indicated that since the noise attribute utility curve is not a linear, the result of the variation (± 10%) does not seem to be symmetrical from the original value.

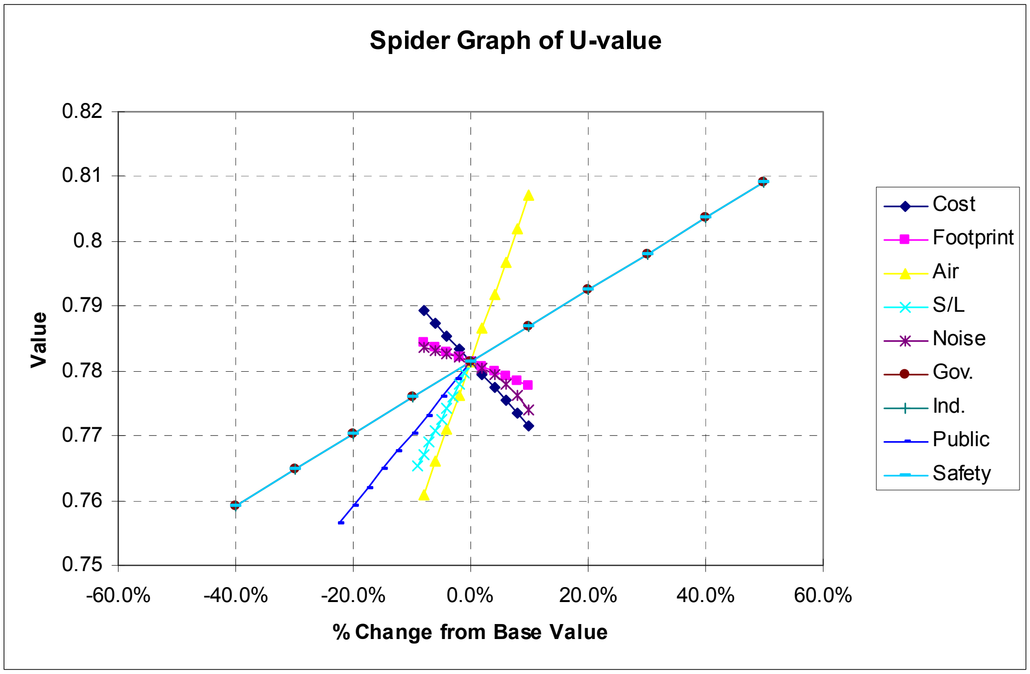


Figure 6-32. Spider graph for SET 1 with 'Even' weight combination in Table 6-7

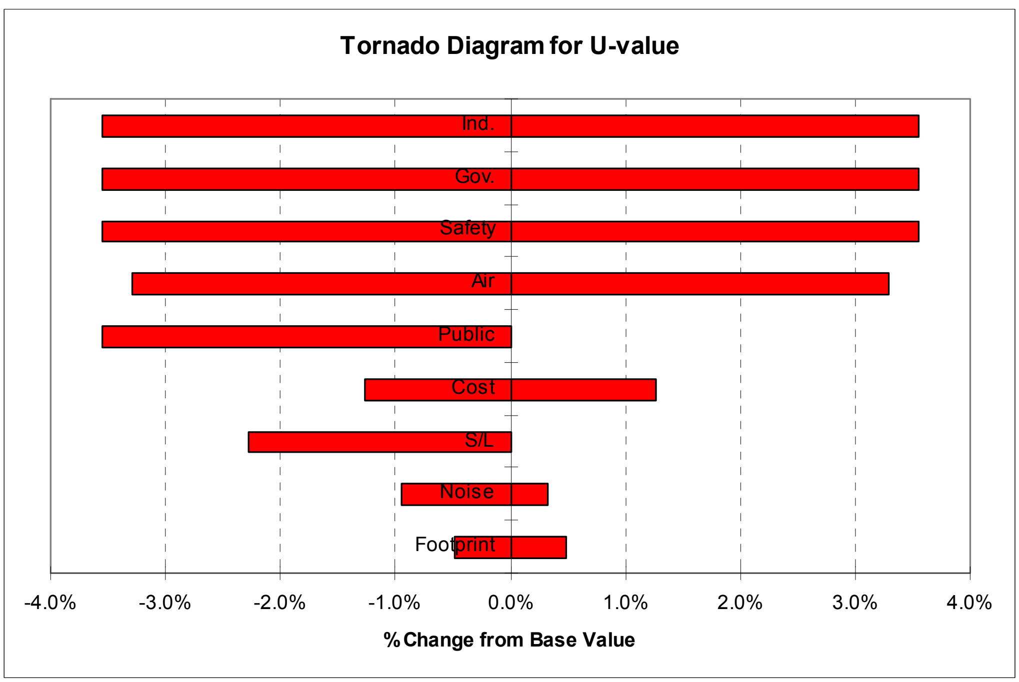


Figure 6-33. Tornado diagram for SET 1 with 'Even' weight combination

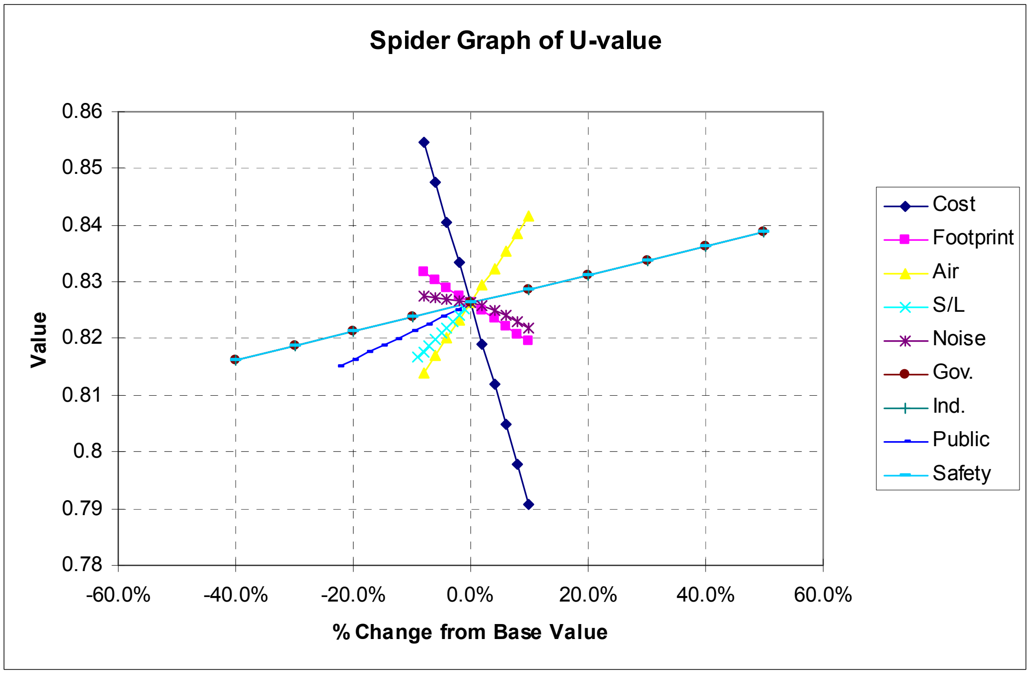


Figure 6-34. Spider graph for SET 1 with 'Base' weight combination in Table 6-7

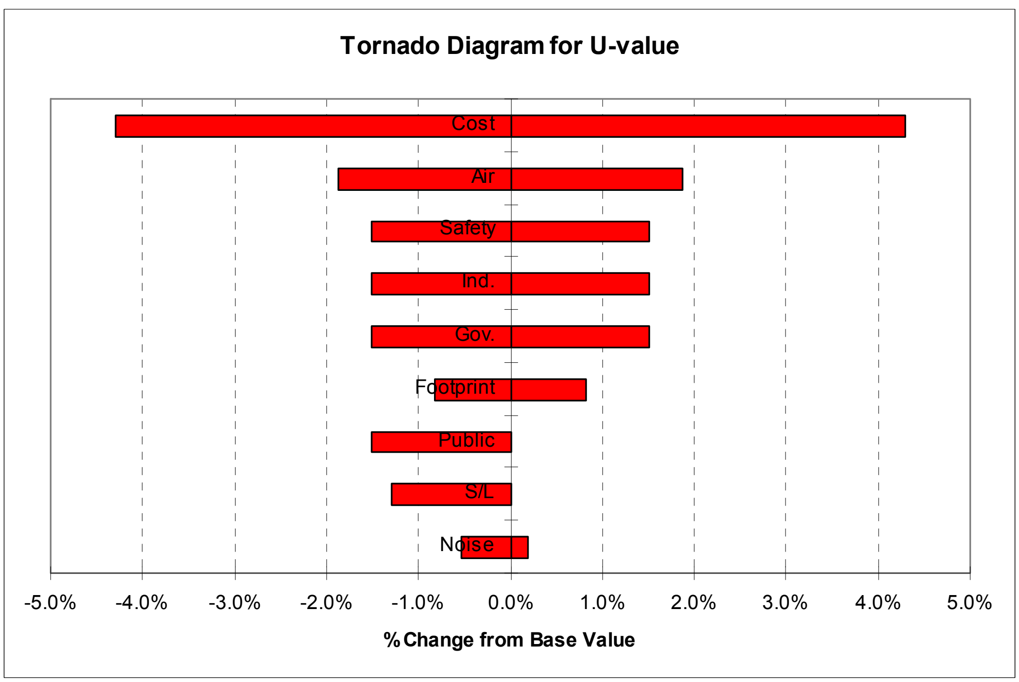


Figure 6-35. Tornado diagram for SET 1 with 'Base' weight combination

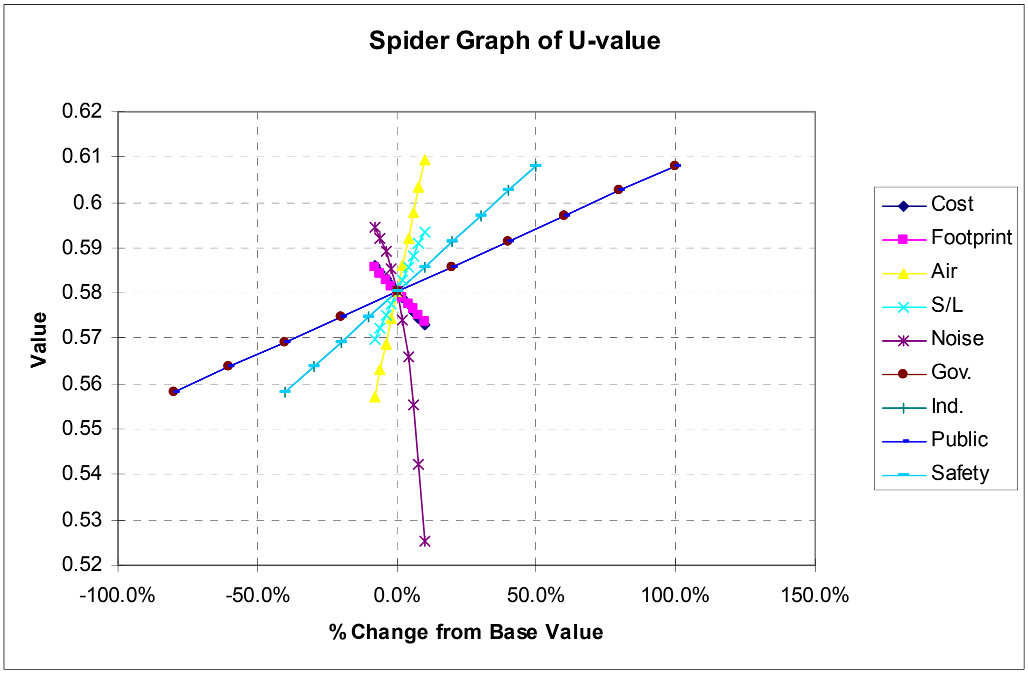


Figure 6-36. Spider graph for SET 6 with ‘Even’ weight combination in Table 6-7

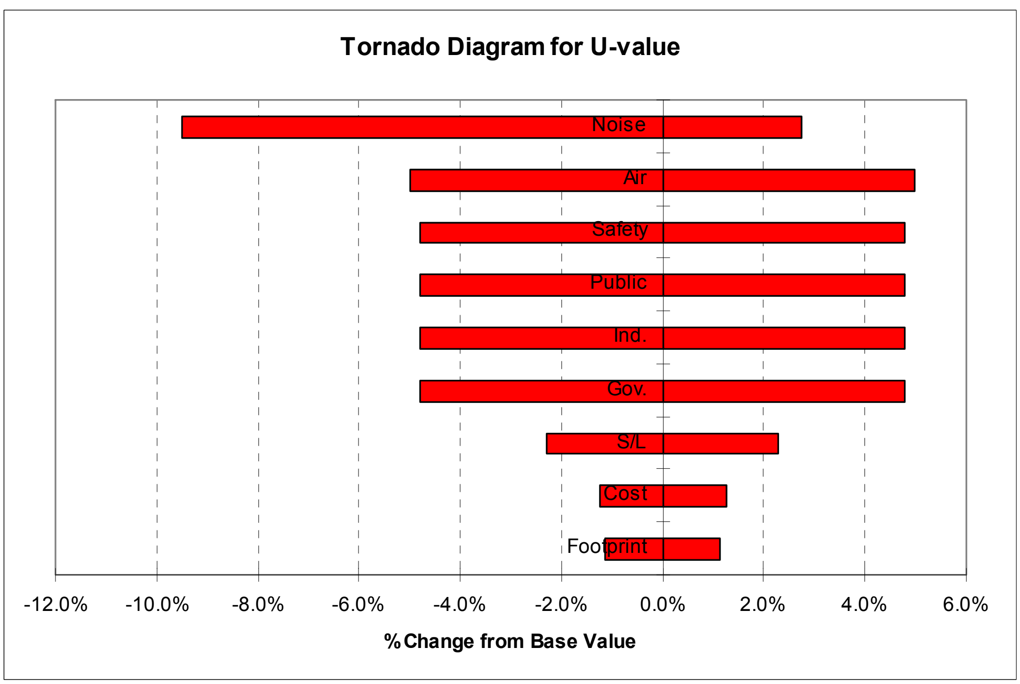


Figure 6-37. Tornado diagram for SET 6 with ‘Even’ weight combination

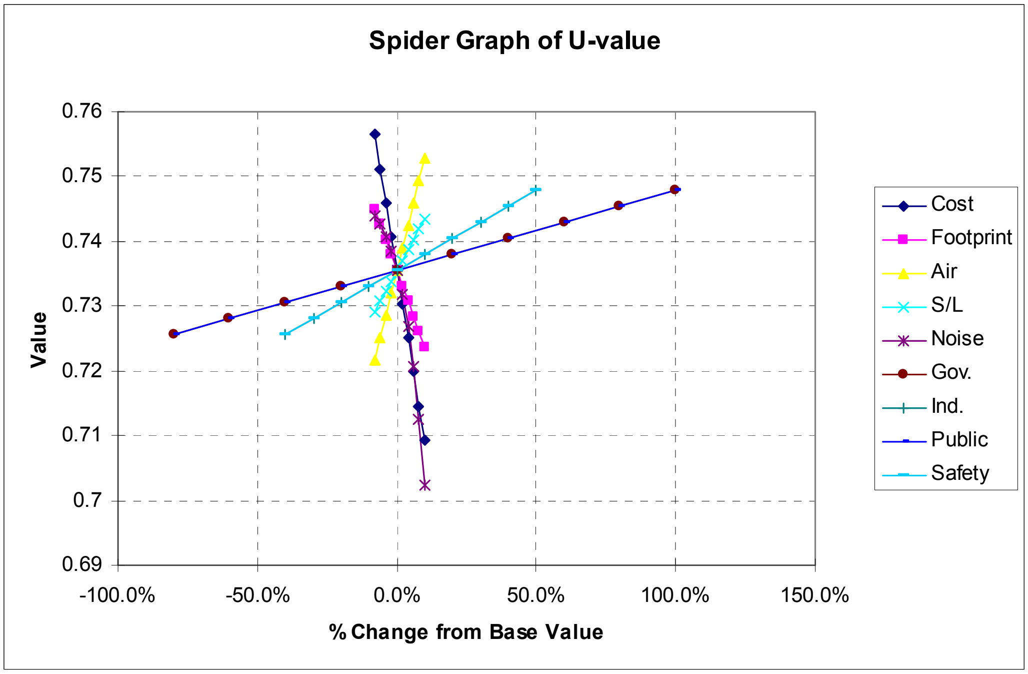


Figure 6-38. Spider graph for SET 6 with ‘Base’ weight combination in Table 6-7

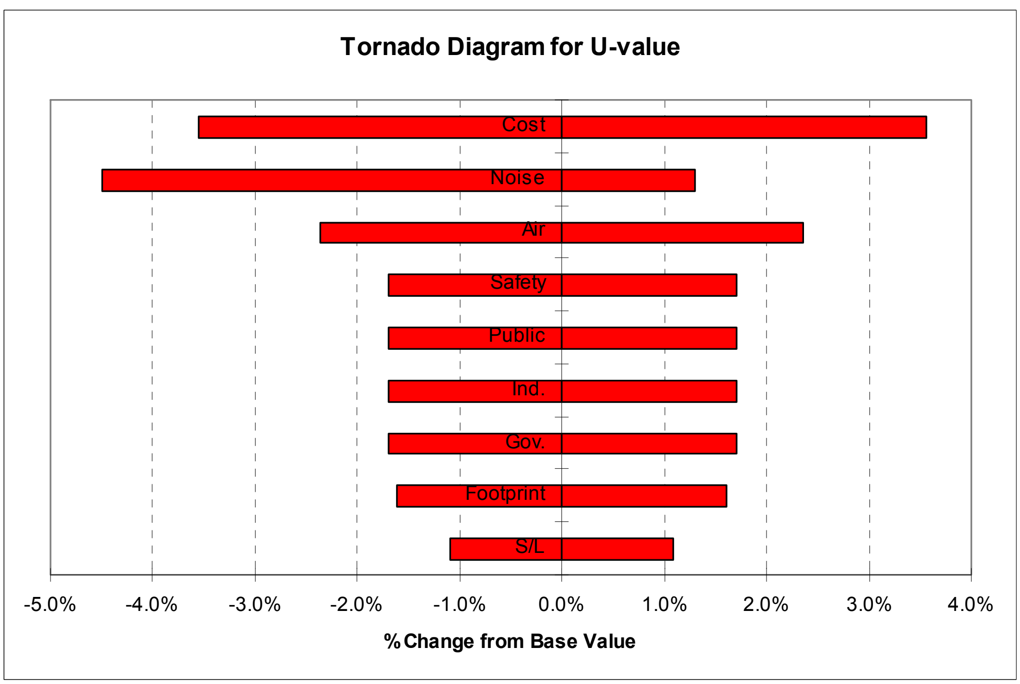


Figure 6-39. Tornado diagram for SET 6 with ‘Base’ weight combination

In summary, if weight factors are evenly distributed to each attribute, air emission score and noise emission score are the most sensitive inputs for SET 1 and SET 6 as shown in Figure 6-32 and Figure 6-36, respectively. On the other hand, if weight factors are not evenly distributed to each attribute, the most sensitive input attribute can be identified after running the sensitivity analysis described in this section.

6.5 Lessons Learned

The knapsack optimization routine (APPENDIX B) was initially run for each weight combination in this case study. However, the critical issue arose while conducting the sensitivity analysis. Using the branch-and-bound optimization algorithm given in "Microsoft Excel Solver", it was not always able to find the global optimal solution. In some cases "Microsoft Excel Solver" was trapped at a local optimal solution. Therefore, in order to always get the global optimal solution (i.e., retain system with maximum overall utility score), an exhaustive search optimization was used in this study, but the complexity of the optimization problem grew rapidly with the number of decision variables. For example, once the number of potential systems was greater than a million, it was not reasonable to perform the exhaustive search analysis due to the computing time. Therefore, it is suggested that the number of possible technologies in some subsets be limited to ensure that the total number of possible system is less than a million. Section 6 illustrates an EFD technology selection problem with a smaller number of possible systems, about twenty thousand systems. The sensitivity analysis was successfully conducted with that smaller number of possible systems. One of the future research tasks is to develop optimization methods that can efficiently search the entire (not truncated) solution space using only standard personal computers.

Throughout this section, it is possible to suggest a small number of suitable systems that are particularly attractive for Green Lake drilling site. Six different drilling systems are suggested for this case study as shown in Figure 6-13. Since there are many uncertainties in the inputs being used, decision-makers want to see whether or not small changes in those inputs they use affect the EFD technology selections. Figure 6-15 gives an example of the optimal systems of varying the weight on the cost attribute (W_1) from zero to one. As W_1 increases in Figure 6-15, cheaper technologies are selected. For example, the technology selected for subset (1) is changed from conventional diesel trucks to low sulphur diesel trucks with tier III engine and with noise suppressor when W_1 increases to 0.6 or more.

Effective displays of sensitivity analyses are crucial as an aid in decision-making process, and also as an aid in explaining EFD technology selections to interested parties. The main purpose of displaying the results of sensitivity analyses graphically is to help the decision-makers better understand what the results mean (Guikema and Milke 2003). Therefore, the display methods chosen in any given situation should be illustrated by the abilities and needs of the decision-makers. For example, more complicated displays such as Figure 6-15 through Figure 6-19 can be used to technically trained people while simpler displays such as Figure 6-20 and Figure 6-29 should be used to less technically trained people.

More extensive sensitivity analyses can be conducted for other input variables such as the utility function for each attribute to suggest more robust optimal systems but they involve a trade-off between increased computational time for the analysis and the potential for increased modeling accuracy. This trade-off needs to be made on a case-specific basis.

7. PROTOTYPE OF A WEB-BASED DECISION OPTIMIZATION TOOL

7.1 Introduction

A prototype of a web-based application has been developed to help decision-makers easily follow the systems approach technology evaluation procedure described in Section 5 and then select an optimal drilling system for a specific site. The main reason to develop the web-based application instead of a stand alone computer application is that the qualified users can use the web-based application as long as they can access the Internet regardless of their locations. Furthermore, it can also help to manage used input parameters permanently if a central repository is maintained regularly so that decision-makers or drilling operators can easily retrieve a previously designed well model for their future operations in different ecosystems.

7.2 Input and Output Appearance

The application has been developed by Active Server Pages (ASP) and uses Microsoft Access database. Figure 7-1 shows how to evaluate available technologies within each subset. The left column in the dashed rectangle of Figure 7-1 shows the list of subsets as described in Section 5.2 and the right column of Figure 7-1 shows evaluated technologies (upper) and the input boxes for the evaluation (lower).

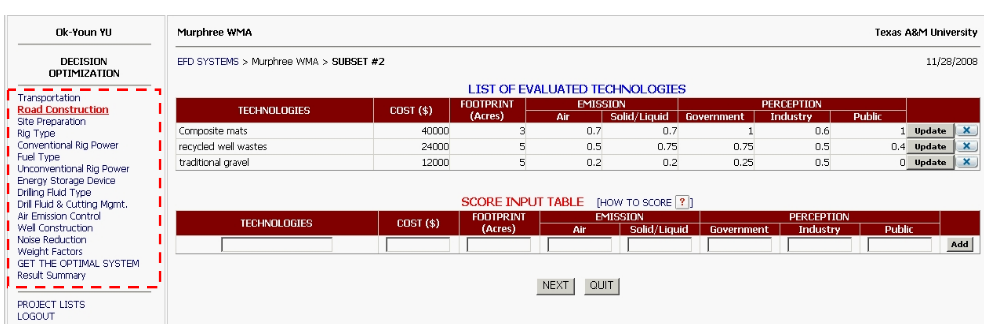


Figure 7-1. Evaluation page for 'Road Construction' subset

After evaluating available technologies within each subset, users should assign weight factor for each attribute to decide how much important each attribute. All of the weights are positive, and they must sum to one (the standard normalization technique used in decision analysis). The following Figure 7-2 shows an example of assigned two different weight scenarios. Once users assign the weight factors, this application shows up to ten optimal systems (top ten results) for one weight scenario among all possible systems according to users' preference as shown in Figure 7-2.

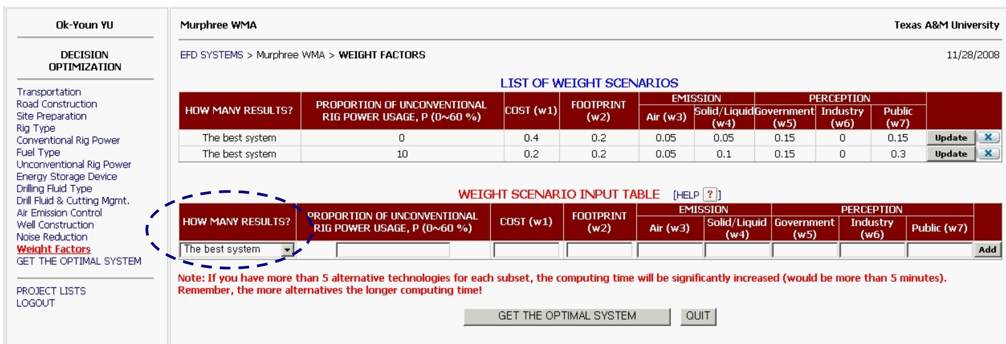


Figure 7-2. Assigned weight scenarios

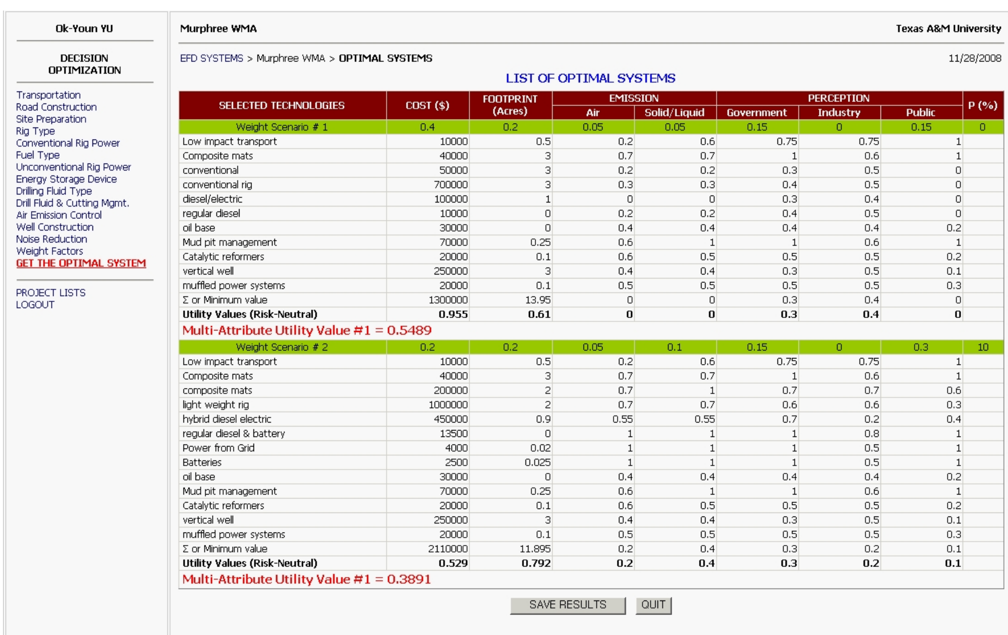


Figure 7-3. An example of the final result page

Figure 7-3 shows an example of the final result page. In this example, this application shows the technologies selected in the optimal system based on the assigned weight scenario as well as the overall utility score associated with the optimal system. The overall utility score is scaled from zero to one and the higher score is the better.

7.3 Evaluation of the Web-Base Application

The Harold Vance Department of Petroleum Engineering at Texas A&M University has incorporated an EFD system design into its PETE 661 graduate drilling class. The "661 Team Challenge" semester project was assigned to the students to "design a well on paper" using low impact drilling technologies. A systems approach to technology evaluation was utilized to incorporate a number of current and emerging EFD technologies into a single clean drilling system with limited environmental impact.

The Team Challenge project provided a number of positive results to its participants. First, the class members learned first hand of some of the newer technologies available to drilling contractors and operators available for lessening the impact for drilling operations. Next the landowner (McFaddin Ranch personnel) learned of the cost benefit of certain technology some of which could not be justified based on its expense. The exercise provided an excellent "field test" in itself of an EFD optimization system with almost 60 students using the web-based optimization tool to select the most appropriate practices to include in their well designs. Lastly, by having such a large group searching for data, the developer of the software populated the database of technologies with actual cost numbers and contact information. At the conclusion of the study more than 100 different techniques had been identified, characterized, and catalogued.

The answer for the question about the usefulness of the web-based decision optimization tool was an unqualified 'yes' as shown in Figure 7-4. Figure 7-4 is the summary of the responses to a questionnaire distributed at the conclusion of the semester. Almost 74% of the class students felt that the program helped select optimal systems for their well designs. A compilation of individual responses is contained in APPENDIX C.

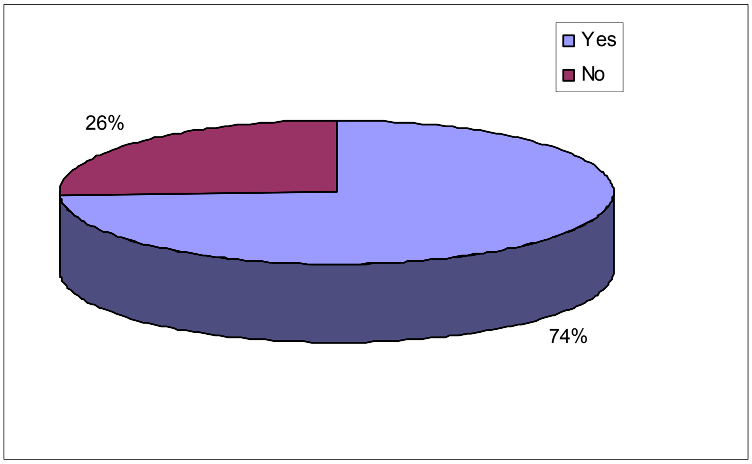


Figure 7-4. Result of survey for the web-based decision optimization tool

It is crucial to keep the web-based application updated as the technology evaluation protocol has been continuously refined by EFD subject matter experts' comments and feedbacks. The list of subsets used in this application, however, is not the same as the one described in Section 5 because the current version of the application has not been updated since January 2008. For example, the technology evaluation protocol described in Section 5 considers 'Cuttings treatment' subset instead of 'Well construction' subset used in the web-based application shown in Figure 7-1. Two other attributes (noise emission and safety) described in Section 5.3 are not also considered in the current web-based application. When estimating the total cost of a technology, drilling time is very important variable because the total cost of the technology should be changed according to the total drilling time of a system. However, it is not also considered in this web-based application yet. One of the future research tasks is to update the current web-based application with the refined technology evaluation protocol.

8. SUMMARY AND CONCLUSIONS

This section reviews the objectives of this research, contribution of this research, and presents the recommendations for future work.

8.1 Summary

The key objectives of this research are to:

1. Help the oil industry engineers to get a basic concept about environmentally friendly foundation designs of a rig or an elevated platform for various weights and soil conditions.
2. Develop a technology evaluation protocol based on a systems analysis to synergistically incorporate a number of current and emerging EFD technologies into a single and clean drilling system with limited environmental impact and then to suggest a small number of systems that should be particularly attractive for a given site.
3. Develop a prototype of a web-based decision optimization tool to help decision-makers easily follow the proposed technology evaluation procedure and then select an optimal drilling system for a specific site.

8.1.1 Parametric Study of Foundations for Drill Sites

Three different types of foundations for drill sites were considered in Section 4. First two types were pile foundations (i.e., driven pile and bored pile). About one thousand different cases of pile capacity calculations were conducted depending on various soil types, pile types, and design methods. The optimal pile selection procedure was also described in Section 4.2.4. The other type was Dura-Base Composite Mat. The feasibility study of using the Dura-Base Composite Mat System for the drill site construction was demonstrated with various applied load areas from 6 inches to 10 ft of diameter and soil types.

8.1.2 Development of a Systems Approach to Technology Evaluation

In order to integrate current and new EFD technologies into a viable drilling system compatible with environmentally sensitive areas and finally to suggest a small number of systems that should be particularly attractive for a given site, a quantitative decision tool has been developed based on a systems analysis in Section 5. An optimization scheme is suggested based on a combination of multi-attribute utility theory and exhaustively enumerating all possible technology combinations to provide a quantitative rationale and suggest the best set of systems according to a set of attribute, with the relative importance of the different attribute defined by the decision-maker.

Since an optimal system for a specific site would be based on subjectively assessed data, there can be considerable uncertainty about the input parameters used. Therefore, a sensitivity analysis was conducted using a case study to address this problem in Section 6. The overall procedure is briefly illustrated as follows:

Step 1: Identify the main subsystems, subsets, and technologies within each subset.

Step 2: Define attributes and develop attribute scales to evaluate technologies.

Step 3: Assign scores to all technologies using the attribute scales.

Step 4: For each attribute, calculate the overall attribute score of a system by adding the technology scores or selecting the minimum technology score.

Step 5: For each attribute and in order to homogenize the scores, develop a "utility function (u_i)" to convert the overall dimensional score of a system (e.g., \$, acres, and grades) into a non-dimensional utility value (between 0 and 1) of the system that reflects the decision-maker(s) value.

Step 6: Decide on a weight factor (k_i) for each attribute (i^{th}).

Step 7: Calculate the overall utility score of the system as "$\sum k_i u_i$."

Step 8: Use optimization technique to evaluate all possible systems and to find the best system for a specific site.

Step 9: Conduct a sensitivity analysis to examine the impacts of possible changes in the attribute scores and weight factors on the optimal system.

Step 10: Suggest a small number of systems that should be attractive for a given site.

8.1.3 A Case Study with Pre-Specified Systems

An application of the proposed approach was described by conducting a case study in Green Lake at McFaddin, TX. The main purpose of this case study was to test the proposed technology evaluation protocol in a real site and then to refine the protocol. The results of the case study which provided a more logical and comprehensive approach that maximized the economic and environmental goals of both the landowner and the oil company leaseholder were fully described in Section 6.

8.1.4 Development of a Prototype of a Web-Based Application

A prototype of a web-based application has been developed to help decision-makers easily follow the proposed technology evaluation procedure and then select an optimal drilling system for a specific site. The web-based application can also help to manage used input parameters permanently if a central repository is maintained regularly so that decision-makers or drilling operators can easily retrieve a previously designed well model for their future operations in different ecosystems.

8.2 Conclusions

Throughout this research, parametric study of foundations for drill sites is conducted, a systems optimization approach is suggested based on a combination of multi-attribute utility theory and exhaustive search optimization, and a web-based decision optimization tool is developed based on the proposed systems approach to technology evaluation. The proposed technology evaluation protocol is designed to help decision-makers with their choices of EFD technology in onshore drilling operations. However, the approach used in this research does have some limitations. The crucial limitation is that the computational burden of the procedure may become prohibitive for problems with a large number of decision variables. One possible way to resolve this problem in this research is if the analyst can identify subsets that will always select the same technology for any weight combinations, the elimination of those subsets from the original thirteen subsets can significantly reduce computational burdens in future steps and also simplify the graphical display of sensitivity results.

Since the suggested systems would be based on subjectively assessed data, there can be considerable uncertainty about the input parameters used. In the case study described in Section 6, the most suggested optimal solution (SET 1) is only optimal for about 42% of the weight combinations tested, which implies that different systems would be suggested for 58% of plausible weight combinations. It indicates that the sensitivity analysis conducted in Section 6.4 is a worthy topic for further investigation. The sensitivity of the optimal solution to the input parameters and the effects of the uncertainty of those parameters were examined and an approach that can be used to conduct a sensitivity analysis for multi-attribute technology selection problems was presented in Section 6.4. Although the focus of the sensitivity analysis presented in this research has been on sensitivity to weights and overall input attribute scores, the approach could also be applied to sensitivity to risk attitude (i.e., risk-neutral, risk-averse, and risk-seeking) or to other input parameters. The sensitivity to those unapplied input parameters is an important area for further research.

The petroleum industries have several candidate selection methods for some technologies and subsets. For example, they have some common concepts in candidate selection for a managed pressure drilling operation (Rehm et al. 2008). However, these selection methods are only available for a specific technology or subset, not for an entire drilling system.

In conclusion, the technology selection process for a drilling system is mainly based on managerial experience, but a more logical approach based on systems analysis is possible, and additional research could reduce the amount of effort required to use systems analysis for technology selection in a drilling project. Even though the technology selection process can be computationally burdensome, it can be very helpful to decision-makers in refining their decisions on a more scientific basis.

8.3 Future Tasks

In order to encourage petroleum industry people to use environmentally friendly foundations such as elevated platforms and composite mat systems more often for their drilling sites instead of using gravel pads, it is suggested that more specific feasibility study of using those methods including cost estimations be conducted.

Estimating input values for available technologies are a very difficult step to proceed with the quantitative approach suggested in this research. The outcomes of the process should be brought into a question without having the adequate input values. Missing input information introduces additional errors into the analysis because the missing information represents another assumption that must be made to proceed with the analysis (Rehm et al. 2008). One of the future research tasks is to get more EFD subject matter experts' inputs and feedbacks to make the proposed technology selection procedure easier and quicker with more confidence.

Even though exhaustive search optimization used in this research is a simple, practical, and very robust method, it is not recommended for a larger problem due to the computing time. Another future research task is to develop advanced optimization methods that can efficiently search the entire (not truncated) solution space using only standard personal computers. In order to encourage oil industry people to use the proposed technology selection procedure for their real works, it seems to be an essential task.

In Section 6.4, the sensitivity analysis was conducted focused on sensitivity to weights and overall input attribute scores. More extensive sensitivity analyses can be applied to sensitivity to risk attitude (i.e., risk-neutral, risk-averse, and risk-seeking), to the utility function for each attribute, or to other input parameters. The sensitivity to those unapplied input parameters is an important area for further research.

Another future research task is to keep the web-based application developed in this research updated as the technology evaluation protocol has been continuously refined by EFD subject matter experts' comments and feedbacks. This is very important task to encourage oil field professionals to try the application for their real works with more confidence.

The single and multi-attribute utility values used in this research represent average estimates that reflect deterministic conditions possibly containing significant and sometimes varying uncertainty components. A new uncertainty-based methodology can be proposed as a future research task for complementing the current technology evaluation protocol by introducing an approach capable of managing properly existing types of evidence (i.e., data, numerical models, and experts' inputs) and their corresponding uncertainty levels. Moreover, it can be proposed to formally account for the causal uncertainty propagation in the common process of a drilling operation, selection of an optimal EFD system, and the assessment of the corresponding environmental impact.

Medina-Cetina et al. (2008) suggested an uncertainty-based system based on causal probability and it will help to identify and quantify major and minor sources of uncertainty, which will propagate towards an uncertainty-based risk index. A risk index will serve as the reference parameter for the selection of an optimal EFD system and will also provide a logical and transparent manner to investigate further key information sources. For instance, two drilling systems with similar overall utility scores may differ significantly in their corresponding uncertainty measures and consequently on the potential losses associated with the selection of one of them. By using a risk index instead, based on default and knowledge building probability distributions (Medina-Cetina et al. 2008), it will be possible to differentiate the impact of new evidence or simply the addition of new information into a system so that an optimal drilling system selected for a specific site can be driven not only by weight combinations, but also by the proper uncertainty management leading to the less uncertain system.

REFERENCES

ADSC (1999). *Drilled Shafts: Construction Procedures and Design Methods*, The International Association of Foundation Drilling (ADSC), Dallas, TX.

API RP2A-WSD (2000). *American Petroleum Institute Design Code*, API, Washington, DC.

API RP2A-LRFD (2003). *American Petroleum Institute Design Code*, API, Washington, DC.

Briaud, J.-L. (1992). *The Pressuremeter*, A.A. Balkema, Rotterdam, The Netherlands

Briaud, J. L. (1997). "SALLOP: Simple approach for lateral loads on piles." *Journal of Geotechnical and Geoenvironmental Engineering*, 123(10), 958.

Call, H., and Merkhofer, M. (1988). "A multi-attribute utility analysis model for ranking superfund sites." *Superfund 88: Proceedings of the 9th National Conference*, Washington, DC, 44-54.

Clemen, R. T., and Reilly, T. (2001). *Making Hard Decisions with DecisionTools*, Duxbury, Pacific Grove, CA.

Cover, K. S., Verbunt, J. P. A., de Munck, J. C., and van Dijk, B. W. (2007). "Fitting a single equivalent current dipole model to MEG data with exhaustive search optimization is a simple, practical and very robust method given the speed of modern computers." *International Congress Series*, 1300, 121-124.

Dyke, K. V. (1997). *Fundamentals of Petroleum*, Petroleum Extension Service, Austin, TX.

Guikema, S., and Milke, M. (1999). "Quantitative decision tools for conservation programme planning: Practice, theory and potential." *Environmental Conservation*, 26(03), 179-189.

Guikema, S. D., and Milke, M. W. (2003). "Sensitivity analysis for multi-attribute project selection problems." *Civil Engineering and Environmental Systems*, 20(3), 143-162.

Hardaker, J. B. (2004). *Coping with Risk in Agriculture*, CABI Publishing, Cambridge, MA.

Harrison, W. (2005). "Current environmental practices in petroleum exploration & production." *Energy and the Environment: A Partnership that Works: The Actual Impacts of Oil and Gas Exploration and Development on our Environment*, L. C. Gerhard, V. J. Yannacone jr, and C. J. Smith, eds., American Association of Petroleum Geologists, Tulsa, 23.

Hovorka, S. D., Doughty, C., Knox, P. R., Green, C. T., Pruess, K., and Benson, S. M. (2001). "Evaluation of brine-bearing sands of the Frio formation, upper Texas Gulf Coast for geological sequestration of CO_2." *First National Conference on Carbon Sequestration*, Washington, DC, May 14-17.

Jimenez, A., Rios-Insua, S., and Mateos, A. (2003). "A decision support system for multiattribute utility evaluation based on imprecise assignments." *Decision Support Systems*, 36(1), 65-79.

Kadaster, A. G., and Millheim, K. K. (2004). "Onshore mobile platform: A modular platform for drilling and production operations in remote and environmentally sensitive areas." *IADC/SPE Drilling Conference*, Dallas, TX, 405-421.

Keeney, R. L. (1974). "Multiplicative utility functions." *Operations Research*, 22(1), 22-34.

Keeney, R. L. (1992). *Value-Focused Thinking: A Path to Creative Decisionmaking*, Harvard University Press, Cambridge, MA.

Keeney, R. L., and Raiffa, H. (1976). *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*, Cambridge University Press, New York, NY.

KNR. (1999). *Design Criteria for Railroad Bridges*, Korean National Railroad (KNR), Republic of Korea.

Medina-Cetina, Z., Feinmberg, J., and Nadim, F. (2008). "Probabilistic Threshold Definition of Early Warning Systems to Natural Hazards." *33rd International Geological Congress*, Oslo, Norway, August 6-14.

Rehm, B., Schubert, J., Haghshenas, A., Paknejad, A., and Hughes, J. (2008). *Managed Pressure Drilling*, Gulf Publishing Company, Houston, TX.

Rogers, J. D., Knoll, B., Haut, R., McDole, B., and Deskins, G. (2006). "Assessments of Technologies for Environmentally Friendly Drilling Project: Land-Based Operations." Texas A&M University Environmentally Friendly Drilling report.

RSMeans. (2006). *Heavy Construction Cost Data*, RS Means Company, Kingston, MA.

Supplemental Sources

Allett, E. J. (1986). "Environmental impact assessment and decision analysis." *The Journal of the Operational Research Society*, 37(9), 901-910.

Baecher, G. B., and Christian, J. T. (2003). *Reliability and Statistics in Geotechnical Engineering*, John Wiley and Sons, Hoboken, NJ.

Butler, J., Morrice, D. J., and Mullarkey, P. W. (2001). "A multiple attribute utility theory approach to ranking and selection." *Management Science*, 47(6), 800-816.

Corner, J. L., and Kirkwood, C. W. (1991). "Decision analysis applications in the operations research literature, 1970-1989." *Operations Research*, 39(2), 206-219.

Crawford, D. M., Huntzinger, B. C., and Kirkwood, C. W. (1978). "Multiobjective decision analysis for transmission conductor selection." *Management Science*, 24(16), 1700-1709.

Freeze, R. A., Massmann, J., Smith, L., Sperling, T., and James, B. (1990). "Hydrogeological decision analysis: 1. A framework." *Ground Water*, 28(5), 738-766.

Freeze, R. A., James, B., Massmann, J., Sperling, T., and Smith, L. (1992). "Hydrogeological decision analysis: 4. The concept of data worth and its use in the development of site investigation strategies." *Ground Water*, 30(4), 574-588.

Golab, K., Kirkwood, C. W., and Sicherman, A. (1981). "Selecting a portfolio of solar energy projects using multiattribute preference theory." *Management Science*, 27(2), 174-189.

Gray, R. L., and Cambridge, V. J. (1989). "Method for optimization of drilling costs." US Patent 4,845,628.

Guikema, S. D., and Pate-Cornell, M. E. (2002). "Component choice for managing risk in engineered systems with generalized risk/cost functions." *Reliability Engineering and System Safety*, 78(3), 227-238.

Insua, D. R. (1990). *Sensitivity Analysis in Multi-objective Decision Making*, Springer-Verlag, New York, NY.

Insua, D. R., and French, S. (1991). "A framework for sensitivity analysis in discrete multi-objective decision-making." *European Journal of Operational Research*, 54(2), 176-190.

Jonsbraten, T. W. (1998). "Oil field optimization under price uncertainty." *The Journal of the Operational Research Society*, 49(8), 811-818.

Keeney, R. L., Lathrop, J. F., and Sicherman, A. (1986). "An analysis of Baltimore Gas and Electric Company's technology choice." *Operations Research*, 34(1), 18-39.

Keeney, R. L., McDaniels, T. L., and Swoveland, C. (1995). "Evaluating improvements in electric utility reliability at British Columbia Hydro." *Operations Research*, 43(6), 933-947.

Keeney, R. L., and Sicherman, A. (1983). "Illustrative comparison of one utility's coal and nuclear choices." *Operations Research*, 31(1), 50-83.

Keeney, R. L., and Winterfeldt, D. (1994). "Managing nuclear waste from power plants." *Risk Analysis*, 14(1), 107-130.

Kim, J., Hobbs, B. F., and Koonce, J. F. (2007). "Analysis of the sensitivity of decision analysis results to errors and simplifications in problem structure: Application to Lake Erie Ecosystem Management." *IEEE Transactions on Systems, Man and Cybernetics, Part A,* 37(4), 505-518.

Martello, S., and Toth, P. (1990). *Knapsack Problems: Algorithms and Computer Implementations*, John Wiley & Sons, New York, NY.

Massmann, J., Freeze, R. A., Smith, L., Sperling, T., and James, B. (1991). "Hydrogeological decision analysis: 2. Applications to ground-water contamination." *Ground Water*, 29(4), 536-548.

Mateos, A., Rios-Insua, S., and Gallego, E. (2001). "Postoptimal analysis in a multi-attribute decision model for restoring contaminated aquatic ecosystems." *The Journal of the Operational Research Society*, 52(7), 727-738.

North, D. W., and Stengel, D. N. (1982). "Decision analysis of program choices in magnetic fusion energy development." *Management Science*, 28(3), 276-288.

Onwubolu, G. C., and Clerc, M. (2004). "Optimal path for automated drilling operations by a new heuristic approach using particle swarm optimization." *International Journal of Production Research*, 42(3), 473-491.

Proll, L. G., Insua, D. R., and Salhi, A. (1993). "Mathematical programming and the sensitivity of multi-criteria decisions." *Annals of Operations Research*, 43(1-4), 109-122.

Reinhold, W. B., and Close, D. A. "Drilling optimization--The driller's role." *SPE Drilling & Completion1997*, 12(1), 5-12.

Reynolds, W. W. (1986). "Economic analysis of drilling plans and contractors by use of a drilling systems approach." *J. Pet. Technol*, 38(8).

Salkin, H. M., and de Kluyver, C. A. (1975). "The knapsack problem: a survey." *Naval Research Logistics Quarterly*, 22(1), 127-44.

Shachter, R. D. (1986). "Evaluating influence diagrams." *Operations Research*, 34(6), 871-882.

Sperling, T., Freeze, R. A., Massmann, J., Smith, L., and James, B. (1992). "Hydrogeological decision analysis: 3. Application to design of a ground-water control system at an open pit mine." *Ground Water*, 30(3), 376-389.

Triantaphyllou, E., and Sanchez, A. (1997). "A sensitivity analysis approach for some deterministic multi-criteria decision-making methods." *Decision Sciences*, 28(1), 151-194.

APPENDIX A

PILE FOUNDATION DESIGNS

▣ Design Condition

Unfactored vertical loads = 1000.000 kips

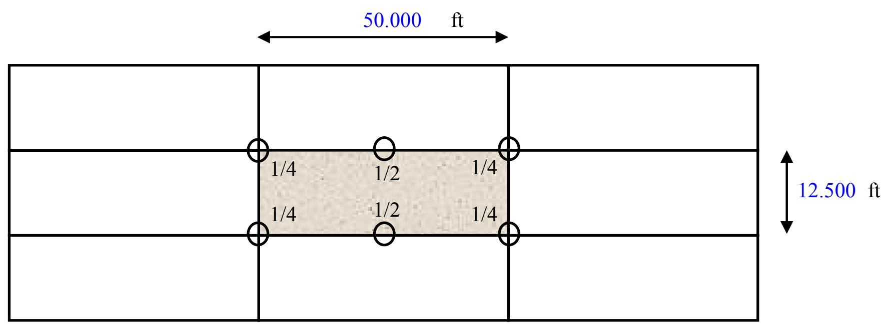
65 % of the vertical loads were distributed across 6 modules,

$$\therefore \frac{1000.000 \times 0.650}{6.000} = 108.333 \text{ kips (per module)}$$

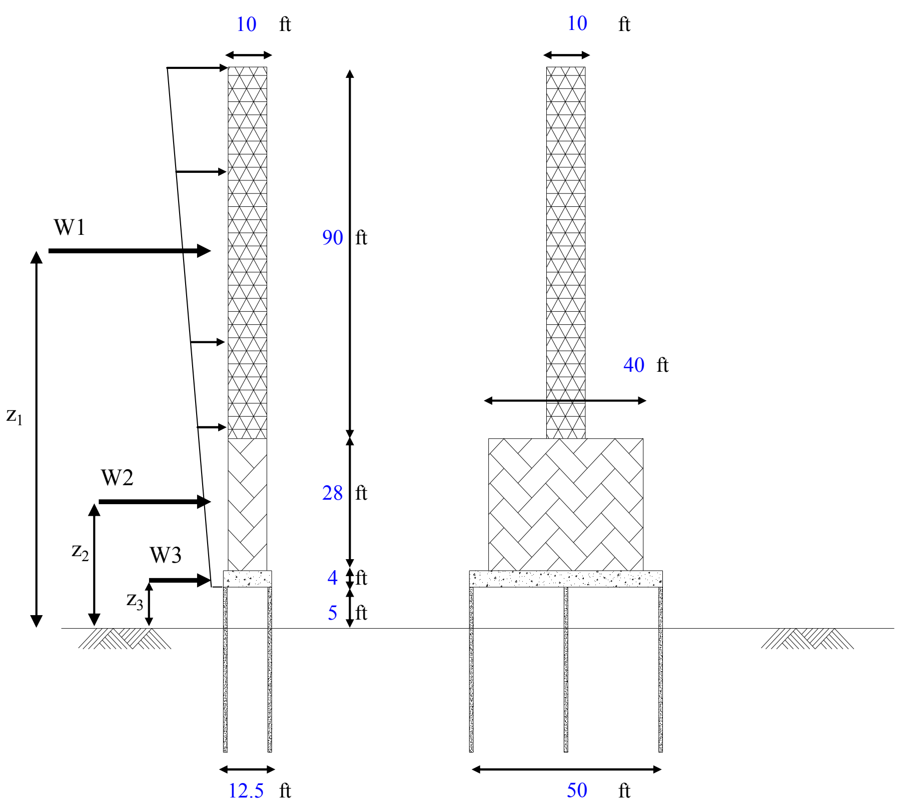
Unfactored dead load (30% of the total vertical loads) = 32.500 kips (per module)

Unfactored live load (70% of the total vertical loads) = 75.833 kips (per module)

▣ Module Layout



▣ Wind Force Calculations (API RP2A - LRFD)



[Cross section of the platform for the one module in design]

z_1	=	82 ft	A1	=	900.000	ft^2	Normal V	=	25 m/s
z_2	=	23 ft	A2	=	1120.000	ft^2	Extreme V	=	49 m/s
z_3	=	7 ft	A3	=	200.000	ft^2	Cs	=	1.0
ρ	=	0.00238 $lb \cdot sec^2/ft^4$							

For the W1 (distance from the top of the pile = 77 ft),

V1	=	$V(1hr, z_R)(z_1/z_R)^{0.125}$	=	$(25\ m/sec)(3.3\ ft/sec)(82/33)^{0.125}$	=	92.441	ft/sec
W1	=	$(\rho/2)(V1)^2CsA$	=	$(0.00238/2)(92.441)^2\ (1)(900)$	=	**9.152**	kips

For the extreme We1,

Ve1	=	$V(1hr, z_R)(z_1/z_R)^{0.125}$	=	$(49\ m/sec)(3.3\ ft/sec)(82/33)^{0.125}$	=	181.185	ft/sec
We1	=	$(\rho/2)(Ve1)^2CsA$	=	$(0.00238/2)(181.185)^2\ (1)(900)$	=	**35.159**	kips

For the W2 (distance from the top of the pile = 18 ft),

V2	=	$V(1hr, z_R)(z_2/z_R)^{0.125}$	=	$(25\ m/sec)(3.3\ ft/sec)(23/33)^{0.125}$	=	78.860	ft/sec
W2	=	$(\rho/2)(V2)^2CsA$	=	$(0.00238/2)(78.86)^2\ (1)(1120)$	=	**8.289**	kips

For the extreme We2,

Ve2	=	$V(1hr, z_R)(z_2/z_R)^{0.125}$	=	$(49\ m/sec)(3.3\ ft/sec)(23/33)^{0.125}$	=	154.565	ft/sec
We2	=	$(\rho/2)(Ve2)^2CsA$	=	$(0.00238/2)(154.565)^2\ (1)(1120)$	=	**31.841**	kips

For the W3 (distance from the top of the pile = 2 ft),

V3	=	$V(1hr, z_R)(z_3/z_R)^{0.125}$	=	$(25\ m/sec)(3.3\ ft/sec)(7/33)^{0.125}$	=	67.964	ft/sec
W3	=	$(\rho/2)(V3)^2CsA$	=	$(0.00238/2)(67.964)^2\ (1)(200)$	=	**1.099**	kips

For the extreme We3,

Ve3	=	$V(1hr, z_R)(z_3/z_R)^{0.125}$	=	$(49\ m/sec)(3.3\ ft/sec)(7/33)^{0.125}$	=	133.209	ft/sec
We3	=	$(\rho/2)(Ve3)^2CsA$	=	$(0.00238/2)(133.209)^2\ (1)(200)$	=	**4.223**	kips

▣ Load Combinations (API RP2A - LRFD)

$Q_1 = 1.3DL + 1.5LL$

$Q_2 = 1.3DL + 1.5LL + 1.2W_o$

$Q_3 = 1.1DL + 1.1LL + 1.35W_e$

where, DL = dead loads

LL = live loads

W_o = wind load for normal condition

W_e = extreme wind load (typically 100 yrs return period)

$Q_1 = 1.30 \times DL + 1.50 \times LL$

$\Sigma V = 1.30 \times 32.500 + 1.50 \times 75.833 = 156.000$ kips

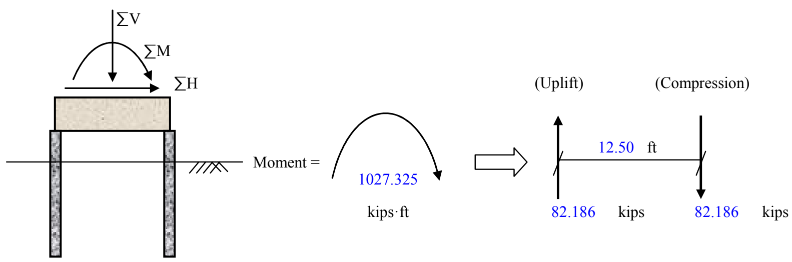
$Q_2 = 1.30 \times DL + 1.50 \times LL + 1.20 \times W_o$

$\Sigma V = 1.30 \times 32.500 + 1.50 \times 75.833 = 156.000$ kips

$\Sigma H = 1.20 \times (9.152 + 8.289 + 1.099) = 22.248$ kips

$\Sigma M = 1.20 \times (9.152 \times 77.000 + 8.289 \times 18.000$

$+ 1.099 \times 2.000) = 1027.325$ kips·ft



Hence,

Total compressive force for one pile = 156.000 / 2 + 82.186 / 3 = **105.395** kips

Total uplift force for one pile = 156.000 / 2 − 82.186 / 3 = **50.605** kips

∴ No uplift force!

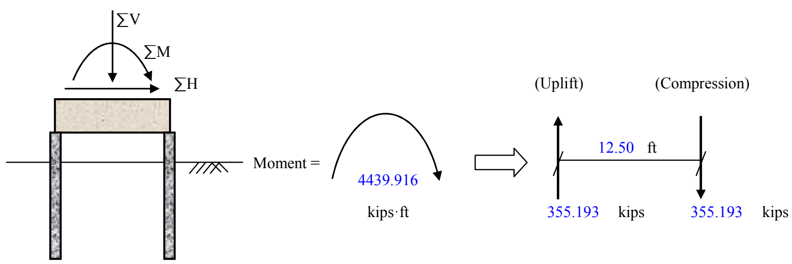
$Q_3 = 1.10 \times DL + 1.10 \times LL + 1.35 \times W_e$

$\Sigma V = 1.10 \times 32.500 + 1.10 \times 75.833 = 119.166$ kips

$\Sigma H = 1.35 \times (35.159 + 31.841 + 4.223) = 96.151$ kips

$\Sigma M = 1.35 \times (35.159 \times 77.000 + 31.841 \times 18.000$

$+ 4.223 \times 2.000) = 4439.916$ kips·ft

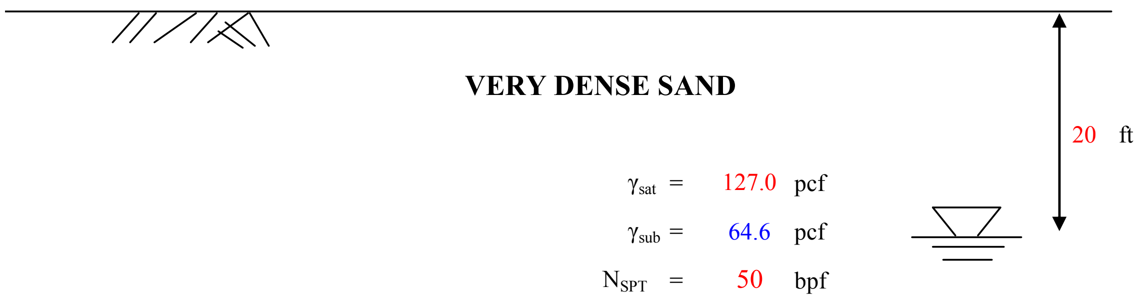


Hence,

Total compressive force for one pile = 119.166 / 2 + 355.193 / 3 = **177.981** kips

Total uplift force for one pile = 119.166 / 2 − 355.193 / 3 = **-58.815** kips

▣ Soil Condition



▣ Vertical Capacity of the Pile (RP2A)

a. Unit end bearing capacity

$q_p = P_o' \cdot N_q$

where: P_o' = effective overburden pressure at the point in question

N_q = dimensionless bearing capacity factor = 50 (very dense)

b. Unit skin friction capacity

$fs = K \cdot P_o' \cdot \tan\delta$

where: K = dimensionless coefficient of lateral earth pressure (ratio of horizontal to vertical normal effective stress)

= 1.00 (full displacement piles, plugged or closed end)

δ = friction angle between the soil and pile wall = 35 ° (very dense)

c. Ultimate vertical capacity

$Qu = Qp + Qs = q_pAp + fsAs$

where: Ap = gross end area of pile = $\pi D^2/4$ (where, D: diameter of pile)

As = side surface area of pile = πDL (where, L: length of pile)

1. Operating Environmental Conditions

Resistance Factors, φ = 0.7

Diameter, D = 12 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	24.936	0.222	3.487	28.423	19.896	2.441
10	1270.000	63.500	49.873	0.445	13.980	63.853	44.697	9.786
15	1905.000	95.250	74.809	0.667	31.432	106.241	74.369	22.002
20	2540.000	127.000	99.746	0.889	55.858	155.604	108.923	39.101
25	2863.000	143.150	112.430	1.090	85.577	198.007	138.605	59.904
30	3186.000	159.300	125.114	1.261	118.846	243.960	170.772	83.192
35	3509.000	175.450	137.798	1.414	155.531	293.329	205.330	108.872
40	3832.000	191.600	150.482	1.538	193.230	343.712	240.598	135.261

Diameter, D = 16 inches

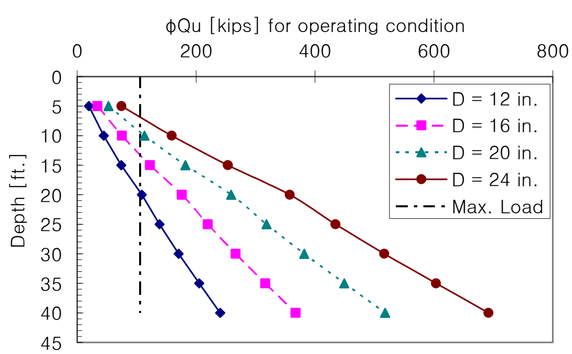
Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	44.331	0.222	4.650	48.981	34.287	3.255
10	1270.000	63.500	88.663	0.445	18.640	107.303	75.112	13.048
15	1905.000	95.250	132.994	0.667	41.909	174.903	122.432	29.336
20	2540.000	127.000	177.325	0.889	74.477	251.802	176.261	52.134
25	2863.000	143.150	199.875	1.090	114.103	313.978	219.785	79.872
30	3186.000	159.300	222.425	1.261	158.462	380.887	266.621	110.923
35	3509.000	175.450	244.974	1.414	207.375	452.349	316.644	145.163
40	3832.000	191.600	267.524	1.538	257.641	525.165	367.616	180.349

Diameter, D = 20 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	69.268	0.222	5.812	75.080	52.556	4.068
10	1270.000	63.500	138.536	0.445	23.300	161.836	113.285	16.310
15	1905.000	95.250	207.803	0.667	52.386	260.189	182.132	36.670
20	2540.000	127.000	277.071	0.889	93.096	370.167	259.117	65.167
25	2863.000	143.150	312.305	1.090	142.628	454.933	318.453	99.840
30	3186.000	159.300	347.539	1.261	198.077	545.616	381.931	138.654
35	3509.000	175.450	382.773	1.414	259.219	641.992	449.394	181.453
40	3832.000	191.600	418.006	1.538	322.051	740.057	518.040	225.436

Diameter, D = 24 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	99.746	0.222	6.974	106.720	74.704	4.882
10	1270.000	63.500	199.491	0.445	27.960	227.451	159.216	19.572
15	1905.000	95.250	299.237	0.667	62.863	362.100	253.470	44.004
20	2540.000	127.000	398.982	0.889	111.715	510.697	357.488	78.201
25	2863.000	143.150	449.719	1.090	171.154	620.873	434.611	119.808
30	3186.000	159.300	500.456	1.261	237.693	738.149	516.704	166.385
35	3509.000	175.450	551.192	1.414	311.063	862.255	603.579	217.744
40	3832.000	191.600	601.929	1.538	386.461	988.390	691.873	270.523



2. Extreme Environmental Conditions

Resistance Factors, φ = 0.8
0.7 (uplift)

Diameter, D = 12 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	24.936	0.222	3.487	28.423	22.738	2.441
10	1270.000	63.500	49.873	0.445	13.980	63.853	51.082	9.786
15	1905.000	95.250	74.809	0.667	31.432	106.241	84.993	22.002
20	2540.000	127.000	99.746	0.889	55.858	155.604	124.483	39.101
25	2863.000	143.150	112.430	1.090	85.577	198.007	158.406	59.904
30	3186.000	159.300	125.114	1.261	118.846	243.960	195.168	83.192
35	3509.000	175.450	137.798	1.414	155.531	293.329	234.663	108.872
40	3832.000	191.600	150.482	1.538	193.230	343.712	274.970	135.261

Diameter, D = 16 inches

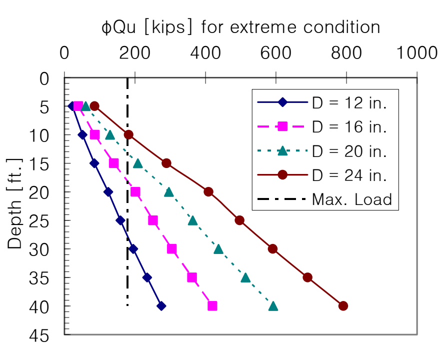
Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	44.331	0.222	4.650	48.981	39.185	3.255
10	1270.000	63.500	88.663	0.445	18.640	107.303	85.842	13.048
15	1905.000	95.250	132.994	0.667	41.909	174.903	139.922	29.336
20	2540.000	127.000	177.325	0.889	74.477	251.802	201.442	52.134
25	2863.000	143.150	199.875	1.090	114.103	313.978	251.182	79.872
30	3186.000	159.300	222.425	1.261	158.462	380.887	304.710	110.923
35	3509.000	175.450	244.974	1.414	207.375	452.349	361.879	145.163
40	3832.000	191.600	267.524	1.538	257.641	525.165	420.132	180.349

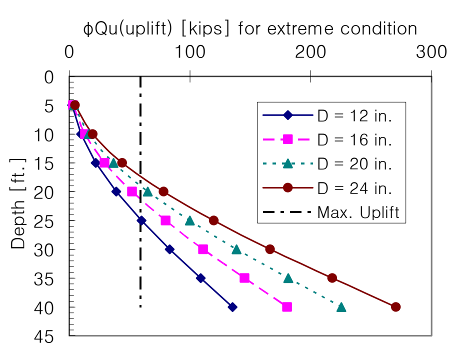
Diameter, D = 20 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	69.268	0.222	5.812	75.080	60.064	4.068
10	1270.000	63.500	138.536	0.445	23.300	161.836	129.469	16.310
15	1905.000	95.250	207.803	0.667	52.386	260.189	208.151	36.670
20	2540.000	127.000	277.071	0.889	93.096	370.167	296.134	65.167
25	2863.000	143.150	312.305	1.090	142.628	454.933	363.946	99.840
30	3186.000	159.300	347.539	1.261	198.077	545.616	436.493	138.654
35	3509.000	175.450	382.773	1.414	259.219	641.992	513.594	181.453
40	3832.000	191.600	418.006	1.538	322.051	740.057	592.046	225.436

Diameter, D = 24 inches

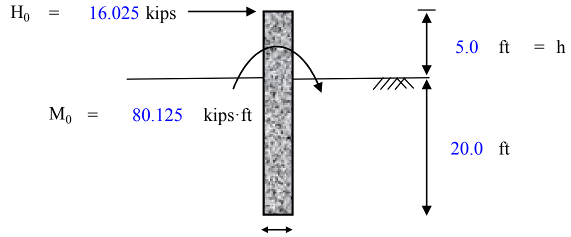
Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0
5	635.000	31.750	99.746	0.222	6.974	106.720	85.376	4.882
10	1270.000	63.500	199.491	0.445	27.960	227.451	181.961	19.572
15	1905.000	95.250	299.237	0.667	62.863	362.100	289.680	44.004
20	2540.000	127.000	398.982	0.889	111.715	510.697	408.558	78.201
25	2863.000	143.150	449.719	1.090	171.154	620.873	496.698	119.808
30	3186.000	159.300	500.456	1.261	237.693	738.149	590.519	166.385
35	3509.000	175.450	551.192	1.414	311.063	862.255	689.804	217.744
40	3832.000	191.600	601.929	1.538	386.461	988.390	790.712	270.523





▣ Horizontal Capacity of the Pile (SALLOP)

<u>For free head,</u>



$E_0 = 4 \cdot N_{SPT} = 4 \times 50 = 200.000$ tsf $= 400.000$ ksf

$K = 2.3 \cdot E_0 = 2.3 \times 400.000 = 920.000$ ksf

$E =$ 2.90E+07 psi (Steel pile) = 4.18E+06 ksf

$I = (\pi D_o^4)/64 - (\pi D_i^4)/64 = 1113.470$ in.^{4} $= 0.05370$ ft^4

$l_0 = (4EI/K)^{1/4} = (4 \times$ 4.18E+06 $\times 0.05370 / 920.000)^{1/4} = 5.588$ ft

where, E_0 = pressuremeter load modulus

K = soil spring constant

E = modulus of elasticity for the pile material

I = moment of inertia for the pile , H_0 = horizontal load

l_0 = transfer length , M_0 = applied moment at the ground surface

Embedded pile length, L = 20.0 ft $\geq 3 \cdot l_o$ = 16.764 ft <u>**∴ long flexible pile!**</u>

1. Lateral Pile Capacity

The zero-shear depth D_v is obtained by setting V (shear force) = 0;

$D_v = l_0 \cdot \tan^{-1}\{1/(1+2h/l_0)\} = 1.923$ ft

$P_L = 0.5 \cdot N_{SPT} = 0.5 \times 50 = 25.000$ tsf $= 50.000$ ksf

$H_{ou} = 0.75 \cdot P_L \cdot B \cdot D_v = 0.75 \times 50.000 \times 1.667 \times 1.923 = 120.188$ kips

$\varphi \cdot H_{ou} = 0.750 \times 120.188 = 90.141$ kips $> H_0 = 16.025$ kips <u>**∴ O.K!**</u>

where, D_v = zero-shear depth

P_L = preboring pressuremeter limit pressure within D_v

H_{ou} = lateral capacity of pile

2. Lateral Movement at The Ground Surface

$y_0 = (1+h/l_0) \cdot H_0 \cdot l_0^3 / (2EI) = 0.012$ ft $= 0.144$ in. < 0.500 in. <u>**∴ O.K!**</u>

3. Lateral Movement at The Pile Head

$\delta = \{(1+h/l_0)^3 + 0.5\} \cdot H_0 \cdot l_0^3 / (3EI) = 0.030$ ft $= 0.360$ in. < 0.500 in. <u>**∴ O.K!**</u>

4. Maximum Bending Moment

Maximum bending moment can be found by finding the value of Z_{max} which satisfied V = 0.

$Z_{max} = D_v = 1.923$ ft

$M_{max} = 0.5 \cdot H_0 l_0 \cdot \exp(-Z_{max}/l_0) \cdot \sqrt{\{(1+2h/l_0)^2 + 1\}}$

$= 94.050$ kips·ft

5. Check for Creep

$P = K \cdot y_0 = 920.000 \times 0.012 = 11.040$ kips/ft

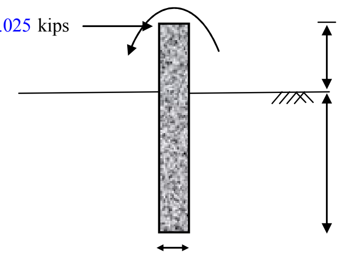
$Pa = P / B = 11.040 / 1.667 = 6.624$ ksf

where, P = the load per unit length of pile

Pa = average corresponding pressure

$F.S = P_L / Pa = 50.000 / 6.624 = 7.548 > 2$ <u>**∴ O.K!**</u>

For fixed head,



$E_0 = 4 \cdot N_{SPT} = 4 \times 50 = 200.000$ tsf $= 400.000$ ksf

$K = 2.3 \cdot E_0 = 2.3 \times 400.000 = 920.000$ ksf

$E = 2.90E+07$ psi (Steel pile) $= 4.18E+06$ ksf

$I = (\pi D_o^4)/64 - (\pi D_i^4)/64 = 1113.470$ in.^{4} $= 0.05370$ ft^4

$l_0 = (4EI/K)^{1/4} = (4 \times 4.18E+06 \times 0.05370 / 920.000)^{1/4} = 5.588$ ft

$M_h = -0.5 \cdot (1 + h/l_0) \cdot H_0 \cdot l_0 = -84.836$ kips·ft (↶)

where, E_0 = pressuremeter load modulus
K = soil spring constant
E = modulus of elasticity for the pile material
I = moment of inertia for the pile , H_0 = horizontal load
l_0 = transfer length , M_h = applied moment at the pile head

Embedded pile length, L = 20.0 ft $\geq 3 \cdot l_o$ = 16.764 ft **<u>∴ long flexible pile!</u>**

1. Lateral Pile Capacity

The zero-shear depth D_v is obtained by setting V (shear force) = 0;

$D_v = l_0 \cdot \tan^{-1}(l_0/h) = 4.699$ ft

$P_L = 0.5 \cdot N_{SPT} = 0.5 \times 50 = 25.000$ tsf $= 50.000$ ksf

$H_{ou} = 0.75 \cdot P_L \cdot B \cdot D_v = 0.75 \times 50.000 \times 1.667 \times 4.699 = 293.688$ kips

$\varphi \cdot H_{ou} = 0.750 \times 293.688 = 220.266$ kips $> H_0 = 16.025$ kips **<u>∴ O.K!</u>**

where, D_v = zero-shear depth
P_L = preboring pressuremeter limit pressure within D_v
H_{ou} = lateral capacity of pile

2. Lateral Movement at The Ground Surface

$y_0 = (1+h/l_0) \cdot H_0 \cdot l_0^3 / (4EI) = 0.006$ ft $= 0.072$ in. < 0.500 in. **<u>∴ O.K!</u>**

3. Lateral Movement at The Pile Head

$\delta = \{(1+h/l_0)^3 + 2\} \cdot H_0 \cdot l_0^3 / (12EI) = 0.009$ ft $= 0.108$ in. < 0.500 in. **<u>∴ O.K!</u>**

4. Maximum Bending Moment

Maximum bending moment can be found by finding the value of Z_{max} which satisfied V = 0.

$Z_{max} = D_v = 4.699$ ft

$M_{max} = 0.5 \cdot H_0 l_0 \cdot \exp(-(Z_{max}/l_0) \cdot \sqrt{\{1+(h/l_0)^2\}}$

$= 25.914$ kips·ft

5. Check for Creep

$P = K \cdot y_0 = 920.000 \times 0.006 = 5.520$ kips/ft

$Pa = P / B = 5.520 / 1.667 = 3.312$ ksf

where, P = the load per unit length of pile
Pa = average corresponding pressure

$F.S = P_L / Pa = 50.000 / 3.312 = 15.097 > 2$ **<u>∴ O.K!</u>**

▣ Load Combinations (API RP2A - WSD)

Q_1 = DL + LL

Q_2 = DL + LL + W_o

Q_3 = DL + LL + W_e

where, DL = dead loads

LL = live loads

W_o = wind load for normal condition

W_e = extreme wind load (typically 100 yrs return period)

Q_1 = 1.00 × DL + 1.00 × LL

∑V = 1.00 × 32.500 + 1.00 × 75.833 = 108.333 kips

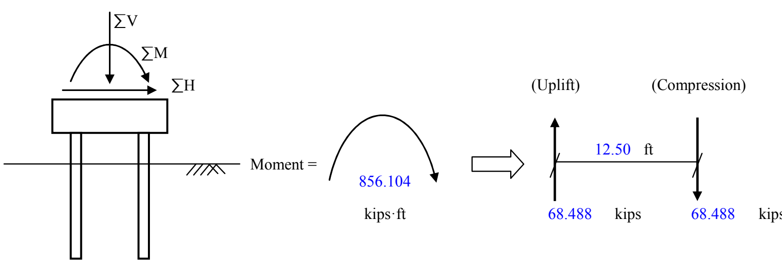
Q_2 = 1.00 × DL + 1.00 × LL + 1.00 × W_o

∑V = 1.00 × 32.500 + 1.00 × 75.833 = 108.333 kips

∑H = 1.00 × (9.152 + 8.289 + 1.099) = 18.540 kips

∑M = 1.00 × (9.152 × 77.000 + 8.289 × 18.000

+ 1.099 × 2.000) = 856.104 kips·ft



Hence,

Total compressive force for one pile = 108.333 / 2 + 68.488 / 3 = **76.996** kips

Total uplift force for one pile = 108.333 / 2 − 68.488 / 3 = **31.337** kips

∴ No uplift force!

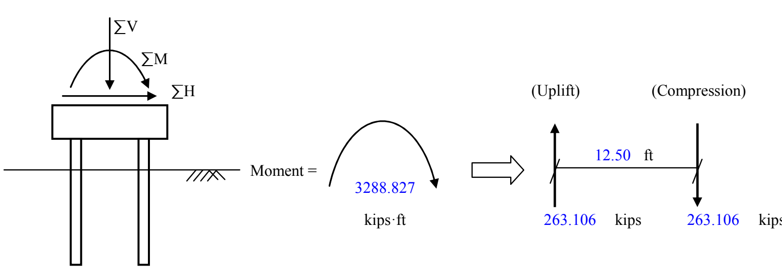
Q_3 = 1.00 × DL + 1.00 × LL + 1.00 × W_e

∑V = 1.00 × 32.500 + 1.00 × 75.833 = 108.333 kips

∑H = 1.00 × (35.159 + 31.841 + 4.223) = 71.223 kips

∑M = 1.00 × (35.159 × 77.000 + 31.841 × 18.000

+ 4.223 × 2.000) = 3288.827 kips·ft

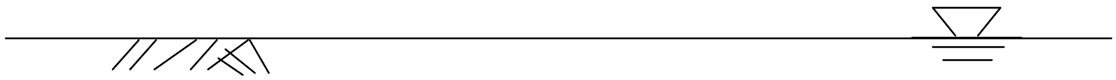


Hence,

Total compressive force for one pile = 108.333 / 2 + 263.106 / 3 = **141.869** kips

Total uplift force for one pile = 108.333 / 2 − 263.106 / 3 = **-33.536** kips

▣ Soil Condition



VERY LOOSE SAND

γ_{sat} = 115.0 pcf

γ_{sub} = 52.6 pcf

N_{SPT} = 10 bpf

▣ Bearing Capacity of the Pile (WSD)

1. Unit end bearing capacity

q_p = $P_o' \cdot N_q$

where: P_o' = effective overburden pressure at the point in question

N_q = dimensionless bearing capacity factor = 8 (very loose)

2. Unit skin friction capacity

fs = $K \cdot P_o' \cdot \tan\delta$

where: K = dimensionless coefficient of lateral earth pressure
(ratio of horizontal to vertical normal effective stress)
= 1.00 (full displacement piles, plugged or closed end)

δ = friction angle between the soil and pile wall = 15 ° (very loose)

3. Ultimate bearing capacity

Qu = Qp + Qs = q_pAp + fsAs

where: Ap = gross end area of pile = $\pi D^2/4$ (where, D: diameter of pile)

As = side surface area of pile = πDL (where, L: length of pile)

4. Allowable bearing capacity

Qa = Qu / Factor of Safety

1. Operating Environmental Conditions

Factor of Safety = 2.0

Diameter, D = 12 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	3.305	0.070	2.199	5.504	2.752	1.100
20	1052.000	8.416	6.610	0.141	8.859	15.469	7.735	4.430
30	1578.000	12.624	9.915	0.211	19.886	29.801	14.901	9.943
40	2104.000	16.832	13.220	0.282	35.437	48.657	24.329	17.719
50	2630.000	21.040	16.525	0.352	55.292	71.817	35.909	27.646
60	3156.000	25.248	19.830	0.423	79.734	99.564	49.782	39.867
70	3682.000	29.456	23.135	0.493	108.416	131.551	65.776	54.208
80	4208.000	33.664	26.440	0.557	139.876	166.316	83.158	69.938

Diameter, D = 16 inches

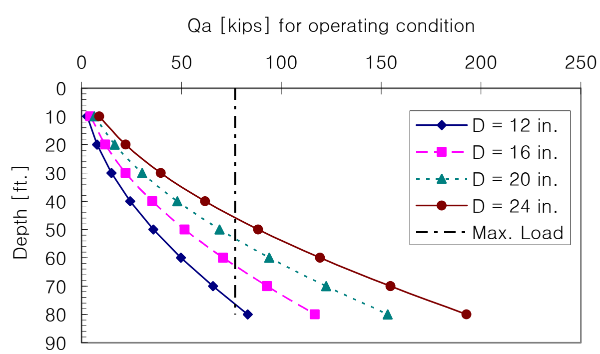
Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	5.875	0.070	2.932	8.807	4.404	1.466
20	1052.000	8.416	11.751	0.141	11.812	23.563	11.782	5.906
30	1578.000	12.624	17.626	0.211	26.515	44.141	22.071	13.258
40	2104.000	16.832	23.502	0.282	47.250	70.752	35.376	23.625
50	2630.000	21.040	29.377	0.352	73.723	103.100	51.550	36.862
60	3156.000	25.248	35.253	0.423	106.311	141.564	70.782	53.156
70	3682.000	29.456	41.128	0.493	144.555	185.683	92.842	72.278
80	4208.000	33.664	47.004	0.557	186.502	233.506	116.753	93.251

Diameter, D = 20 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	9.180	0.070	3.665	12.845	6.423	1.833
20	1052.000	8.416	18.361	0.141	14.765	33.126	16.563	7.383
30	1578.000	12.624	27.541	0.211	33.144	60.685	30.343	16.572
40	2104.000	16.832	36.722	0.282	59.062	95.784	47.892	29.531
50	2630.000	21.040	45.902	0.352	92.153	138.055	69.028	46.077
60	3156.000	25.248	55.083	0.423	132.889	187.972	93.986	66.445
70	3682.000	29.456	64.263	0.493	180.694	244.957	122.479	90.347
80	4208.000	33.664	73.443	0.557	233.127	306.570	153.285	116.564

Diameter, D = 24 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	13.220	0.070	4.398	17.618	8.809	2.199
20	1052.000	8.416	26.440	0.141	17.719	44.159	22.080	8.860
30	1578.000	12.624	39.659	0.211	39.773	79.432	39.716	19.887
40	2104.000	16.832	52.879	0.282	70.874	123.753	61.877	35.437
50	2630.000	21.040	66.099	0.352	110.584	176.683	88.342	55.292
60	3156.000	25.248	79.319	0.423	159.467	238.786	119.393	79.734
70	3682.000	29.456	92.539	0.493	216.833	309.372	154.686	108.417
80	4208.000	33.664	105.759	0.557	279.753	385.512	192.756	139.877



2. Extreme Environmental Conditions

Factor of Safety = 1.5
2.0 (uplift)

Diameter, D = 12 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	3.305	0.070	2.199	5.504	3.669	1.100
20	1052.000	8.416	6.610	0.141	8.859	15.469	10.313	4.430
30	1578.000	12.624	9.915	0.211	19.886	29.801	19.867	9.943
40	2104.000	16.832	13.220	0.282	35.437	48.657	32.438	17.719
50	2630.000	21.040	16.525	0.352	55.292	71.817	47.878	27.646
60	3156.000	25.248	19.830	0.423	79.734	99.564	66.376	39.867
70	3682.000	29.456	23.135	0.493	108.416	131.551	87.701	54.208
80	4208.000	33.664	26.440	0.557	139.876	166.316	110.877	69.938

Diameter, D = 16 inches

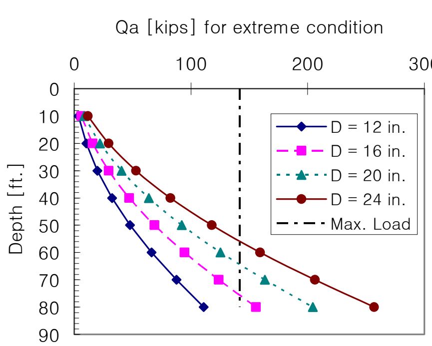
Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	5.875	0.070	2.932	8.807	5.871	1.466
20	1052.000	8.416	11.751	0.141	11.812	23.563	15.709	5.906
30	1578.000	12.624	17.626	0.211	26.515	44.141	29.427	13.258
40	2104.000	16.832	23.502	0.282	47.250	70.752	47.168	23.625
50	2630.000	21.040	29.377	0.352	73.723	103.100	68.733	36.862
60	3156.000	25.248	35.253	0.423	106.311	141.564	94.376	53.156
70	3682.000	29.456	41.128	0.493	144.555	185.683	123.789	72.278
80	4208.000	33.664	47.004	0.557	186.502	233.506	155.671	93.251

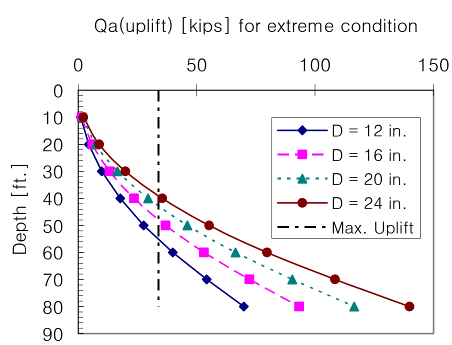
Diameter, D = 20 inches

Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	9.180	0.070	3.665	12.845	8.563	1.833
20	1052.000	8.416	18.361	0.141	14.765	33.126	22.084	7.383
30	1578.000	12.624	27.541	0.211	33.144	60.685	40.457	16.572
40	2104.000	16.832	36.722	0.282	59.062	95.784	63.856	29.531
50	2630.000	21.040	45.902	0.352	92.153	138.055	92.037	46.077
60	3156.000	25.248	55.083	0.423	132.889	187.972	125.315	66.445
70	3682.000	29.456	64.263	0.493	180.694	244.957	163.305	90.347
80	4208.000	33.664	73.443	0.557	233.127	306.570	204.380	116.564

Diameter, D = 24 inches

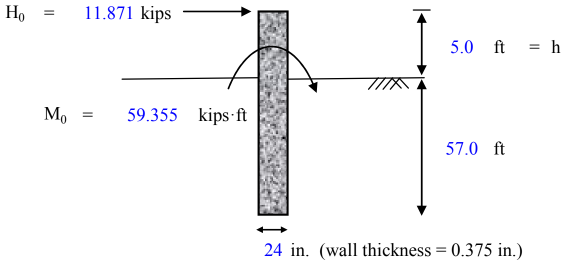
Depth [ft]	P_o' [psf]	q_p [ksf]	Qp [kips]	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0
10	526.000	4.208	13.220	0.070	4.398	17.618	11.745	2.199
20	1052.000	8.416	26.440	0.141	17.719	44.159	29.439	8.860
30	1578.000	12.624	39.659	0.211	39.773	79.432	52.955	19.887
40	2104.000	16.832	52.879	0.282	70.874	123.753	82.502	35.437
50	2630.000	21.040	66.099	0.352	110.584	176.683	117.789	55.292
60	3156.000	25.248	79.319	0.423	159.467	238.786	159.191	79.734
70	3682.000	29.456	92.539	0.493	216.833	309.372	206.248	108.417
80	4208.000	33.664	105.759	0.557	279.753	385.512	257.008	139.877





▣ Horizontal Capacity of the Pile (SALLOP)

For free head,



E_0 = $4 \cdot N_{SPT}$ = 4 × 10 = 40.000 tsf = 80.000 ksf

K = $2.3 \cdot E_0$ = 2.3 × 80.000 = 184.000 ksf

E = 2.90E+07 psi (Steel pile) = 4.18E+06 ksf

I = $(\pi D_o^4)/64 - (\pi D_i^4)/64$ = 1942.299 $in.^4$ = 0.09367 ft^4

l_0 = $(4EI/K)^{1/4}$ = (4 × 4.18E+06 × 0.09367 / 184.000 $)^{1/4}$ = 9.603 ft

where, E_0 = pressuremeter load modulus

K = soil spring constant

E = modulus of elasticity for the pile material

I = moment of inertia for the pile , H_0 = horizontal load

l_0 = transfer length , M_0 = applied moment at the ground surface

Embedded pile length, L = 57.0 ft ≥ $3 \cdot l_o$ = 28.809 ft **∴ long flexible pile!**

1. Lateral Pile Capacity

The zero-shear depth D_v is obtained by setting V (shear force) = 0;

D_v = $l_0 \cdot \tan^{-1}\{1/(1+2h/l_0)\}$ = 4.374 ft

P_L = $0.5 \cdot N_{SPT}$ = 0.5 × 10 = 5.000 tsf = 10.000 ksf

H_{ou} = $0.75 \cdot P_L \cdot B \cdot D_v$ = 0.75 × 10.000 × 2.000 × 4.374 = 65.610 kips

H_{allow} = 65.610 / 3.000 = 21.870 kips > H_0 = 11.871 kips **∴ O.K!**

where, D_v = zero-shear depth

P_L = preboring pressuremeter limit pressure within D_v

H_{ou} = lateral capacity of pile

2. Lateral Movement at The Ground Surface

y_0 = $(1+h/l_0) \cdot H_0 \cdot l_0^3 / (2EI)$ = 0.020 ft = 0.240 in. < 0.500 in. **∴ O.K!**

3. Lateral Movement at The Pile Head

δ = $\{(1+h/l_0)^3 + 0.5\} \cdot H_0 \cdot l_0^3 / (3EI)$ = 0.036 ft = 0.432 in. < 0.500 in. **∴ O.K!**

4. Maximum Bending Moment

Maximum bending moment can be found by finding the value of Z_{max} which satisfied V = 0.

$Z_{max} = D_v$ = 4.374 ft

M_{max} = $0.5 \cdot H_0 l_0 \cdot \exp(-Z_{max}/l_0) \cdot \sqrt{\{(1+2h/l_0)^2 + 1\}}$

= 82.162 kips·ft

5. Check for Creep

P = $K \cdot y_0$ = 184.000 × 0.020 = 3.680 kips/ft

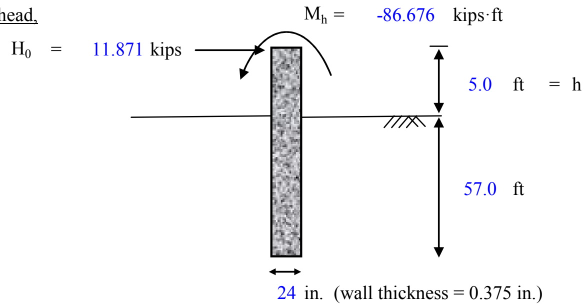
Pa = P / B = 3.680 / 2.000 = 1.840 ksf

where, P = the load per unit length of pile

Pa = average corresponding pressure

F.S = P_L / Pa = 10.000 / 1.840 = 5.435 > 2 **∴ O.K!**

For fixed head,



$E_0 = 4 \cdot N_{SPT} = 4 \times 10 = 40.000$ tsf $= 80.000$ ksf

$K = 2.3 \cdot E_0 = 2.3 \times 80.000 = 184.000$ ksf

$E = 2.90E+07$ psi (Steel pile) $= 4.18E+06$ ksf

$I = (\pi D_o^4)/64 - (\pi D_i^4)/64 = 1942.299$ in.^{4} $= 0.09367$ ft^4

$l_0 = (4EI/K)^{1/4} = (4 \times 4.18E+06 \times 0.09367 / 184.000)^{1/4} = 9.603$ ft

$M_h = -0.5 \cdot (1 + h/l_0) \cdot H_0 \cdot l_0 = -86.676$ kips·ft (↶)

where, E_0 = pressuremeter load modulus

K = soil spring constant

E = modulus of elasticity for the pile material

I = moment of inertia for the pile , H_0 = horizontal load

l_0 = transfer length , M_h = applied moment at the pile head

Embedded pile length, L = 57.0 ft $\geq 3 \cdot l_o$ = 28.809 ft **<u>∴ long flexible pile!</u>**

1. Lateral Pile Capacity

The zero-shear depth D_v is obtained by setting V (shear force) = 0;

$D_v = l_0 \cdot \tan^{-1}(l_0/h) = 10.474$ ft

$P_L = 0.5 \cdot N_{SPT} = 0.5 \times 10 = 5.000$ tsf $= 10.000$ ksf

$H_{ou} = 0.75 \cdot P_L \cdot B \cdot D_v = 0.75 \times 10.000 \times 2.000 \times 10.474 = 157.110$ kips

$H_{allow} = 157.110 / 3.000 = 52.370$ kips $> H_0 = 11.871$ kips **<u>∴ O.K!</u>**

where, D_v = zero-shear depth

P_L = preboring pressuremeter limit pressure within D_v

H_{ou} = lateral capacity of pile

2. Lateral Movement at The Ground Surface

$y_0 = (1+h/l_0) \cdot H_0 \cdot l_0^3 / (4EI) = 0.010$ ft $= 0.120$ in. $<$ 0.500 in. **<u>∴ O.K!</u>**

3. Lateral Movement at The Pile Head

$\delta = \{(1+h/l_0)^3 + 2\} \cdot H_0 \cdot l_0^3 / (12EI) = 0.012$ ft $= 0.144$ in. $<$ 0.500 in. **<u>∴ O.K!</u>**

4. Maximum Bending Moment

Maximum bending moment can be found by finding the value of Z_{max} which satisfied V = 0.

$Z_{max} = D_v = 10.474$ ft

$M_{max} = 0.5 \cdot H_0 l_0 \cdot \exp(-(Z_{max}/l_0)) \cdot \sqrt{\{1+(h/l_0)^2\}}$

$= 21.591$ kips·ft

5. Check for Creep

$P = K \cdot y_0 = 184.000 \times 0.010 = 1.840$ kips/ft

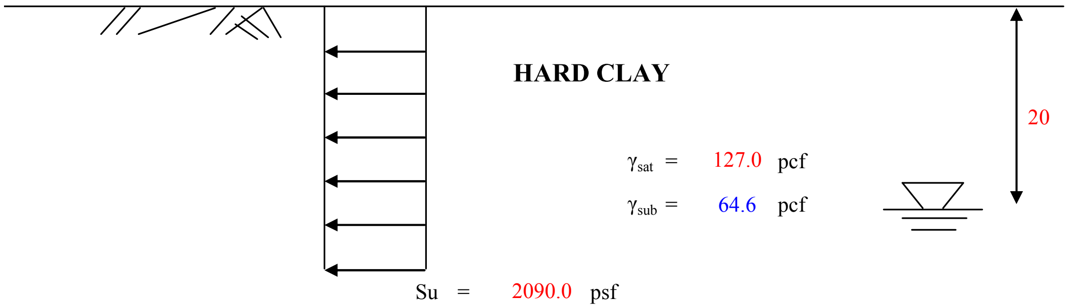
$Pa = P / B = 1.840 / 2.000 = 0.920$ ksf

where, P = the load per unit length of pile

Pa = average corresponding pressure

$F.S = P_L / Pa = 10.000 / 0.920 = 10.870 > 2$ **<u>∴ O.K!</u>**

▣ Soil Condition



▣ Bearing Capacity of the Pile (ADSC-LRFD)

1. Unit end bearing capacity

q_p = 9 · Su (If Su ≥ 2000 psf, and depth of base ≥ 3B, B = diameter of pile)

= N^*_c · Su (If Su < 2000 psf, and depth of base ≥ 3B, B = diameter of pile)

= (2/3) [1 + (1/6)(D/B)] N*c · Su (If depth of base(D) < 3B)

2. Unit skin friction capacity

fs = α · Su

α = 0.55 (for Su / Pa ≤ 1.5 and varying linearly between 0.55 and 0.45 for 1.5 < Su / Pa < 2.5)

α = 0 (for top five feet, and bottom one diameter)

where: α = a dimensionless adhesion factor

Pa = the atmospheric pressure = 2116 psf

3. Ultimate bearing capacity

Qu = Qp + Qs = q_pAp + fsAs

where: Ap = gross end area of pile = $\pi D^2/4$ (where, D: diameter of pile)

As = side surface area of pile = πDL (where, L: length of pile)

1. Operating Environmental Conditions

Resistance Factors (φ) for end bearing = 0.55 , skin friction = 0.65 , uplift = 0.55

Diameter, D = 12 inches

Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	18.810	14.773	0.00	0.000	0.000	14.773	8.125	0.000
10	9.00	18.810	14.773	0.55	1.150	14.451	29.224	17.518	7.948
15	9.00	18.810	14.773	0.55	1.150	32.515	47.288	29.260	17.883
20	9.00	18.810	14.773	0.55	1.150	50.580	65.353	41.002	27.819
25	9.00	18.810	14.773	0.55	1.150	68.644	83.417	52.744	37.754
30	9.00	18.810	14.773	0.55	1.150	86.708	101.481	64.485	47.689
35	9.00	18.810	14.773	0.55	1.150	104.772	119.545	76.227	57.625
40	9.00	18.810	14.773	0.55	1.150	122.836	137.609	87.969	67.560

Diameter, D = 16 inches

Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	18.810	26.264	0.00	0.000	0.000	26.264	14.445	0.000
10	9.00	18.810	26.264	0.55	1.150	17.663	43.927	25.926	9.715
15	9.00	18.810	26.264	0.55	1.150	41.748	68.012	41.581	22.961
20	9.00	18.810	26.264	0.55	1.150	65.834	92.098	57.237	36.209
25	9.00	18.810	26.264	0.55	1.150	89.919	116.183	72.893	49.455
30	9.00	18.810	26.264	0.55	1.150	114.005	140.269	88.548	62.703
35	9.00	18.810	26.264	0.55	1.150	138.090	164.354	104.204	75.950
40	9.00	18.810	26.264	0.55	1.150	162.176	188.440	119.860	89.197

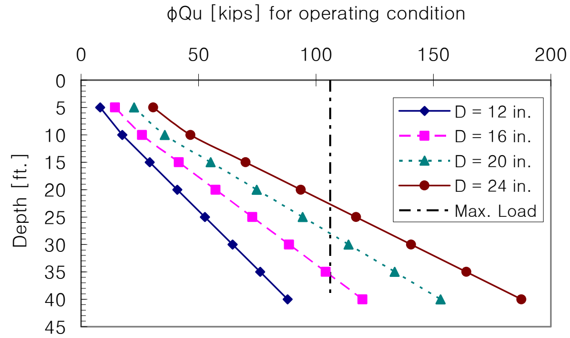
Diameter, D = 20 inches

Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	18.810	41.037	0.00	0.000	0.000	41.037	22.570	0.000
10	9.00	18.810	41.037	0.55	1.150	20.071	61.108	35.617	11.039
15	9.00	18.810	41.037	0.55	1.150	50.178	91.215	55.186	27.598
20	9.00	18.810	41.037	0.55	1.150	80.285	121.322	74.756	44.157
25	9.00	18.810	41.037	0.55	1.150	110.392	151.429	94.325	60.716
30	9.00	18.810	41.037	0.55	1.150	140.499	181.536	113.895	77.274
35	9.00	18.810	41.037	0.55	1.150	170.606	211.643	133.464	93.833
40	9.00	18.810	41.037	0.55	1.150	200.713	241.750	153.034	110.392

Diameter, D = 24 inches

Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	17.765	55.810	0.00	0.000	0.000	55.810	30.696	0.000
10	9.00	18.810	59.093	0.55	1.150	21.677	80.770	46.591	11.922
15	9.00	18.810	59.093	0.55	1.150	57.805	116.898	70.074	31.793
20	9.00	18.810	59.093	0.55	1.150	93.934	153.027	93.558	51.664
25	9.00	18.810	59.093	0.55	1.150	130.062	189.155	117.041	71.534
30	9.00	18.810	59.093	0.55	1.150	166.190	225.283	140.525	91.405
35	9.00	18.810	59.093	0.55	1.150	202.319	261.412	164.009	111.275
40	9.00	18.810	59.093	0.55	1.150	238.447	297.540	187.492	131.146

ϕQu [kips] for operating condition



2. Extreme Environmental Conditions

Resistance Factors, φ = 1.0
1.0 (uplift)

Diameter, D = 12 inches

Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	18.810	14.773	0.00	0.000	0.000	14.773	14.773	0.000
10	9.00	18.810	14.773	0.55	1.150	14.451	29.224	29.224	14.451
15	9.00	18.810	14.773	0.55	1.150	32.515	47.288	47.288	32.515
20	9.00	18.810	14.773	0.55	1.150	50.580	65.353	65.353	50.580
25	9.00	18.810	14.773	0.55	1.150	68.644	83.417	83.417	68.644
30	9.00	18.810	14.773	0.55	1.150	86.708	101.481	101.481	86.708
35	9.00	18.810	14.773	0.55	1.150	104.772	119.545	119.545	104.772
40	9.00	18.810	14.773	0.55	1.150	122.836	137.609	137.609	122.836

Diameter, D = 16 inches

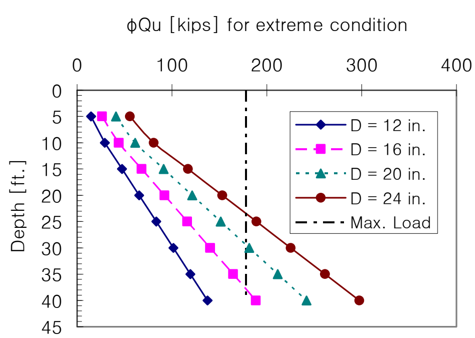
Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	18.810	26.264	0.00	0.000	0.000	26.264	26.264	0.000
10	9.00	18.810	26.264	0.55	1.150	17.663	43.927	43.927	17.663
15	9.00	18.810	26.264	0.55	1.150	41.748	68.012	68.012	41.748
20	9.00	18.810	26.264	0.55	1.150	65.834	92.098	92.098	65.834
25	9.00	18.810	26.264	0.55	1.150	89.919	116.183	116.183	89.919
30	9.00	18.810	26.264	0.55	1.150	114.005	140.269	140.269	114.005
35	9.00	18.810	26.264	0.55	1.150	138.090	164.354	164.354	138.090
40	9.00	18.810	26.264	0.55	1.150	162.176	188.440	188.440	162.176

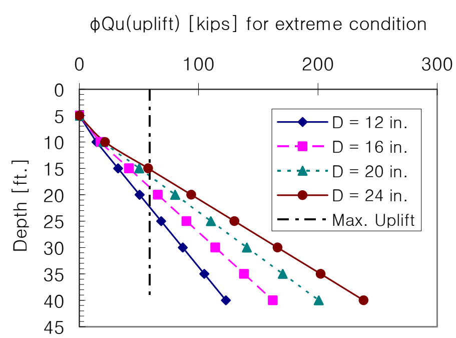
Diameter, D = 20 inches

Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	18.810	41.037	0.00	0.000	0.000	41.037	41.037	0.000
10	9.00	18.810	41.037	0.55	1.150	20.071	61.108	61.108	20.071
15	9.00	18.810	41.037	0.55	1.150	50.178	91.215	91.215	50.178
20	9.00	18.810	41.037	0.55	1.150	80.285	121.322	121.322	80.285
25	9.00	18.810	41.037	0.55	1.150	110.392	151.429	151.429	110.392
30	9.00	18.810	41.037	0.55	1.150	140.499	181.536	181.536	140.499
35	9.00	18.810	41.037	0.55	1.150	170.606	211.643	211.643	170.606
40	9.00	18.810	41.037	0.55	1.150	200.713	241.750	241.750	200.713

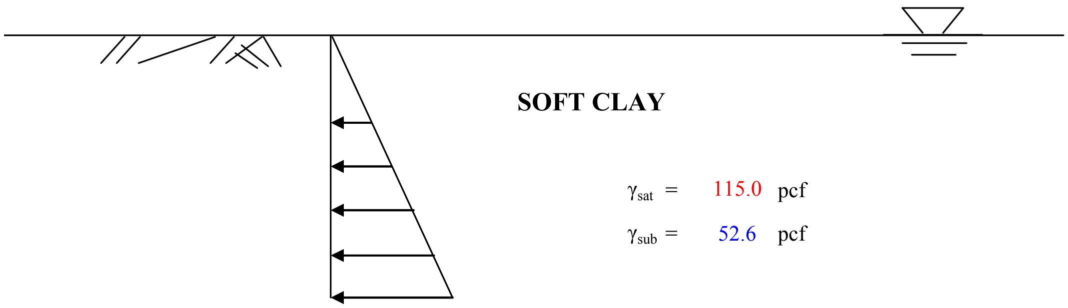
Diameter, D = 24 inches

Depth [ft]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	φQu [kips]	φQu(uplift)
0	0	0	0	0	0	0	0	0	0
5	9.00	17.765	55.810	0.00	0.000	0.000	55.810	55.810	0.000
10	9.00	18.810	59.093	0.55	1.150	21.677	80.770	80.770	21.677
15	9.00	18.810	59.093	0.55	1.150	57.805	116.898	116.898	57.805
20	9.00	18.810	59.093	0.55	1.150	93.934	153.027	153.027	93.934
25	9.00	18.810	59.093	0.55	1.150	130.062	189.155	189.155	130.062
30	9.00	18.810	59.093	0.55	1.150	166.190	225.283	225.283	166.190
35	9.00	18.810	59.093	0.55	1.150	202.319	261.412	261.412	202.319
40	9.00	18.810	59.093	0.55	1.150	238.447	297.540	297.540	238.447





▣ Soil Condition



γ_{sat} = 115.0 pcf

γ_{sub} = 52.6 pcf

Su = 0.25 · P_o'

P_o' = effective overburden pressure at the point in question

▣ Bearing Capacity of the Pile (ADSC-WSD)

1. Unit end bearing capacity

q_p = 9 · Su (If Su ≥ 2000 psf, and depth of base ≥ 3B, B = diameter of pile)

= N^*_c · Su (If Su < 2000 psf, and depth of base ≥ 3B, B = diameter of pile)

= (2/3) [1 + (1/6)(D/B)] N*c · Su (If depth of base(D) < 3B)

2. Unit skin friction capacity

fs = α · Su

α = 0.55 (for Su / Pa ≤ 1.5 and varying linearly between 0.55 and 0.45 for 1.5 < Su / Pa < 2.5)

α = 0 (for top five feet, and bottom one diameter)

where: α = a dimensionless adhesion factor

Pa = the atmospheric pressure = 2116 psf

3. Ultimate bearing capacity

Qu = Qp + Qs = q_pAp + fsAs

where: Ap = gross end area of pile = $\pi D^2/4$ (where, D: diameter of pile)

As = side surface area of pile = πDL (where, L: length of pile)

4. Allowable bearing capacity

Qa = Qu / Factor of Safety

1. Operating Environmental Conditions

Factor of Safety = 3.0

Diameter, D = 12 inches

Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	1.343	0.55	0.073	3.211	4.554	1.518	1.070
40	0.526	6.58	3.460	2.717	0.55	0.145	15.488	18.205	6.068	5.163
60	0.789	7.37	5.813	4.566	0.55	0.217	36.813	41.379	13.793	12.271
80	1.052	8.05	8.471	6.653	0.55	0.289	67.186	73.839	24.613	22.395
100	1.315	8.32	10.934	8.588	0.55	0.362	106.902	115.490	38.497	35.634
120	1.578	8.58	13.536	10.631	0.55	0.434	155.433	166.064	55.355	51.811
140	1.841	8.84	16.276	12.783	0.55	0.507	213.434	226.217	75.406	71.145
160	2.104	9.00	18.936	14.872	0.55	0.579	280.123	294.995	98.332	93.374

Diameter, D = 16 inches

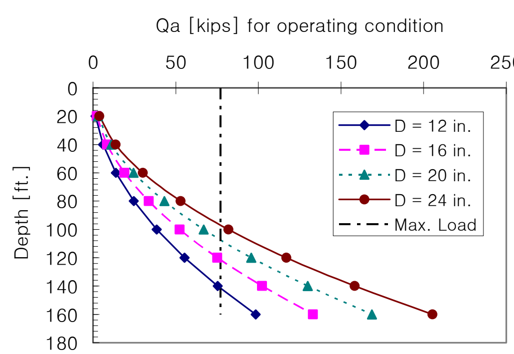
Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	2.388	0.55	0.073	4.179	6.567	2.189	1.393
40	0.526	6.58	3.460	4.831	0.55	0.145	20.448	25.279	8.426	6.816
60	0.789	7.37	5.813	8.116	0.55	0.217	48.781	56.897	18.966	16.260
80	1.052	8.05	8.471	11.828	0.55	0.289	89.178	101.006	33.669	29.726
100	1.315	8.32	10.934	15.267	0.55	0.362	142.031	157.298	52.433	47.344
120	1.578	8.58	13.536	18.900	0.55	0.434	206.639	225.539	75.180	68.880
140	1.841	8.84	16.276	22.726	0.55	0.507	283.870	306.596	102.199	94.623
160	2.104	9.00	18.936	26.440	0.55	0.579	372.689	399.129	133.043	124.230

Diameter, D = 20 inches

Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	3.731	0.55	0.073	5.096	8.827	2.942	1.699
40	0.526	6.58	3.460	7.549	0.55	0.145	25.307	32.856	10.952	8.436
60	0.789	7.37	5.813	12.682	0.55	0.217	60.598	73.280	24.427	20.199
80	1.052	8.05	8.471	18.481	0.55	0.289	110.968	129.449	43.150	36.989
100	1.315	8.32	10.934	23.854	0.55	0.362	176.907	200.761	66.920	58.969
120	1.578	8.58	13.536	29.531	0.55	0.434	257.541	287.072	95.691	85.847
140	1.841	8.84	16.276	35.509	0.55	0.507	353.953	389.462	129.821	117.984
160	2.104	9.00	18.936	41.312	0.55	0.579	464.851	506.163	168.721	154.950

Diameter, D = 24 inches

Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	5.372	0.55	0.073	5.963	11.335	3.778	1.988
40	0.526	6.58	3.460	10.870	0.55	0.145	30.065	40.935	13.645	10.022
60	0.789	7.37	5.813	18.262	0.55	0.217	72.263	90.525	30.175	24.088
80	1.052	8.05	8.471	26.612	0.55	0.289	132.556	159.168	53.056	44.185
100	1.315	8.32	10.934	34.350	0.55	0.362	211.530	245.880	81.960	70.510
120	1.578	8.58	13.536	42.525	0.55	0.434	308.140	350.665	116.888	102.713
140	1.841	8.84	16.276	51.133	0.55	0.507	423.681	474.814	158.271	141.227
160	2.104	9.00	18.936	59.489	0.55	0.579	556.609	616.098	205.366	185.536



2. Extreme Environmental Conditions

Factor of Safety = 2.0

3.0 (uplift)

Diameter, D = 12 inches

Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	1.343	0.55	0.073	3.211	4.554	2.277	1.070
40	0.526	6.58	3.460	2.717	0.55	0.145	15.488	18.205	9.103	5.163
60	0.789	7.37	5.813	4.566	0.55	0.217	36.813	41.379	20.690	12.271
80	1.052	8.05	8.471	6.653	0.55	0.289	67.186	73.839	36.920	22.395
100	1.315	8.32	10.934	8.588	0.55	0.362	106.902	115.490	57.745	35.634
120	1.578	8.58	13.536	10.631	0.55	0.434	155.433	166.064	83.032	51.811
140	1.841	8.84	16.276	12.783	0.55	0.507	213.434	226.217	113.109	71.145
160	2.104	9.00	18.936	14.872	0.55	0.579	280.123	294.995	147.498	93.374

Diameter, D = 16 inches

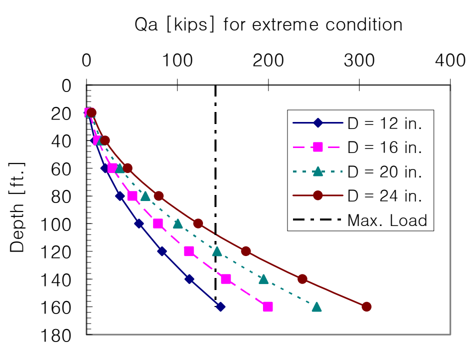
Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	2.388	0.55	0.073	4.179	6.567	3.284	1.393
40	0.526	6.58	3.460	4.831	0.55	0.145	20.448	25.279	12.640	6.816
60	0.789	7.37	5.813	8.116	0.55	0.217	48.781	56.897	28.449	16.260
80	1.052	8.05	8.471	11.828	0.55	0.289	89.178	101.006	50.503	29.726
100	1.315	8.32	10.934	15.267	0.55	0.362	142.031	157.298	78.649	47.344
120	1.578	8.58	13.536	18.900	0.55	0.434	206.639	225.539	112.770	68.880
140	1.841	8.84	16.276	22.726	0.55	0.507	283.870	306.596	153.298	94.623
160	2.104	9.00	18.936	26.440	0.55	0.579	372.689	399.129	199.565	124.230

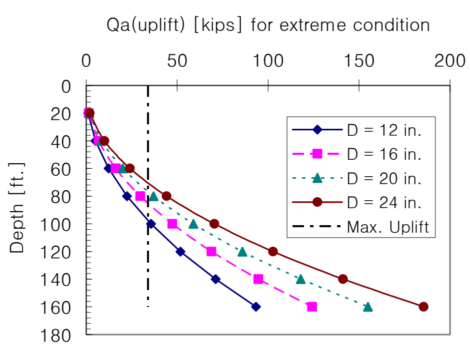
Diameter, D = 20 inches

Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	3.731	0.55	0.073	5.096	8.827	4.414	1.699
40	0.526	6.58	3.460	7.549	0.55	0.145	25.307	32.856	16.428	8.436
60	0.789	7.37	5.813	12.682	0.55	0.217	60.598	73.280	36.640	20.199
80	1.052	8.05	8.471	18.481	0.55	0.289	110.968	129.449	64.725	36.989
100	1.315	8.32	10.934	23.854	0.55	0.362	176.907	200.761	100.381	58.969
120	1.578	8.58	13.536	29.531	0.55	0.434	257.541	287.072	143.536	85.847
140	1.841	8.84	16.276	35.509	0.55	0.507	353.953	389.462	194.731	117.984
160	2.104	9.00	18.936	41.312	0.55	0.579	464.851	506.163	253.082	154.950

Diameter, D = 24 inches

Depth [ft]	Su [ksf]	N^*_c	q_p [ksf]	Qp [kips]	α	fs [ksf]	ΣQs [kips]	Qu [kips]	Qa [kips]	Qa (uplift)
0	0	0	0	0	0	0	0	0	0	0
20	0.263	6.50	1.710	5.372	0.55	0.073	5.963	11.335	5.668	1.988
40	0.526	6.58	3.460	10.870	0.55	0.145	30.065	40.935	20.468	10.022
60	0.789	7.37	5.813	18.262	0.55	0.217	72.263	90.525	45.263	24.088
80	1.052	8.05	8.471	26.612	0.55	0.289	132.556	159.168	79.584	44.185
100	1.315	8.32	10.934	34.350	0.55	0.362	211.530	245.880	122.940	70.510
120	1.578	8.58	13.536	42.525	0.55	0.434	308.140	350.665	175.333	102.713
140	1.841	8.84	16.276	51.133	0.55	0.507	423.681	474.814	237.407	141.227
160	2.104	9.00	18.936	59.489	0.55	0.579	556.609	616.098	308.049	185.536





APPENDIX B

INPUT PARAMETERS USED IN THE CASE STUDY, SIX SUGGESTED SYSTEMS FOR THE CAST STUDY, AND KNAPSACK OPTIMIZATION ROUTINE

- INPUT VALUES

Rig type	Rig name	Weight (lb)	Drilling time (days)	Move/rig up (days)	Rent/day ($)	Footprint (acres)	Diesel (gal/day)	Natural gas (gal/day)	Site Preparation: Gravels ($)	Site Preparation: Mats ($)	Site Preparation: Modules +piles ($)
1	Traditional older vintage rig	1,200,000	12	4	$12,500	2	1680	2100	$137,813	$122,500	$1,862,041
2	Rapid Rig	976,470	11	0.5	$14,000	1	1200	1500	$101,250	$90,000	$1,126,503
3	LOC250 (CWD)	1,048,000	10	1	$15,000	1	1200	1500	$101,250	$90,000	$1,126,503

Rig type	Rig name	Emissions: *Air*	Emissions: *Solid& Liquid*	Emissions: *Noise (TWA)*	Perceptions: *Gov.*	Perceptions: *Ind.*	Perceptions: *Public*	Safety Value	How many trucks?
1	Traditional older vintage rig	0.973		78.630	0.500	1.000	0.500	0.500	20
2	Rapid Rig	0.978		77.020	1.000	0.500	1.000	1.000	16
3	LOC250 (CWD)	0.977		77.458	1.000	0.500	1.000	1.000	17

Type	Engine name	Rent/day ($)	Ecological Footprint (Acres)	Emissions: *Air*	Emissions: *Solid& Liquid*	Emissions: *Noise (TWA)*	Perceptions: *Gov.*	Perceptions: *Ind.*	Perceptions: *Public*	Safety Value
1	Internal combustion engine	$5,000	0.011	0.118		110.073	0.500	1.000	0.500	0.750
	Internal combustion engine w/SCR, w/noise suppressor	$7,411	0.011	0.431		88.059	0.750	0.750	0.750	0.750
2	Lean-burn natural gas engines w/noise suppressor	$7,817	0.005	0.878		88.059	1.000	0.500	1.000	0.750

Type	Drilling method	Drilling time rate	Rent/day ($)	Ecological Footprint (Acres)	Emissions: *Air*	Emissions: *Solid& Liquid*	Emissions: *Noise (TWA)*	Perceptions: *Gov.*	Perceptions: *Ind.*	Perceptions: *Public*	Safety Value
1	Conventional overbalanced drilling	100%	$17,000				116.700	1.000	0.500	0.500	0.500
2	Underbalanced drilling w/noise suppressor	90%	$20,500				97.360	0.750	0.750	0.750	0.750
3	Managed pressure drilling w/noise suppressor	90%	$21,500				95.760	0.750	0.750	1.000	1.000

Type	Transportation type	Cost ($)	Ecological Footprint (Acres)	Emissions: *Air*	Emissions: *Solid& Liquid*	Emissions: *Noise (TWA)*	Perceptions: *Gov.*	Perceptions: *Ind.*	Perceptions: *Public*	Safety Value	
1	Coventional diesel truck	$20,000					0.250	1.000	0.250	0.750	Cost factor
2	Low sulphur diesel truck w/tier III engine, w/noise suppressor	$28,000					1.000	0.500	1.000	0.750	1.4

● Emission of Rig Transportation (standard)

Rig types	Transportation types	Unit	0.2 CO	0.4 NO_x	0.4 PM	Overall score	Operating hrs 1	
1	Diesel truck	(gram/hp-hr)	15.5	4	0.1			
		(lb/hp-hr)	0.03418	0.00882	0.00022			
		(lb/hr)/unit	13.671	3.528	0.088	0.973		
		(lb/operating)	273.420	70.560	1.764		HP	units
		U-value	0.916	0.985	0.990		400	20
	Low sulphur diesel truck w/tier III engin	(gram/hp-hr)	15.5	0.2	0.01			
		(lb/hp-hr)	0.03418	0.00044	0.00002			
		(lb/hr)/unit	13.671	0.176	0.009	0.982		
		(lb/operating)	273.420	3.528	0.176		HP	units
		U-value	0.916	0.999	0.999		400	20
2	Diesel truck	(gram/hp-hr)	15.5	4	0.1			
		(lb/hp-hr)	0.03418	0.00882	0.00022			
		(lb/hr)/unit	13.671	3.528	0.088	0.978		
		(lb/operating)	218.736	56.448	1.411		HP	units
		U-value	0.933	0.988	0.992		400	16
	Low sulphur diesel truck w/tier III engin	(gram/hp-hr)	15.5	0.2	0.01			
		(lb/hp-hr)	0.03418	0.00044	0.00002			
		(lb/hr)/unit	13.671	0.176	0.009	0.986		
		(lb/operating)	218.736	2.822	0.141		HP	units
		U-value	0.933	0.999	0.999		400	16
3	Diesel truck	(gram/hp-hr)	15.5	4	0.1			
		(lb/hp-hr)	0.03418	0.00882	0.00022			
		(lb/hr)/unit	13.671	3.528	0.088	0.977		
		(lb/operating)	232.407	59.976	1.499		HP	units
		U-value	0.928	0.987	0.991		400	17
	Low sulphur diesel truck w/tier III engin	(gram/hp-hr)	15.5	0.2	0.01			
		(lb/hp-hr)	0.03418	0.00044	0.00002			
		(lb/hr)/unit	13.671	0.176	0.009	0.985		
		(lb/operating)	232.407	2.999	0.150		HP	units
		U-value	0.928	0.999	0.999		400	17

Noise for drilling site		Suppressor factor 20%	
Noise (dBA/unit)	76	Total length (hr)	5.0
How many trucks	4	Ref. duration (hr)	24.2
Noise (dBA)	82.0	Noise dose (%)	20.7
TWA	78.6	TWA w/suppressor	62.9
Noise (dBA/unit)	74	Total length (hr)	5.0
How many trucks	4	Ref. duration (hr)	31.9
Noise (dBA)	80.0	Noise dose (%)	15.7
TWA	76.6	TWA w/suppressor	61.3
Noise (dBA/unit)	76	Total length (hr)	4.0
How many trucks	4	Ref. duration (hr)	24.2
Noise (dBA)	82.0	Noise dose (%)	16.5
TWA	77.0	TWA w/suppressor	61.6
Noise (dBA/unit)	74	Total length (hr)	4.0
How many trucks	4	Ref. duration (hr)	31.9
Noise (dBA)	80.0	Noise dose (%)	12.5
TWA	75.0	TWA w/suppressor	60.0
Noise (dBA/unit)	76	Total length (hr)	4.3
How many trucks	4	Ref. duration (hr)	24.2
Noise (dBA)	82.0	Noise dose (%)	17.6
TWA	77.5	TWA w/suppressor	62.0
Noise (dBA/unit)	74	Total length (hr)	4.3
How many trucks	4	Ref. duration (hr)	31.9
Noise (dBA)	80.0	Noise dose (%)	13.3
TWA	75.5	TWA w/suppressor	60.4

● Emission of Road Construction (standard)

Technologies	Unit	0.2	0.4	0.4	Overall score	Operating hrs					
		CO	NO_x	PM		1					
Gravel: Diesel truck + dust	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	79.3
	(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
	(lb/hr)/unit	10.253	2.646	0.216	0.566			Noise (dBA)	82.0	Noise dose (%)	327.7
	(lb/operating)	3250.280	838.782	68.520		HP	units	TWA	98.6	TWA w/suppressor	78.8
	U-value	0.000	0.822	0.593		300	317				
Mat: Diesel truck	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	9.0
	(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
	(lb/hr)/unit	10.253	2.646	0.066	0.964			Noise (dBA)	82.0	Noise dose (%)	37.2
	(lb/operating)	369.117	95.256	2.381		HP	units	TWA	82.9	TWA w/suppressor	66.3
	U-value	0.886	0.980	0.986		300	36				
Gravel: Low sulphur diesel truck w/tier III engine + dust	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	79.3
	(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
	(lb/hr)/unit	10.253	0.132	0.157	0.679			Noise (dBA)	80.0	Noise dose (%)	248.4
	(lb/operating)	3250.280	41.939	49.647		HP	units	TWA	96.6	TWA w/suppressor	77.2
	U-value	0.000	0.991	0.705		300	317				
Mat: Low sulphur diesel truck w/tier III engine	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	9.0
	(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
	(lb/hr)/unit	10.253	0.132	0.007	0.976			Noise (dBA)	80.0	Noise dose (%)	28.2
	(lb/operating)	369.117	4.763	0.238		HP	units	TWA	80.9	TWA w/suppressor	64.7
	U-value	0.886	0.999	0.999		300	36				

● Emission of Site Preparation (standard)

Rig types	Technologies	Unit	0.2	0.4	0.4	Overall score	Operating hrs					
			CO	NO_x	PM		1					
1	Gravel: Diesel truck + dust	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	73.5
		(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
		(lb/hr)/unit	10.253	2.646	0.216	0.598			Noise (dBA)	82.0	Noise dose (%)	303.9
		(lb/operating)	3014.456	777.924	63.548		HP	units	TWA	98.0	TWA w/suppressor	78.4
		U-value	0.073	0.835	0.623		300	294				
	Mat: Diesel truck	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	8.3
		(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
		(lb/hr)/unit	10.253	2.646	0.066	0.967			Noise (dBA)	82.0	Noise dose (%)	34.1
		(lb/operating)	338.357	87.318	2.183		HP	units	TWA	82.2	TWA w/suppressor	65.8
		U-value	0.896	0.981	0.987		300	33				
	Module: Diesel truck + hammer	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	5.0
		(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
		(lb/hr)/unit	10.253	2.646	0.066	0.973			Noise (dBA)	82.0	Noise dose (%)	287.3
		(lb/operating)	270.686	69.854	1.746		HP	units	TWA	97.6	TWA w/suppressor	78.1
		U-value	0.917	0.985	0.990		300	20				
	Gravel: Low sulphur diesel truck w/tier III engine+ dust	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	73.5
		(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
		(lb/hr)/unit	10.253	0.132	0.157	0.702			Noise (dBA)	80.0	Noise dose (%)	230.3
		(lb/operating)	3014.456	38.896	46.045		HP	units	TWA	96.0	TWA w/suppressor	76.8
		U-value	0.073	0.992	0.727		300	294				
	Mat: Low sulphur diesel truck w/tier III engine	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	8.3
		(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
		(lb/hr)/unit	10.253	0.132	0.007	0.978			Noise (dBA)	80.0	Noise dose (%)	25.9
		(lb/operating)	338.357	4.366	0.218		HP	units	TWA	80.2	TWA w/suppressor	64.2
		U-value	0.896	0.999	0.999		300	33				
	Module: Low sulphur diesel truck w/tier III engine + hammer	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	5.0
		(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
		(lb/hr)/unit	10.253	0.132	0.007	0.983			Noise (dBA)	80.0	Noise dose (%)	282.3
		(lb/operating)	270.686	3.493	0.175		HP	units	TWA	97.5	TWA w/suppressor	78.0
		U-value	0.917	0.999	0.999		300	20				
2 & 3	Gravel: Diesel truck + dust	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	54.0
		(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
		(lb/hr)/unit	10.253	2.646	0.216	0.704			Noise (dBA)	82.0	Noise dose (%)	223.3
		(lb/operating)	2214.702	571.536	46.688		HP	units	TWA	95.8	TWA w/suppressor	76.6
		U-value	0.319	0.879	0.723		300	216				
	Mat: Diesel truck	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	6.0
		(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
		(lb/hr)/unit	10.253	2.646	0.066	0.976			Noise (dBA)	82.0	Noise dose (%)	24.8
		(lb/operating)	246.078	63.504	1.588		HP	units	TWA	79.9	TWA w/suppressor	64.0
		U-value	0.924	0.987	0.991		300	24				
	Module: Diesel truck + hammer	(gram/hp-hr)	15.5	4	0.1				Noise (dBA/unit)	76	Total length (hr)	3.0
		(lb/hp-hr)	0.03418	0.00882	0.00022				How many trucks	4	Ref. duration (hr)	24.2
		(lb/hr)/unit	10.253	2.646	0.066	0.983			Noise (dBA)	82.0	Noise dose (%)	212.4
		(lb/operating)	172.255	44.453	1.111		HP	units	TWA	95.4	TWA w/suppressor	76.3
		U-value	0.947	0.991	0.993		300	12				
	Gravel: Low sulphur diesel truck w/tier III engine+ dust	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	54.0
		(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
		(lb/hr)/unit	10.253	0.132	0.157	0.781			Noise (dBA)	80.0	Noise dose (%)	169.2
		(lb/operating)	2214.702	28.577	33.829		HP	units	TWA	93.8	TWA w/suppressor	75.0
		U-value	0.319	0.994	0.799		300	216				
	Mat: Low sulphur diesel truck w/tier III engine	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	6.0
		(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
		(lb/hr)/unit	10.253	0.132	0.007	0.984			Noise (dBA)	80.0	Noise dose (%)	18.8
		(lb/operating)	246.078	3.175	0.159		HP	units	TWA	77.9	TWA w/suppressor	62.4
		U-value	0.924	0.999	0.999		300	24				
	Module: Low sulphur diesel truck w/tier III engine + hammer	(gram/hp-hr)	15.5	0.2	0.01				Noise (dBA/unit)	74	Total length (hr)	3.0
		(lb/hp-hr)	0.03418	0.00044	0.00002				How many trucks	4	Ref. duration (hr)	31.9
		(lb/hr)/unit	10.253	0.132	0.007	0.989			Noise (dBA)	80.0	Noise dose (%)	209.4
		(lb/operating)	172.255	2.223	0.111		HP	units	TWA	95.3	TWA w/suppressor	76.3
		U-value	0.947	1.000	0.999		300	12				

● Emission of Engine (rate)

Proportion	Engine types	Unit	0.2 CO	0.4 NO_x	0.4 PM	Overall score
Proportion 100%	Internal Combustion Engine	(lb/MWh)	6.2	21.8	0.78	0.118
		(lb/hr)/unit	6.200	21.800	0.780	
		(lb/hr)*portion	6.200	21.800	0.780	
		(lb/operating)	1339.200	4708.800	168.480	
		U-value	0.588	0.000	0.000	
	Internal Combustion Engine with SCR	(lb/MWh)	6.2	4.7	0.78	0.431
		(lb/hr)/unit	6.200	4.700	0.780	
		(lb/hr)*portion	6.200	4.700	0.780	
		(lb/operating)	1339.200	1015.200	168.480	
		U-value	0.588	0.784	0.000	
	Lean-burn natural gas engine (SI)	(lb/MWh)	5	2.2	0.03	0.878
		(lb/hr)/unit	5.000	2.200	0.030	
		(lb/hr)*portion	5.000	2.200	0.030	
		(lb/operating)	1080.000	475.200	6.480	
		U-value	0.668	0.899	0.962	
Proportion 0%	Power from grid	(lb/MWh)	0	0	0	1.000
		(lb/hr)/unit	0.000	0.000	0.000	
		(lb/hr)*portion	0.000	0.000	0.000	
		(lb/operating)	0.000	0.000	0.000	
		U-value	1.000	1.000	1.000	

Power (MW)	units
1	1

Noise (dBA/unit)	86	Total length (hr)	144.0
How many engines	1	Ref. duration (hr)	13.4
Noise (dBA)	86.3	Noise dose (%)	1616.3
TWA	110.1	TWA w/suppressor	88.1
Noise (dBA/unit)	86	Total length (hr)	144.0
How many engines	1	Ref. duration (hr)	13.4
Noise (dBA)	86.3	Noise dose (%)	1616.3
TWA	110.1	TWA w/suppressor	88.1
Noise (dBA/unit)	86	Total length (hr)	144.0
How many engines	1	Ref. duration (hr)	13.4
Noise (dBA)	86.3	Noise dose (%)	1616.3
TWA	110.1	TWA w/suppressor	88.1

Power (MW)	units
1	1

Noise (dBA/unit)	0	Total length (hr)	144.0
How many engines	1	Ref. duration (hr)	2097152.0
Noise (dBA)	0.0	Noise dose (%)	0.0
TWA	0.0	TWA w/suppressor	

● Drill Noise

Overbalanced drilling (OB)

Noise (dBA/unit)	95	Total length (hr)	144.0
How many drills	1	Ref. duration (hr)	4.0
Noise (dBA)	95.0	Noise dose (%)	4050.0
TWA	116.7	TWA w/suppressor	93.4

Underbalanced drilling (UB)

Noise (dBA/unit)	100	Total length (hr)	144.0
How many drills	1	Ref. duration (hr)	2.0
Noise (dBA)	100.0	Noise dose (%)	8100.0
TWA	121.7	TWA w/suppressor	97.4

Managed pressure drilling

Noise (dBA/unit)	98	Total length (hr)	144.0
How many drills	1	Ref. duration (hr)	2.6
Noise (dBA)	98.0	Noise dose (%)	6138.7
TWA	119.7	TWA w/suppressor	95.8

[When 'Traditional older vintage rig' is selected]

Sub-sets	Technologies	Buy($)	Resale Value ($)	Rent /day ($)	Daily Rate ($)	Total cost ($)	Ecological Footprint (Acres)	Emissions: *Air*	Emissions: *Solid& Liquid*	Emissions: *Noise (TWA)*	Perceptions: *Gov.*	Perceptions: *Ind.*	Perceptions: *Public*	Safety Value
1	Coventional diesel truck										0.250	1.000	0.250	0.750
2	Gravel roads	$148,500	$0		$9,281	$148,500	3.030	0.566		98.562	0.250	1.000	0.250	0.500
	DURA-BASE from Composite Mat (buy)	$2,706,000	$2,164,800		$33,825	$541,200	1.515	0.964		82.870	1.000	0.500	1.000	1.000
	DURA-BASE from Composite Mat (rent)					$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
3	Gravel pad	$137,813	$0		$8,613	$137,813	2.812	0.598		98.019	0.250	1.000	0.250	0.500
	DURA-BASE from Composite Mat (buy)	$2,511,250	$2,009,000		$31,391	$502,250	1.406	0.967		82.242	0.750	0.750	0.750	1.000
	DURA-BASE from Composite Mat (rent)					$122,500	1.406	0.967		82.242	0.750	0.750	0.750	1.000
	Aluminum modules + driven piles	$1,862,041	$1,489,633		$23,276	$372,408	0.007	0.973		97.614	1.000	0.500	1.000	0.500
4	Traditional older vintage rig			$12,500	$12,500	$220,000		0.973		78.630	0.500	1.000	0.500	0.500
5	Internal combustion engine			$5,000	$5,000	$80,000		0.118		110.073	0.500	1.000	0.500	0.750
	Internal combustion engine w/SCR, w/noise suppressor			$7,411	$7,411	$118,569		0.431		88.059	0.750	0.750	0.750	0.750
	Lean-burn natural gas engines w/noise suppressor			$7,817	$7,817	$125,073		0.878		88.059	1.000	0.500	1.000	0.750
6	Conventional diesel			$6,720	$6,720	$94,080					0.500	1.000	0.500	0.500
	Low sulphur diesel			$7,056	$7,056	$98,784					0.750	0.750	1.000	0.750
	Natural gas			$4,200	$4,200	$58,800					1.000	0.500	1.000	0.750
7	N/A			$0	$0	$0	0.000	1.000		0.000	0.250	1.000	0.250	1.000
8	N/A	$0	$0		$0	$0	0.000				0.250	1.000	0.250	1.000
9	Conventional overbalanced drilling			$17,000	$17,000	$204,000				116.700	1.000	0.500	0.500	0.500
10	Water-based muds					$47,940					1.000	1.000	1.000	1.000
11	Lined reserve pit + solid control equip.*			$2,000	$2,000	$24,000	0.037		0.500		0.750	0.750	0.750	0.500
	Closed loop + containers + solid control equip.*			$3,000	$3,000	$36,000	0.000		1.000		1.000	0.500	1.000	0.750
12	Cuttings injection			$5,000	$5,000	$60,000			1.000		1.000	0.500	1.000	0.750
	Chemical fixation and solidification (CFS)					$61,710			0.250		0.750	0.750	1.000	0.500
13	N/A													

[When 'Rapid Rig' is selected]

Sub-sets	Technologies	Buy($)	Resale Value ($)	Rent /day ($)	Daily Rate ($)	Total cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
								Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
1	Low sulphur diesel truck w/tier III engine, w/noise suppressor										1.000	0.500	1.000	0.750
2	Gravel roads	$198,396	$0		$19,077	$198,396	3.030	0.679		77.250	0.500	0.750	0.500	0.500
	DURA-BASE from Composite Mat (buy)	$2,721,840	$2,177,472		$52,343	$544,368	1.515	0.976		64.696	1.000	0.500	1.000	1.000
	DURA-BASE from Composite Mat (rent)					$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
3	Gravel pad	$135,270	$0		$13,007	$135,270	2.066	0.781		75.036	0.500	0.750	0.500	0.500
	DURA-BASE from Composite Mat (buy)	$1,855,800	$1,484,640		$35,688	$371,160	1.033	0.984		62.356	0.750	0.750	0.750	1.000
	DURA-BASE from Composite Mat (rent)					$100,800	1.033	0.984		62.356	0.750	0.750	0.750	1.000
	Aluminum modules + driven piles	$1,131,303	$905,042		$21,756	$226,261	0.005	0.989		76.265	1.000	0.500	1.000	0.500
4	Rapid Rig			$14,000	$14,000	$168,000		0.986		60.016	1.000	0.500	1.000	1.000
5	Internal combustion engine			$4,500	$4,500	$46,800		0.345		107.691	0.500	1.000	0.500	0.750
	Internal combustion engine w/SCR, w/noise suppressor			$6,670	$6,670	$69,363		0.578		86.153	0.750	0.750	0.750	0.750
	Lean-burn natural gas engines w/noise suppressor			$7,035	$7,035	$73,168		0.909		86.153	1.000	0.500	1.000	0.750
6	Conventional diesel			$4,320	$4,320	$43,848					0.500	1.000	0.500	0.500
	Low sulphur diesel			$4,536	$4,536	$46,040					0.750	0.750	1.000	0.750
	Natural gas			$2,700	$2,700	$27,405					1.000	0.500	1.000	0.750
7	Electric power from grid (10%)			$384	$384	$3,994	0.000	1.000		0.000	0.500	1.000	1.000	1.000
8	Flywheels	$150,000	$120,000		$2,885	$30,000	0.000				0.500	1.000	1.000	0.750
9	Underbalanced drilling w/noise suppressor			$20,500	$20,500	$202,950				96.250	0.750	0.750	0.750	0.750
10	Water-based muds					$47,940					1.000	1.000	1.000	1.000
11	Lined reserve pit + solid control equip.*			$2,000	$2,000	$19,800	0.037		0.500		0.750	0.750	0.750	0.500
	Closed loop + containers + solid control equip.*			$3,000	$3,000	$29,700	0.000		1.000		1.000	0.500	1.000	0.750
12	Cuttings injection			$5,000	$5,000	$49,500			1.000		1.000	0.500	1.000	0.750
	Chemical fixation and solidification (CFS)					$61,710			0.250		0.750	0.750	1.000	0.500
13	N/A													

[When 'LOC250 (CWD)' is selected]

Sub-sets	Technologies	Buy($)	Resale Value ($)	Rent /day ($)	Daily Rate ($)	Total cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
								Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
1	Low sulphur diesel truck w/tier III engine, w/noise suppressor										1.000	0.500	1.000	0.750
2	Gravel roads	$198,396	$0		$19,840	$198,396	3.030	0.679		77.250	0.500	0.750	0.500	0.500
	DURA-BASE from Composite Mat (buy)	$2,721,840	$2,177,472		$54,437	$544,368	1.515	0.976		64.696	1.000	0.500	1.000	1.000
	DURA-BASE from Composite Mat (rent)					$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
3	Gravel pad	$135,270	$0		$13,527	$135,270	2.066	0.781		75.036	0.500	0.750	0.500	0.500
	DURA-BASE from Composite Mat (buy)	$1,855,800	$1,484,640		$37,116	$371,160	1.033	0.984		62.356	0.750	0.750	0.750	1.000
	DURA-BASE from Composite Mat (rent)					$100,800	1.033	0.984		62.356	0.750	0.750	0.750	1.000
	Aluminum modules + driven piles	$1,131,303	$905,042		$22,626	$226,261	0.005	0.989		76.265	1.000	0.500	1.000	0.500
4	LOC250 (CWD)			$15,000	$15,000	$173,800		0.985		60.366	1.000	0.500	1.000	1.000
5	Internal combustion engine			$3,500	$3,500	$35,000		0.537		104.678	0.500	1.000	0.500	0.750
	Internal combustion engine w/SCR, w/noise suppressor			$5,187	$5,187	$51,874		0.701		83.742	0.750	0.750	0.750	0.750
	Lean-burn natural gas engines w/noise suppressor			$5,472	$5,472	$54,720		0.936		83.742	1.000	0.500	1.000	0.750
6	Conventional diesel			$3,360	$3,360	$31,920					0.500	1.000	0.500	0.500
	Low sulphur diesel			$3,528	$3,528	$33,516					0.750	0.750	1.000	0.750
	Natural gas			$2,100	$2,100	$19,950					1.000	0.500	1.000	0.750
7	Electric power from grid (30%)			$1,152	$1,152	$11,520	0.000	1.000		0.000	0.500	1.000	1.000	1.000
8	Flywheels	$450,000	$360,000		$9,000	$90,000	0.000				0.500	1.000	1.000	0.750
9	Managed pressure drilling w/noise suppressor			$21,500	$21,500	$193,500				94.100	0.750	0.750	1.000	1.000
10	Water-based muds					$47,940					1.000	1.000	1.000	1.000
11	Lined reserve pit + solid control equip.*			$2,000	$2,000	$18,000	0.037		0.500		0.750	0.750	0.750	0.500
	Closed loop + containers + solid control equip.*			$3,000	$3,000	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
12	Cuttings injection			$5,000	$5,000	$45,000			1.000		1.000	0.500	1.000	0.750
	Chemical fixation and solidification (CFS)					$61,710			0.250		0.750	0.750	1.000	0.500
13	N/A													

[Input values and single-attribute utility scores of SET 1]

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: Aluminum modules + driven piles	$226,261	0.005	0.989		76.265	1.000	0.500	1.000	0.500
(4) Rig type: LOC250 (CWD)	$173,800		0.985		60.366	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	$70,354		0.918		85.603	1.000	0.500	1.000	0.750
(6) Fuel type: Natural gas	$25,650					1.000	0.500	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$3,840	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Managed pressure drilling w/noise suppressor	$193,500				94.100	0.750	0.750	1.000	1.000
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$991,184	1.520	4.868	2.000	381.030	0.500	0.500	1.000	0.500
Single Attribute Utility Values	0.811	1.000	0.989	1.000	0.988	0.500	0.500	1.000	0.500

[Input values and single-attribute utility scores of SET 2]

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: DURA-BASE from Composite Mat (rent)	$100,800	1.033	0.984		62.356	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	$173,800		0.985		60.366	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	$70,354		0.918		85.603	1.000	0.500	1.000	0.750
(6) Fuel type: Natural gas	$25,650					1.000	0.500	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	$3,840	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	$184,500				95.700	0.750	0.750	0.750	0.750
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$856,724	2.548	4.863	2.000	368.721	0.500	0.500	0.750	0.750
Single Attribute Utility Values	0.931	0.764	0.986	1.000	0.998	0.500	0.500	0.750	0.750

[Input values and single-attribute utility scores of SET 3]

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: DURA-BASE from Composite Mat (rent)	$90,000	1.033	0.976		79.945	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	$167,000		0.977		77.458	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	$78,171		0.908		86.399	1.000	0.500	1.000	0.750
(6) Fuel type: Natural gas	$28,500					1.000	0.500	1.000	0.750
(7) Rig power (Unconventional): N/A (0 %)	$0	0.000	1.000		0.000	0.250	1.000	0.250	1.000
(8) Energy storage: N/A	$0	0.000				0.250	1.000	0.250	1.000
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	$184,500				95.700	0.750	0.750	0.750	0.750
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$800,111	2.548	4.825	2.000	422.371	0.250	0.500	0.250	0.750
Single Attribute Utility Values	0.982	0.764	0.962	1.000	0.911	0.250	0.500	0.250	0.750

[Input values and single-attribute utility scores of SET 4]

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Low sulphur diesel truck w/tier III engine, w/noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$147,840	1.515	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: Aluminum modules + driven piles	$226,261	0.005	0.989		76.265	1.000	0.500	1.000	0.500
(4) Rig type: LOC250 (CWD)	$173,800		0.985		60.366	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Lean-burn natural gas engines w/noise suppressor	$54,720		0.936		83.742	1.000	0.500	1.000	0.750
(6) Fuel type: Natural gas	$19,950					1.000	0.500	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (30 %)	$11,520	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	$90,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Managed pressure drilling w/noise suppressor	$193,500				94.100	0.750	0.750	1.000	1.000
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$1,037,530	1.520	4.886	2.000	379.169	0.500	0.500	1.000	0.500
Single Attribute Utility Values	0.769	1.000	1.000	1.000	0.989	0.500	0.500	1.000	0.500

[Input values and single-attribute utility scores of SET 5]

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: DURA-BASE from Composite Mat (rent)	$90,000	1.033	0.976		79.945	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	$167,000		0.977		77.458	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Internal combustion engine	$50,000		0.338		107.998	0.500	1.000	0.500	0.750
(6) Fuel type: Low sulphur diesel	$47,880					0.750	0.750	1.000	0.750
(7) Rig power (Unconventional): N/A (0 %)	$0	0.000	1.000		0.000	0.250	1.000	0.250	1.000
(8) Energy storage: N/A	$0	0.000				0.250	1.000	0.250	1.000
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	$184,500				95.700	0.750	0.750	0.750	0.750
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	$27,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$791,320	2.548	4.254	2.000	443.971	0.250	0.500	0.250	0.750
Single Attribute Utility Values	0.990	0.764	0.613	1.000	0.820	0.250	0.500	0.250	0.750

[Input values and single-attribute utility scores of SET 6]

Selected Technologies in Each Subset	Total Cost ($)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
			Air	*Solid& Liquid*	*Noise (TWA)*	*Gov.*	*Ind.*	*Public*	
(1) Transportation: Coventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: DURA-BASE from Composite Mat (rent)	$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: DURA-BASE from Composite Mat (rent)	$90,000	1.033	0.976		79.945	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	$167,000		0.977		77.458	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Internal combustion engine	$50,000		0.338		107.998	0.500	1.000	0.500	0.750
(6) Fuel type: Conventional diesel	$45,600					0.500	1.000	0.500	0.500
(7) Rig power (Unconventional): N/A (0 %)	$0	0.000	1.000		0.000	0.250	1.000	0.250	1.000
(8) Energy storage: N/A	$0	0.000				0.250	1.000	0.250	1.000
(9) Drilling tech.: Underbalanced drilling w/noise suppressor	$184,500				95.700	0.750	0.750	0.750	0.750
(10) Fluid type: Water-based muds	$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Lined reserve pit + solid control equip.*	$18,000	0.037		0.500		0.750	0.750	0.750	0.500
(12) Cuttings mgmt.: Cuttings injection	$45,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction: N/A									
Overall Attribute Scores (Σ or minimum value)	$780,040	2.585	4.254	1.500	443.971	0.250	0.500	0.250	0.500
Single Attribute Utility Values	1.000	0.756	0.613	0.600	0.820	0.250	0.500	0.250	0.500

The knapsack optimization model for the EFD technology selection problem with nine attributes is given as follows:

$$\text{Maximize } \ U = \sum_{j=1}^{J} y_j \left[\sum_{i=1}^{9} k_i u_i (X_{ij}) \right]$$

where j is the index for systems, J is the number of possible systems, i is the index for the attributes, k_i is the weight assigned to the i^{th} attribute (k must sum to 1), X_{ij} is the overall score of the j^{th} system on the i^{th} attribute, $u_i(X_{ij})$ is the single-attribute utility value for system j on attribute i, scaled from 0 to 1, and y_j is a binary decision variable that is one if system j is selected and zero if it is not. In order to calculate the overall score of a system on the i^{th} attribute (X_i), Eq. (5-1), Eq. (5-2), and Eq. (5-3) should be considered. The other constraint required to consider for this optimization problem is:

$$\sum_{j=1}^{J} y_j = 1$$

where y_j is a binary decision variable.

APPENDIX C

QUESTIONNAIRES ABOUT THE WEB-BASED DECISION OPTIMIZATION TOOL [VERSION 1.1]

1. <u>What do you think the biggest advantage of using the Web-based decision optimization application is?</u>

- Well guided for selecting the options
- It optimized the data for us
- It allows you to consider impacts based on factors other than cost-like environmental effects
- It allows you to weigh the options
- You can weigh the options
- Generate optimized values based on weight factor we want to assign
- Convenience
- Brings out the best combination scenario for any particulate area
- We managed to use the system efficiently and the system was able to optimize our data
- It relates the perception value to a dollar amount
- Each section is very systematic
- Easy to input ➔ location, ➔ multiple users
- We can keep the video as note and choose the part that we need to review
- Easy, handy, and comprehensive
- Eases the calculation
- Making the decision simple
- This will be helping to organize the input and output process of the information
- Pulling data from multiple sources, and consolidation of sources
- Time saving
- Optimizing function. Easy, quick and efficient
- Give a good idea about technologies and methods for different areas
- Ready made cost and perception
- Being impacts based on factor and not only upon cost/ environment
- It lets you grade different attractive using weighting factors appropriate for each criterion. It makes it easy to evaluate alternatives since it outputs the best combination
- There is a consistent rubric that forces every group to consider the same factors
- Makes the optimization easier
- Does weighting technique extremely well. Very easy to use
- Ready made cost and perception

2. <u>Do you think the application is ease to use? If no, please explain what the most difficult part of using the application is.</u>

- Yes, the options were elaborate and therefore selecting was not cumbersome
- Yes, it’s fairly easy to use and understand with basic knowledge of software and optimization principles
- No, setting up the system was complicated in the beginning. Making our own

modifications was difficult

- I did not think it was super easy to use. It was difficult to set up
- Basic design of each action item might be not independent
- Fairly easy. Requires basic knowledge
- It's easy to use but some more explanation about how the perceptions should be chosen (i.e., 1 is what, 0 is what, what your answer represents?)
- Yes, but how to input the weighting factors was a bit confusing
- It was hard to start, but the example posted by Dr. Burnett was very helpful
- Application is easy enough to use but not flexible
- Result sheet
- Yes, but it is not practical
- Yes, but it does not have "Save as" option
- Some data were hard to obtain (e.g., perception from industry and public)
- No, it was very complex. It took us a lot of time to understand how to determine the points. It is also wage
- Most difficult part was to access the values to the emissions and what the public and government would think
- Modification not easy after set up
- The application is decently easy to use. The log in and user interface need to be improved
- Was easy but only if you explored it a little
- Yes, but if possible, develop a calculation for specific scenarios

3. <u>Which part should be modified soon for the application?</u>

- Maybe give a "Set-up" section with instructions
- Good instructions on what to do
- Better instructions on what to do and how to use it
- Some errors found in the results
- Put more description about scoring
- Not very familiar with system
- A little more instructions
- More instructions
- It would be good to simplify the process of inputting weighting factors.
- Perceptions are hard to estimate
- A percentage of power input, or power supplied needs to be added
- Can we show every step for the calculation?
- Minimum number of technologies analyzed should be less than 4
- The weighting point section
- The optimization matrix assumes that
- The factors and weight that are inserted are difficult and cumbersome to determine. Some fixed costs (standards) should be fixed

- Units should be mad consistent
- The result summary page
- The optimization matrix assumes that power will be constant
- The outputs generated. I am not aware if there is a tutorial and manual on how to use it

4. <u>Any other suggestion and comments for the application?</u>

- If you do not want to select a technology from a certain Subset, just skip it. (Do not need to fill out "0" for that).
- Should be more specific details about perception factors
- Make it more secure. Want some permission thing
- Can be a powerful and very useful tool
- More examples would be helpful
- If you can add an option of populating the results in a pdf file
- Give options to input and remove parameters
- Neatly charted and user friendly
- Include columns for fixed cost and daily costs and give direction on how to prorate capitalized costs. Needs to be more finance based in order to find the present net values for the wells
- Matrix versatile
- Lab view type design
- Unique and informative source

VITA

Name: Ok-Youn Yu

Address: Zachry Department of Civil Engineering
Texas A&M University
College Station, TX 77843-3136, USA

Email Address: tg0918@tamu.edu

Education

2006-2009 Ph.D., Civil Engineering, Texas A&M University, TX.
2003-2005 M.S., Construction Management, Texas A&M University, TX.
1992-1999 B.S., Civil Engineering, KonKuk University, Korea.

Experience

2006-2009 Texas A&M University, College Station, TX.
Research Assistant, Zachry Department of Civil Engineering.

2004-2005 Texas A&M University, College Station, TX.
Research Assistant, Department of Construction Science.

2000-2003 Daehan Consultants Co., Ltd., Seoul, Korea.
Bridge and Tunnel Design Engineer, Structural Department II.

1998-2000 Dongshin Engineering & Development Co., Ltd., Seoul, Korea.
Structural Engineer, Structural Department.