FAD 5.2.3

Users Guide

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A. FAD DOCUMENTATION

A.1. Introduction

A.1.1. General

FAD Tools is a software package that assists in the design and analysis of electric transmission line structure foundations. FAD Tools includes the following modules:

- MFAD (Moment Foundation Analysis and Design) – design of reinforced concrete drilled shaft and direct embedment pole foundations subject to high overturning loads and relatively low compression loads.
- HFAD (H-Frame Foundation Analysis and Design) – design of reinforced concrete drilled shaft and direct embedment pole foundations for H-frame pole structures subject to combined overturning, uplift and compression loads.
- TFAD (Tower Foundation Analysis and Design) – design of reinforced concrete drilled shaft foundations for lattice tower structures subject to uplift or compression with shear loads.

These modules are specifically created to assess loads induced by electric system transmission line structures on relatively short rigid shaft foundations. It is essential that the foundation designer understand the applied loads, foundation reactions, subsurface conditions and the geotechnical resistance parameters to properly use FAD Tools. This guide presents the following information:

- Description of the FAD Tools geotechnical resistance models,
- Reliability-Based Design methodology used in FAD Tools,
- FAD Tools model calibrations for Reliability-Based Design,
- Foundation Design Process for FAD Tools,
- Geotechnical design parameters used in FAD Tools,
- Performance parameters used in FAD Tools,
- Reinforced concrete design for drilled shaft foundations within FAD Tools modules, and
- Step-by-step use of the FAD Tools program.

This document is an updated version of the FAD 5.1 User Guide (2015). The development of MFAD, HFAD and TFAD is summarized in in the Electric Power Research Institute (EPRI) *Transmission Foundation Design Guide* (EPRI 2012, EL-1024138) document.

A.1.2. FAD Tools Background

The original program called Pier Analysis and Design for Lateral Loads (PADLL) was developed and released by EPRI in 1982 (EPRI 1982, EL-2197). Subsequent versions of the MFAD program were released by EPRI through their Transmission Line Work Station program (EPRI 2006, 1012318). The MFAD model was updated and re-calibrated for the development of FAD Tools 5.0 (2010).

HFAD (for H-Frame structure foundations) and TFAD (for tower structure foundations) were developed by EPRI through subsequent efforts (EPRI 2010, TR-1020739 and EPRI 2015, TR-1019957). Below is a brief list of published commercial versions to date:

Table A-1. FAD Versions

Version	Release	Description
5.0	2010	Commercial Version
5.1.9	2010	EPRI Version (Offered to funders only)
5.1.16	2014	Commercial Version (Minor Revisions)
5.1.17	2014	Commercial Version (Minor Revisions)
5.1.18	2014	Commercial Version (Minor Revisions)
5.1.19	2015	EPRI Version (Offered to funders only)
5.2.0	2018	Commercial Version (User comment updates)
5.2.1	2018	Commercial Version (Minor Revisions)
5.2.2	2023	Commercial Version (New Licensing System)
5.2.3	2023	Commercial Version (User recommended updates and improvements)

A.2. Geotechnical Resistance Models

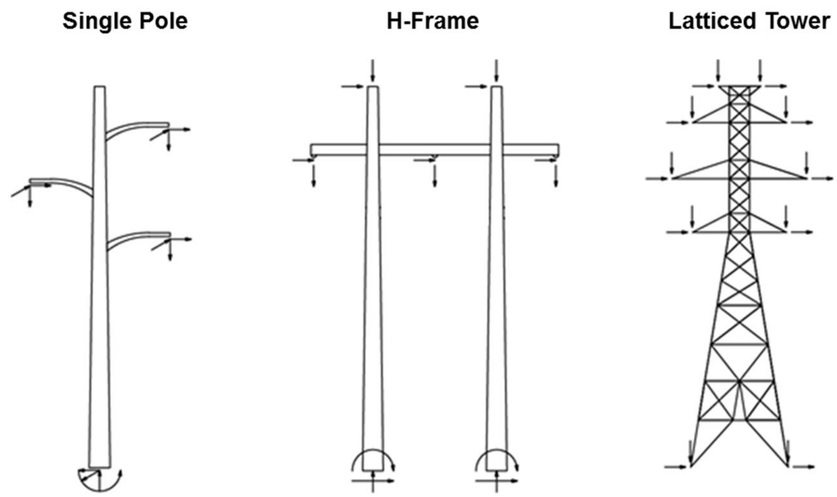
A.2.1. Introduction

The objective of this section is to discuss the geotechnical resistance model used within FAD to calculate both the lateral and axial capacity of drilled shafts and direct embedded poles. Drilled shafts are a common foundation alternative for single pole, H-frame, and lattice tower structures while direct embedded poles are common for single pole and H-frame structures. The FAD geotechnical resistance model is semi-empirical, in that the results of full-scale foundation tests are used (where applicable) to adjust the theoretical models (See EPRI 1982, El-2197 for discussion of models). The FAD geotechnical resistance model is further calibrated for Reliability-Based Design (RBD) (see discussion in Section A.4). Three FAD foundation design modules (MFAD, HFAD and TFAD) are developed to adequately model particular pier-type foundation reactions to applied loads with variable subsurface conditions.

A.2.2. Structure Types and Modes of Foundation Loads

Different electric transmission line structure types will produce different modes of foundation behavior. It is important for the transmission line engineer to recognize the foundation behavior expected under the applied loads and design the foundations to ensure geotechnical and structural integrity. Transmission structures and foundations should be designed for a combination of probabilistic weather loads, construction loads, maintenance loads, and failure containment loads in accordance with regulatory codes or standards (i.e. Nation Electric Safety Code (NESC), ASCE Manual 74—Guidelines for Electrical Transmission Line Structural Loading) and a utility's specific design criteria.

Depending on code requirements and the importance of the line, individual loads may or may not be factored. To maintain a consistent reliability between the structure and the foundations, the maximum reactions generated from these load cases (including load factors) should be used for the design of the foundation (See Section A.3 for further discussion on applied loads in FAD). The modes of the foundation behavior are illustrated in the following discussions.



	Single Pole	H-Frame	Latticed Tower
Moment M	High	Moderate – High	None
Shear V	Moderate	Low – Moderate	Moderate
Axial P	Low	High – Moderate	High

Figure A.1
Foundation Reactions for various structures

A.2.3. Single Pole Structures

Single pole (monopole, un-guyed) structures act as cantilevers. Primary forces on the foundations are the consequence of loading near the top of these tall monopole structures (conductor weight, line tension, wind/ice on conductors, broken conductors, etc.), which induce high overturning moments at relatively moderate shear with low axial forces at the top of foundations (Figure A.1a). These lateral pole loads are transferred to the foundation and, in turn, the foundation applies lateral pressures to subsurface soil/rock on opposite sides of the drilled shaft. For short rigid foundations, soil lateral resistance develops above and below the center of rotation of the shaft (inflection point), resulting in a force couple resisting the lateral reactions (See Section A.2.8) (EPRI 1982, EL-2197). The MFAD module analyzes a single pole foundation (either drilled shaft or direct embedment), which resists the critical case of one or more applied load cases.

The MFAD drilled shaft model is based on full-scale testing using a prototype base-plated tubular steel pole founded on reinforced concrete piers (EPRI 1982, EL-2197, vol. 2; EPRI 1997, TR-108254). The MFAD direct embedment module is based on full-scale testing of steel poles without base plates, prestressed concrete poles, and wood poles using annulus backfill comprised of native soil or crushed stone (EPRI 1989, EL-6309). Additional full-scale testing done for the direct embedment model utilized steel poles without base plates embedded within rock or soil and rock using annulus backfill comprised of crushed stone, sand and gravel, grouted gravel or concrete (EPRI 1997, TR-108254).

A.2.4. H-Frame Structures

H-frames are two-pole systems connected by cross members so that the poles act as a single structural frame. Conductors are attached near the top of one or more horizontal frame members. The rigidity of the system dictates the primary foundation reaction, where axial loads are predominate with rigid frames and moment reactions are predominate with flexible frames. Typically, reactions at the base of most electric system H-frame structures take the form of high axial forces with moderate moment and low shear forces (Figure A.1b). Foundation reactions are transferred to the foundation from either direct embedment of a steel pole within backfill in the ground or from a pole base plate to anchor bolts embedded into a reinforced concrete drilled shaft. H-Frame structure foundation reactions include both axial and lateral reactions (See Section A.2.8 for discussion of laterally loaded foundations and Section A.2.9 for discussion of axially loaded foundations). The HFAD module is used to design a foundation for the critical case of either uplift or compression loading with associated lateral reactions. Input requires one critical load case for uplift and compression, and two critical load cases for moment with maximum uplift and compression representing both foundation legs as the foundation design is adequate for both legs of the structure. The HFAD model does not assess guyed structures.

A.2.5. Latticed Tower Structures

Lattice towers are truss systems where loads are transferred through structural members via compression and tension. Four-legged lattice towers are typically used to suspend high voltage transmission lines due to their ability to support substantial loads at height, allowing for longer line spans. Structure loads result in high axial reactions (often two legs in uplift and two legs in compression) with moderate lateral shear forces at the top of foundation (Figure A.1c). These reactions are transferred to the foundation through steel stub angles or anchored base plates into a reinforced concrete drilled shaft foundation. Uplift tends to control lattice tower foundation design. Axial loads are assumed to transfer to surrounding soils by cylindrical shear resistance that develops around the perimeter of the drilled shaft foundation. The focus of design is to properly size the perimeter dimension of drilled shafts to mobilize shear resistance and counter high axial loads (See Section A.2.9 for discussion of axially loaded foundations). The TFAD module is used to design foundations for the critical case of either uplift force with associated shear reaction or compression loading with associated shear reaction. The TFAD program designs a single foundation to satisfy all four legs of a lattice tower. The TFAD model does not assess guyed structures.

A.2.6. Foundation Types and Limits

Drilled shafts have diameters that typically range from 2.5 feet to 12 feet depending on the structure type, structure size and foundation loads. For transmission structures, the ratio of the drilled shaft embedment depth to diameter typically ranges from 2 to 10, again depending on the loads and subsurface conditions (see section A.2.7 for specific relationship). Drilled shafts primarily consist of concrete with steel reinforcement. Drilled shafts are reinforced with both longitudinal and transverse steel reinforcing bars that are designed in accordance with various sections of the latest version of the ACI 318 building code for concrete structures (ACI 2014). Detailed reinforced concrete foundation design is presented in Section A.8. .

Direct embedded pole foundation diameters depend on the diameter of the portion of the transmission line pole that is embedded in the soil and/or rock along with the thickness of the backfill annulus. Since the poles are typically tapered, the drilled shaft diameter is often determined by the maximum pole or butt plate diameter. The poles are embedded in oversized shafts drilled into the soil and/or rock and the annulus between the embedded pole and the ground is backfilled with a variety of materials (see Backfill Section A.2.8.2 for discussion). FAD determines the critical conditions of failure for direct embedment foundations, which may occur at the pole-annulus interface, within the annulus material, or within the subsurface material. The direct embedment model in FAD is based on full-scale tests using steel monopoles without baseplates.

A.2.7. Behavior of Laterally Loaded Piers

Laterally loaded drilled shaft piers behave differently depending on embedment depth, diameter and relative stiffness between the surrounding soil and the foundation. A number of researchers have observed the need for different analysis methods for short, intermediate and long shafts (under free head conditions) and have developed classifications based on shaft properties (diameter, embedment depth, soil stiffness, shaft bending stiffness) (Broms 1964, Woodward, et al. 1972; Vallabhan and Alikhanlou 1982; Ashour, et al. 2000) (Figure A.2).

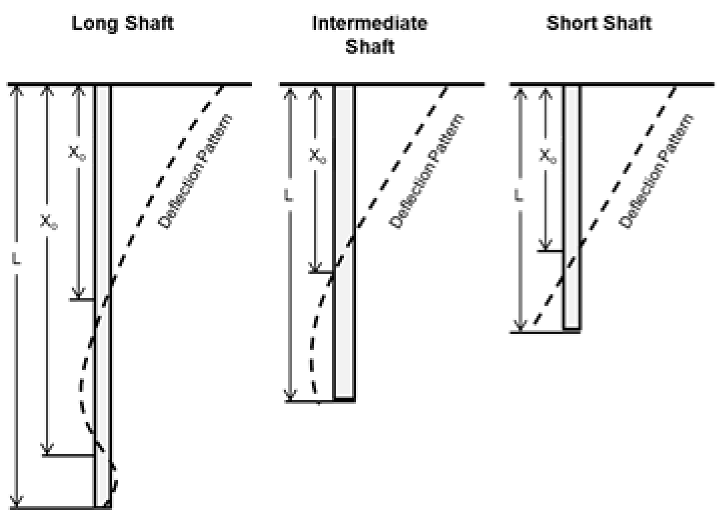


Figure A.2
Laterally Loaded Pile/Pier Behavior

A short pier (as modeled in the FAD modules) exhibits a near linear lateral deflection profile with a single point of rotation point (center of rotation) approximately within the lower one-third of the foundation depth (Figure A.2, short shaft) (EPRI EL-2197). Bending stiffness (EI) remains constant along the full length of the pier. As such, FAD does not consider the stiffness of the foundation (unlike FAD 4.0 which performed a check of rigidity). In general, a short rigid shaft will have a depth to diameter ratio between 2 and 10. If the rigidity of the shaft relative to subgrade soils is in question, the designer should verify relative rigidity. The following equation of rigidity is incorporated within the MFAD model (EPRI 1982, EL-2197, Equation 4-7):

$$\frac{EI_p}{E_s D^4} \geq 1$$

Where:

EI_p = effective flexural stiffness of the foundation;

D = embedment length;

E_s = the modulus of elasticity of the soil (pressuremeter modulus).

A mathematical relationship exists between performance criteria of top of pier deflection and rotation in terms of shaft diameter since a short rigid shaft rotates linearly (as seen in Figure A.3) (Kandaris, et al. 2012). In FAD version 5.1.20, the user is only required to enter maximum allowable pier rotation or deflection, not both, and the program calculates the other property based on this mathematical relationship.

$$\frac{\delta_T}{B} = Cos\ \theta_T \left(\frac{L'}{B} tan\left(\theta_T + tan^{-1}\left(\frac{B}{2L'}\right)\right) - \frac{1}{2}\right)$$

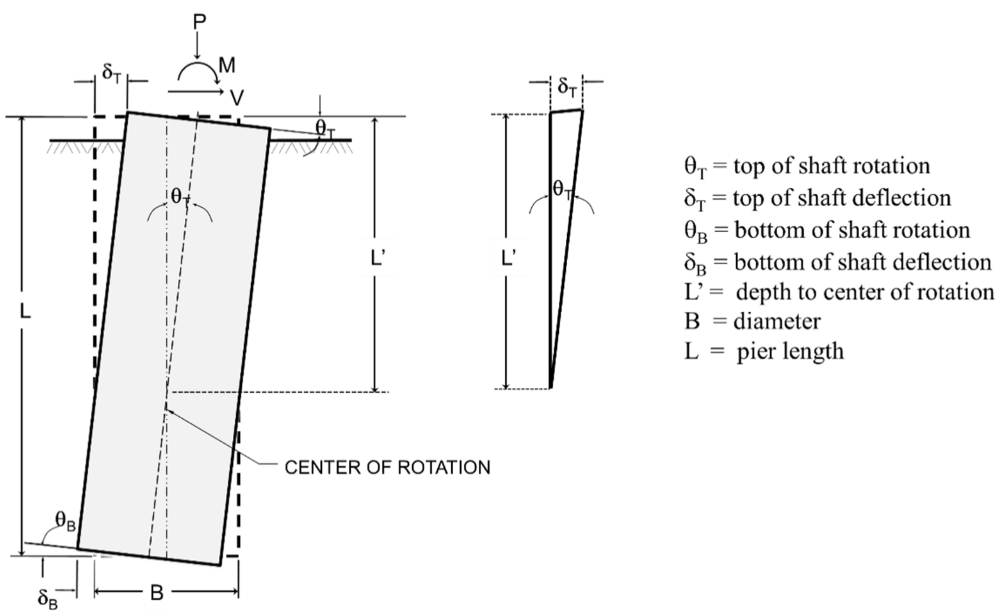


Figure A.3
Rigid Body Motion of Laterally Loaded Short Shafts

A.2.8. MFAD Module

MFAD was developed from existing theoretical analytical models for ultimate lateral capacity and non-linear deflection responses (see EPRI EL-2197 for a full discussion of theoretical models). The theoretical models were subsequently modified from the results of full-scale lateral load tests of drilled pier and direct embedment foundations to obtain a semi-empirical model which provided the best-fit to the test results (EPRI 1982, EL-2197; EPRI 2012, TR-1024138). Resistance factors were determined from calibration of the model for RBD (see Section A.3 and A.4).

MFAD analyzes and designs short rigid reinforced concrete drilled shaft and direct embedment foundations for electric transmission line pole structures that are subject to lateral load with large overturning moments occurring at the top of the foundation. The methodology is based on a semi-empirical ultimate capacity model (calibrated from Hansen 1961) combined with a four-spring, non-linear load deflection model. A subsurface-annulus interaction analysis subroutine based on a two-spring model is used for direct embedment foundations. The foundation is analyzed as a finite beam with 0.1-ft increments (i) along the foundation depth (Figure A.4).

The four-spring model is as follows (drilled shafts):

- Lateral translational springs are used in the analytical model to characterize the lateral force-displacement response of subsurface material.
- Rotational springs are used to characterize the moment developed at the pier centerline by the vertical shear stress at the perimeter of the pier induced by pier rotation (can be turned off).
- A base translational spring is used to characterize the horizontal shearing force-base displacement response (can be turned off).
- A base moment spring is used to characterize the base normal force-rotation response (can be turned off).

The two-spring model is as follows (direct embedment):

- Combined lateral translational springs are used in the analytical model to characterize the lateral force-displacement response of the annulus and the subsurface material.
- Combined rotational springs are used to characterize the moment developed at the pier centerline by the vertical shear stress at the perimeter of the pole and perimeter of the annulus material which induced by pier rotation (can be turned off).

A.2.8.1. Contribution of Springs

The MFAD module was designed for structures subjected to large overturning loads which are resisted largely by lateral resistance (lateral springs). The user can turn various spring types on and off to represent different construction conditions, but is cautioned as the full-scale testing model and model calibrations utilized all springs. The original full-scale foundation tests conducted by EPRI identified the percent contribution each spring type has on the drilled shaft foundation capacity (EPRI 1982, EL-2197). The contribution of the lateral spring increases with increasing depth-to-diameter ratios and the base moment spring contribution increases with the relative stiffness of the base material.

Per the full-scale foundation testing (EPRI 1982, EL-2197):

- Lateral springs provide 52 to 78 percent of the total lateral capacity,
- Vertical Side-Shear springs provide 8 to 26 percent of the total lateral capacity,
- Base Shear spring provides 9 to 19 percent of the total lateral capacity,
- Base Moment spring provides 1 to 5 percent of the total lateral capacity.

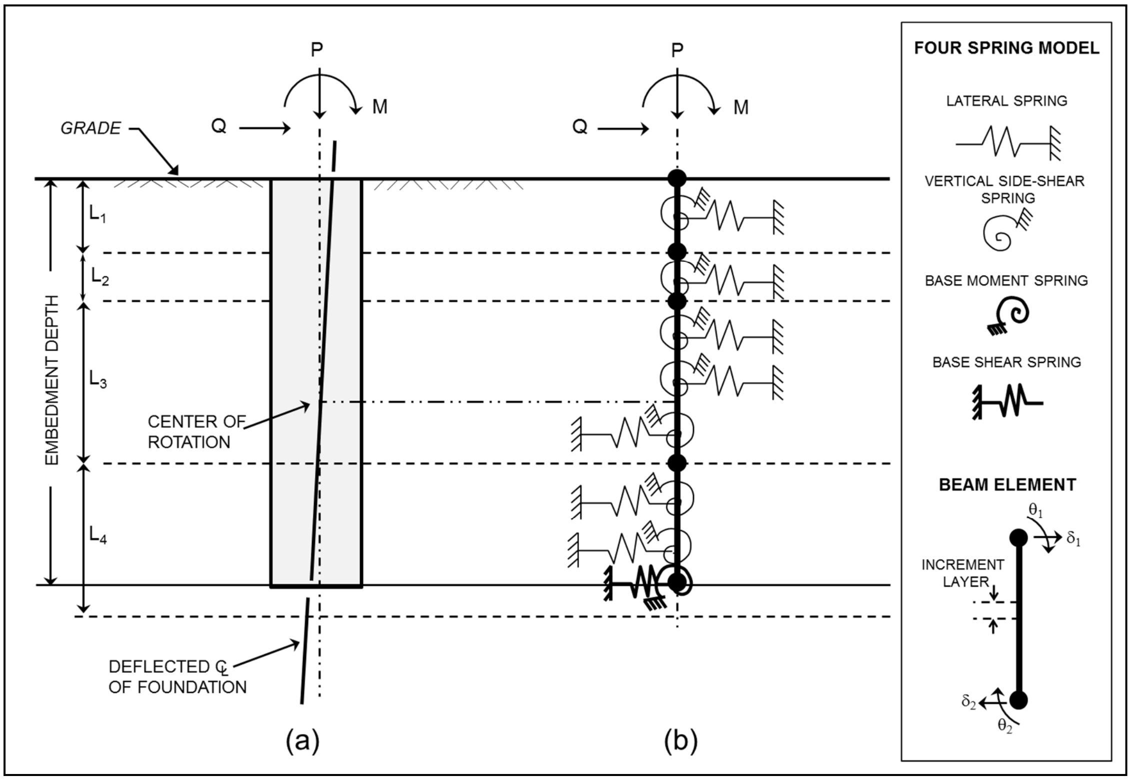


Figure A.4
Schematic Diagram of the MFAD 5.1 Drilled Shaft Design Model

Figure A.4 shows a schematic diagram of a drilled shaft foundation supporting a single pole structure embedded in multiple layers of soil and/or rock. This figure illustrates that the applied foundation reactions P, M and Q are resisted by a combination of lateral pressures, vertical side shear forces, base shear and base moment. The MFAD module computes the nominal capacities and design capacity of a drilled shaft having a given diameter, depth of embedment, and a given subsurface profile.

The MFAD schematic diagram for direct embedded pole foundations in soil and/or rock is shown in Figure A.5. The free-body diagram shows the applied loads are resisted by a combination of lateral pressures and vertical side shear forces of the annulus and subsurface. Base resistance is not included in MFAD direct embedment design mode. The MFAD module computes the nominal shear and moment capacity of a direct embedded pole having a given diameter and depth of embedment for a given subsurface profile, backfill thickness and type. The MFAD module does not assess bearing capacity or rotational torsion in the design of laterally loaded foundations.

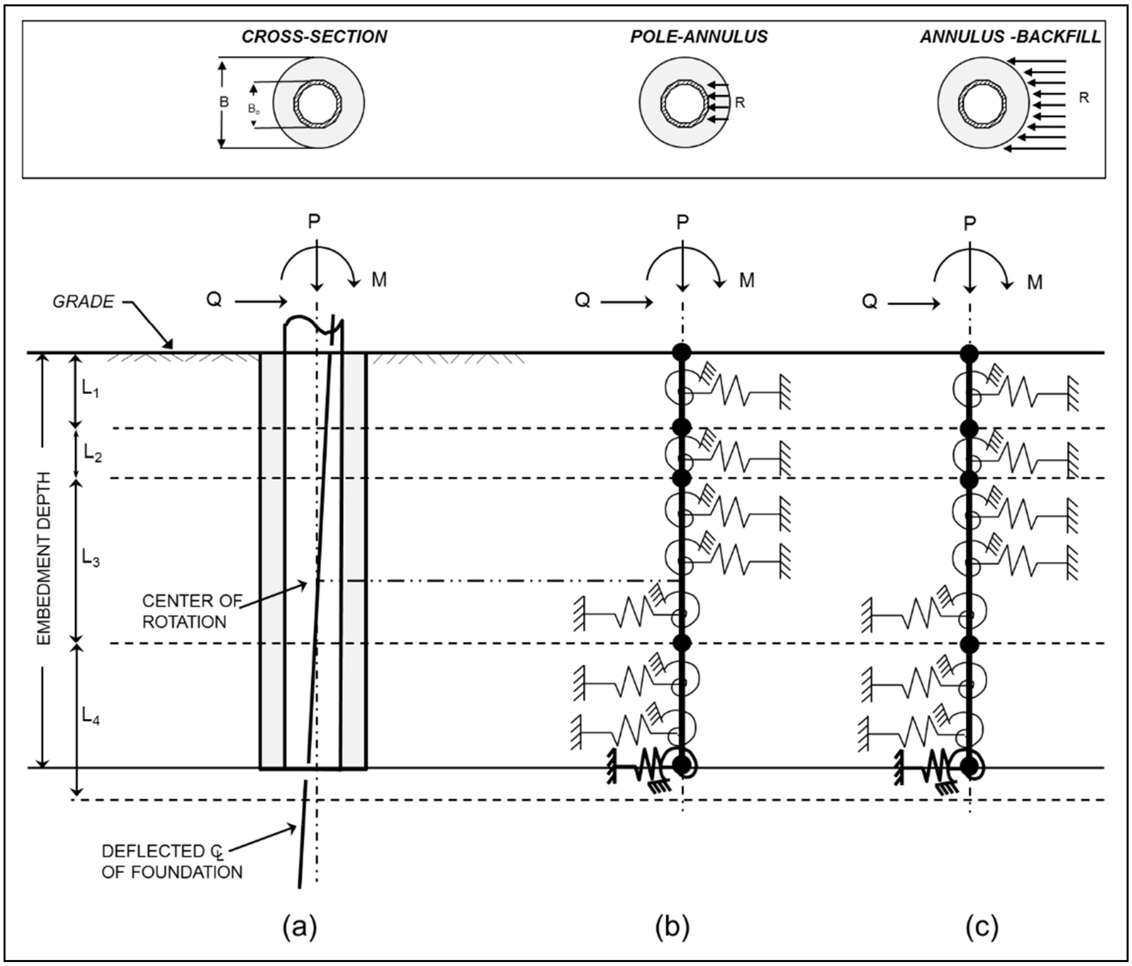


Figure A.5
Schematic Diagram of the MFAD 5.1 Direct Embedment Design Model

A.2.8.2. Annulus Backfill

MFAD was originally developed to account for cohesive (silty clay) and granular (crushed rock) backfill materials (EPRI 1989, EL-6309, EPRI 1997, EL-6849). The full-scale foundation tests included a thickness of the annulus ranging from 6 inches to 12 inches depending on the size of the pole, the foundation loads, the soil conditions and the backfill material. Beginning with MFAD version 5.1.18, the direct embedment model allows for the analysis of concrete backfill (assumed to be within the range of normal concrete strength). The model has not been calibrated for low strength concrete or slurry materials.

The direct embedment model accounts for the interaction of the pole-annulus, annulus-subsurface interfaces, and interaction of the pole-annulus-subsurface. Within the lateral capacity calculations, MFAD considers three possible reactions – the pole rotating at the interface with the annulus, the pole and annulus rotating into the subsurface, and the pole rotating within the annulus. There are two reactions evaluated considering the vertical side shear moment – the pole-annulus interface and the annulus-subsurface interface.

In FAD, the annulus thickness is defined as the drilled shaft diameter (B) minus the pole diameter (B_o) divided by two (Figure A.5).

A.2.9. Behavior of Axially Loaded Piers

Design of drilled shafts for axial loading requires an understanding of strength and service limit states for compression and uplift forces. Resistances consist of combined side shear capacity, pier weight and bearing capacity. Typically, side shear and bearing resistance develop as a function of shaft displacement and full mobilization of each occurs at different displacement limits for axial loading (Kulhawy 1991). Transmission line foundations are often subject to combined axial and lateral loading. Implicit in the HFAD and TFAD modules is the assumption that there is only minimal vertical displacement where bearing capacity is not a controlling factor in design. The user is encouraged to perform supplemental analyses outside of the program to verify bearing capacity when site specific conditions vary from program assumptions (e.g. negative skin friction, shrink-swell, and collapsible soils).

A.2.9.1. HFAD Module

As shown in Figure A.6a and Figure A.7a, short-rigid shaft foundations of H-Frame structures are subjected to a combination of moment, lateral shear and uplift or compression reactions. Thus, the HFAD design module has been developed for the design of drilled shafts and direct embedded H-Frame legs that are subjected to these load combinations. The design model, which does not consider load-deflection interaction or torsion, uses the following subroutines.

- Moment and Lateral Shear Loads for Drilled Shafts and Direct Embedded H-Frame Legs – – Lateral resistance only (no side shear spring and no base spring contributions).
- Uplift Loads for Drilled Shaft and Direct Embedded H-Frame legs –Cylindrical Shear Design Model for Side Shear Resistance (vertical side shear and foundation weight are considered for drilled shafts and only vertical side shear considered for direct embedment).
- Compression Loads for Drilled Shafts – Cylindrical Shear Design Model for Side Shear Resistance and Vesic (1963) Design Model for End Bearing Capacity.
- Compression Loads for Direct Embedment H-Frame Legs – Cylindrical Shear Design Model. End bearing is neglected.

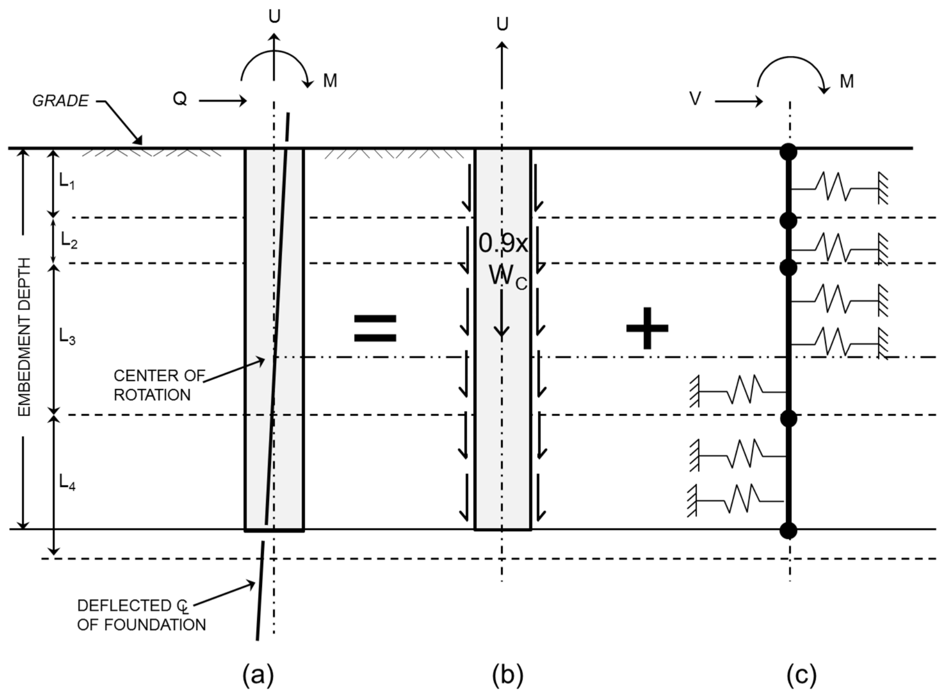


Figure A.6
Schematic Diagram of the HFAD 5.2.3 Design Model for Uplift

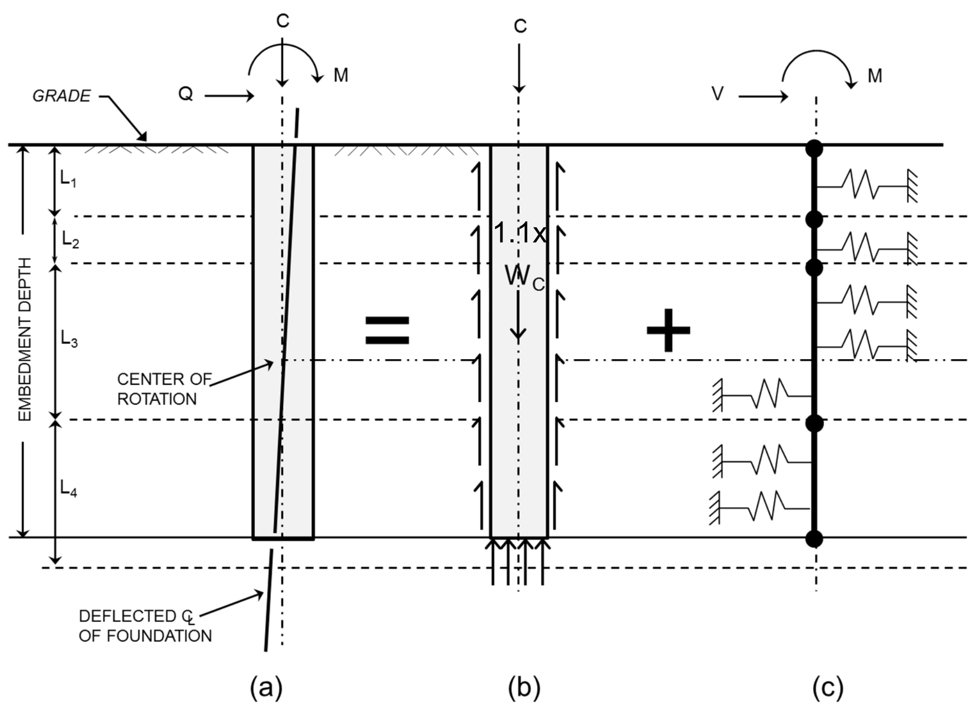


Figure A.7
Schematic Diagram of the HFAD 5.2.3 Design Model for Compression

Moment and Shear Loads: The HFAD free-body diagrams for drilled shaft and direct embedded pole foundations under moment and lateral shear reactions are shown in Figure A.6c and Figure A.7c. As noted previously, the HFAD module uses only the lateral resistance spring to resist lateral loading; that is, the applied shear load, V, and moment, M, are resisted solely by lateral resistance for both drilled shafts and direct embedded poles. The HFAD module computes nominal shear load and moment capacities of a given drilled shaft or direct embedded pole geometry and subsurface profile.

Uplift Loads: The HFAD free-body diagram for uplift loads, U, is shown in Figure A.6a for drilled shafts. The HFAD module uses the cylindrical shear design model and determines the uplift capacity based on side shear at the concrete/soil and/or concrete/rock interfaces on a layer-by-layer basis, then computes the minimum total nominal uplift capacity. Ninety percent (90%) of the drilled shaft weight is used in computing this uplift capacity. When the water level is above the base of the foundation, submerged unit weights are used to compute the drilled shaft weight and the side shear values.

For direct embedment H-Frame poles (Figure A.6a), HFAD uses the cylindrical shear design model for uplift loads to compute the nominal uplift capacity at both the pole-annulus interface and at the annulus-soil or annulus-rock interface, then selects the minimum nominal uplift capacity for each increment. Since the weight of the embedded section of the pole is assumed to be included in the applied foundation loads, this weight is not included in the computation of the uplift capacity. Submerged unit weights of the soil and backfill are used in computing the side shear values when the water table is above the base of the direct embedded pole foundation.

Compression Loads: The HFAD free-body diagram for compression loads is shown in Figure A.7b. The HFAD module calculates the nominal capacity of a drilled shaft under a compression load, P, through a combination of side shear resistance and end-bearing. The cylindrical shear model is used to compute the nominal side shear resistance and the nominal end-bearing resistance is based on the model developed by Vesic (1963).

Direct embedded H-Frame pole analysis assumes compression loads are resisted by side shear only (neglects any end bearing resistance). The HFAD module computes the nominal compression capacity at both the pole/backfill interface and at the backfill/soil or backfill/rock interface, then selects the minimum nominal side shear compression capacity.

A.2.9.2. TFAD Module

As illustrated in Figure A.8a and Figure A.9a tower structure foundations are subjected to a combination of a lateral shear loads and associated uplift or compression loads. Thus, the TFAD module has been developed so that drilled shaft foundations resist these load combinations. Only concrete drilled shafts are considered in the TFAD module (no direct embedment). The design module incorporated within TFAD (which also does not consider moment-uplift interaction or torsion) uses the following subroutines:

- Lateral Shear Loads – MFAD 5.1 Design Model – Lateral Resistance only (no side shear and no base contributions).
- Uplift Loads – Cylindrical Shear Design Model for Side Shear Resistance (only side shear and foundation weight are considered).
- Compression Loads – Cylindrical Shear Design Model for Side Shear Resistance and Vesic (1963) Design Model for End Bearing Capacity.

Lateral Shear Loads: The TFAD free-body diagram for a drilled shaft under a lateral shear load is shown is Figure A.8c and Figure A.9c. The TFAD 5.1 model uses only the lateral resistance portion of the MFAD module; that is, the applied shear, V, is resisted solely by lateral soil/rock pressures for drilled shafts. Depending on the height of the stickup, the drilled shaft will also be subjected to a small moment. The TFAD module computes the nominal lateral shear and moment capacities for a given drilled shaft pole geometry and subsurface profile.

Uplift Loads: The TFAD free-body diagram for uplift load is shown in Figure A.8b. The TFAD module for drilled shafts uses the cylindrical shear design model and determines the uplift capacity at the drilled shaft concrete/soil or concrete/rock interface on a layer-by-layer basis. Ninety percent (90%) of the effective weight of the foundation is included in the computation of the uplift capacity.

Compression Loads: The TFAD free-body diagram for compression load is shown in Figure A.9b. The TFAD module calculates the nominal capacity of a drilled shaft under compression loading, P, through a combination of side shear resistance and end-bearing. A cylindrical shear model is used to compute the side shear resistance. End-bearing resistance is based on the model developed by Vesic (1963).

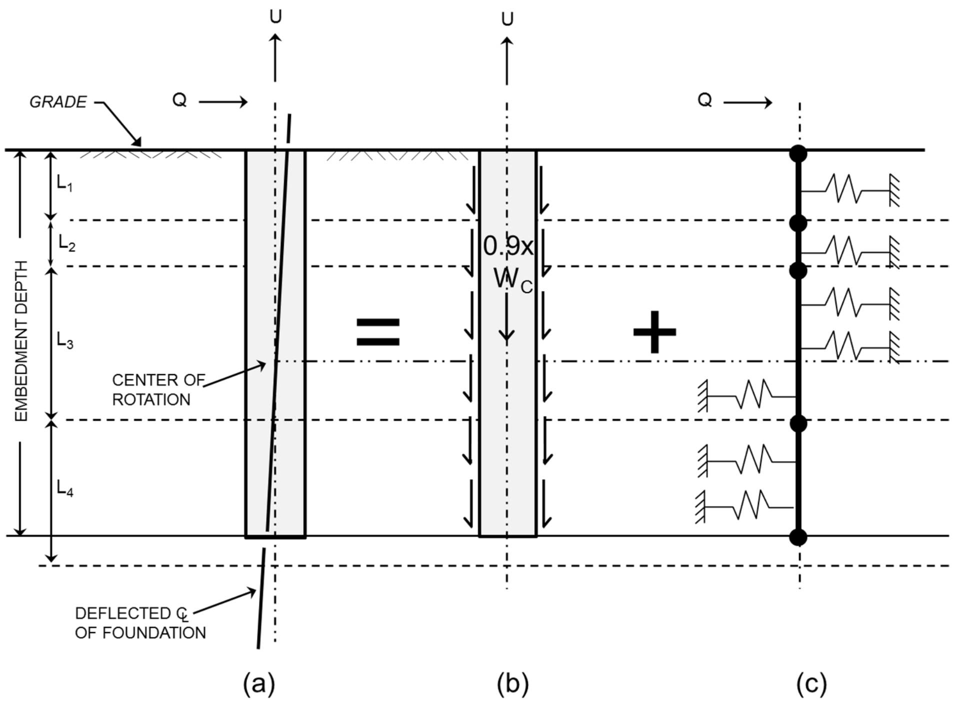


Figure A.8
Schematic Diagram of the TFAD 5.2.3 Design Model for Uplift

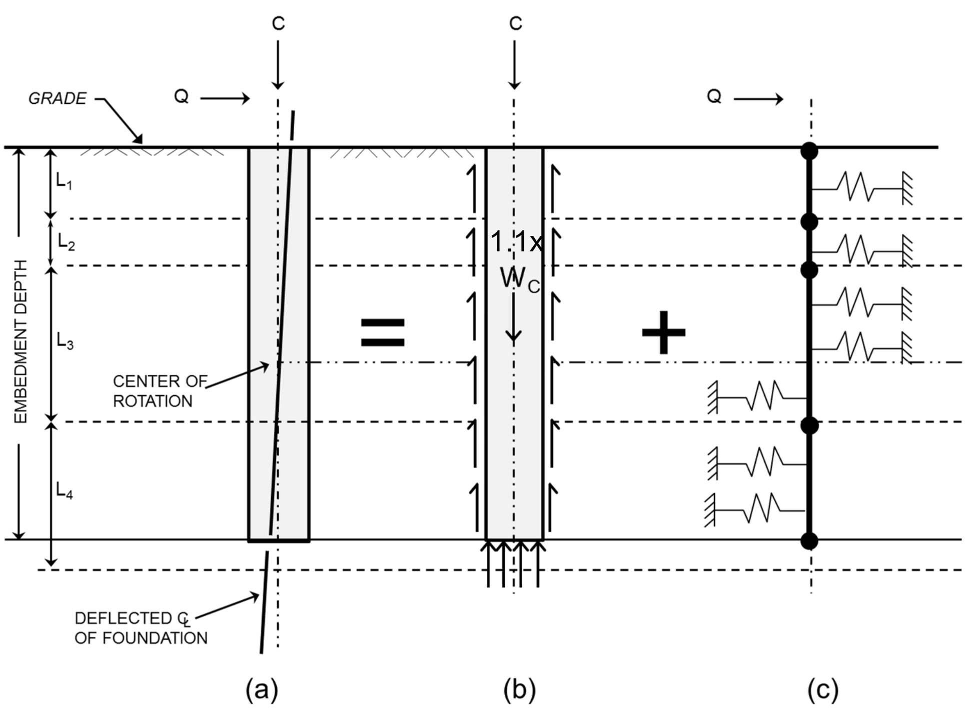


Figure A.9
Schematic Diagram of the TFAD 5.2.3 Design Model for Compression

A.3. Reliability-Based Design

A.3.1. Introduction

Each FAD Tools module is intended to be used with probabilistic RBD methods, in which factored loads are resisted by the nominal capacity of the soil-structure interaction. It is possible to use allowable stress design methods (ASD), but consideration must be given in terms of where each methodology resides on the elastic versus non-elastic region of the stress-strain curve in the FAD report (also known as free-head push-over analysis).

In the past, the ASD approach was the most commonly used method to design foundations for transmission line structures. The ASD approach is shown schematically in Figure A.10. This design method is based on the assumption that component reactions and component capacities can be determined as unique quantities, i.e. component loads and component capacities have no variability and can be represented by straight vertical lines (100% probability of being a straight line).

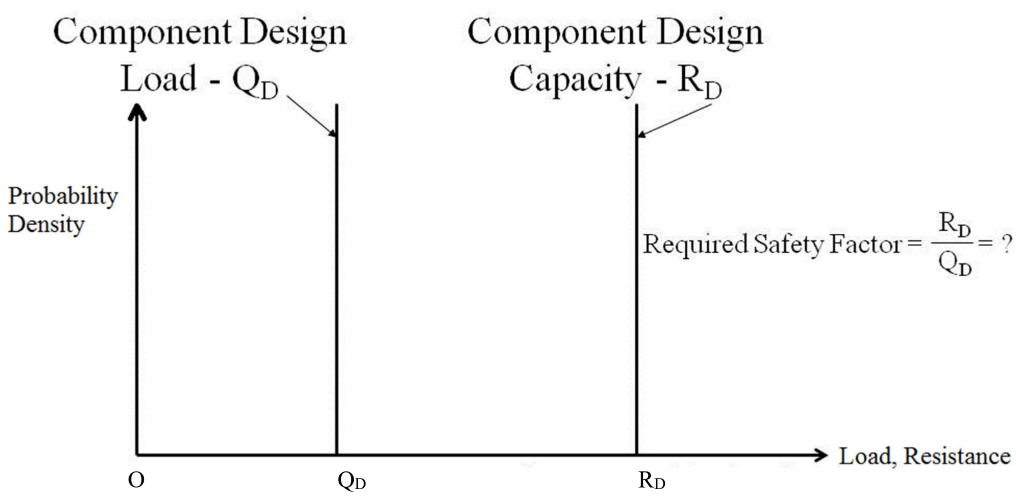


Figure A.10
Allowable Design Approach

Knowing that variability in loads and capacities exist, the foundation designer introduces safety into design by separating the component design load (Q_D) from component design capacity (R_D) through the use of a safety factor. The selection of an adequate safety factor requires a great deal of professional judgment and experience and can vary significantly from one foundation designer to another; thus, the level of reliability of foundations designed by the ASD approach can be quite variable.

Over the past 20 to 30 years, RBD methods have been developed and implemented for the design of foundations for buildings, bridges, and other structures. A significant effort has been made by professional societies and standard-developing organizations to publish design manuals and standards concerning RBD of transmission line structures and foundations. The following is a partial list of published utility industry RBD-oriented design manuals and standards:

- ASCE Manual and Reports of Engineering Practice – No. 74 – Guidelines for Transmission Line Structural Loading, 1991;
- ASCE Manual and Reports of Engineering Practice – No. 111 – Reliability Based Designs of Utility Pole Structures, 2005;
- EPRI TR–1005000 Reliability Based Designs of Foundations for Transmission Line Structures, 1995; and
- EPRI EL–4793 Reliability – Based Design of Transmission Line Structures, 1987.

Figure A.11 is a schematic representation of the variability of component load (Q) and of component strength (R) in RBD analysis. The variability of component load is schematically shown by a probability load distribution function and the component strength is schematically shown by a probability resistance distribution function. The goal in RBD is to separate the two functions so that the probability of failure, and thus the level of reliability, of components are compatible and acceptable.

A.3.2. Load Resistance Factor Design (LRFD) Format

In ASCE Manual 74, the relative location of the two probability distribution functions is set by the following Load Resistance Factor Designs (LRFD) design equation:

R_{DES} (Component Design Capacity) > Effect of [Dead Load + γ Q_{50}]

Where:

$R_{DES} = R_5$ is the lower 5% exclusive limit component capacity,

γ is a load factor that is used to modify the reliability level of a line (normally set at 1.0), and

Q_{50} is the applied load (Q_{APPL}) resulting from a 50-year return period climatic event.

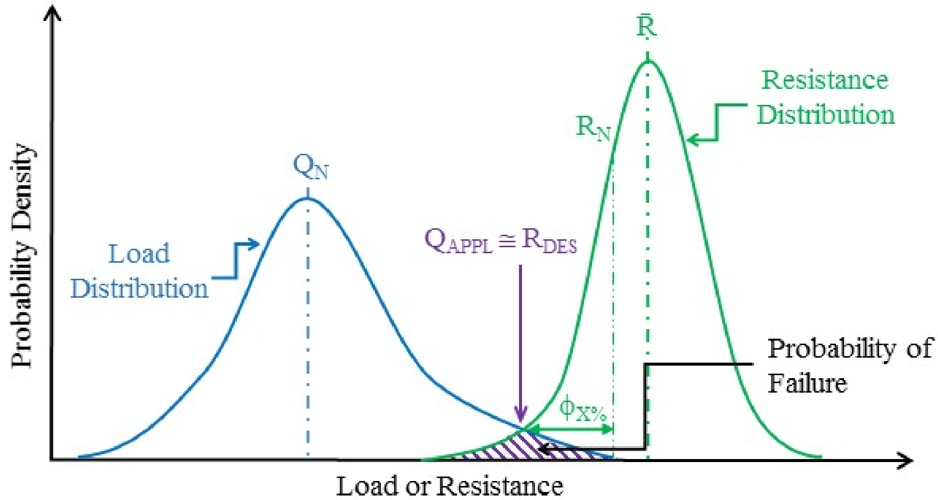


Figure A.11
Reliability-Based Design Approach

Following this approach, in FAD the user enters the applied load (Q_{appl}), which includes load factors, and enters nominal soil parameters, which provide a nominal resistance capacity (R_N). The strength factor (ϕ_5) is applied to the nominal resistance capacity (R_N) to calculate the design capacity (R_{DES}). A foundation which has a design capacity greater than the applied load is considered sufficient by the FAD program.

Depending upon the assumed shape of resistance distribution function, there is a relationship between R_5 and R_N. The shape of resistance distribution function is often assumed to be either normal or log normal. For a log normal distribution function at the lower 5% exclusive limit, the following equation provides the relationship between R_5 and R_N:

$$R_5 = m_m * [1 - 0.01\,(1.64 - 0.00925 * V_m) * V_m] * R_N$$

Rewriting the above equation gives:

$$R_5 = \phi_5 * R_N$$

Where

$$\phi_5 = m_m * [1 - 0.01\,(1.64 - 0.00925 * V_m) * V_m]\text{, and}$$

ϕ_5 is the 5% lower limit strength factor;

m_m is the slope of the least square fit line of a plot of test capacities (R_T) versus nominal foundation capacities (R_N) for the design model being calibrated, assuming a constant coefficient of variation least square fit;

R_N is the predicted nominal capacity for a specific full-scale foundation load test using the foundation design method being calibrated; and

V_m is the coefficient of variation of the foundation design model in %.

Figure A.12 shows the relationship between the coefficient of variation (V_m) for the design model being calibrated and the strength factor (φ_5) for various values of m_m.

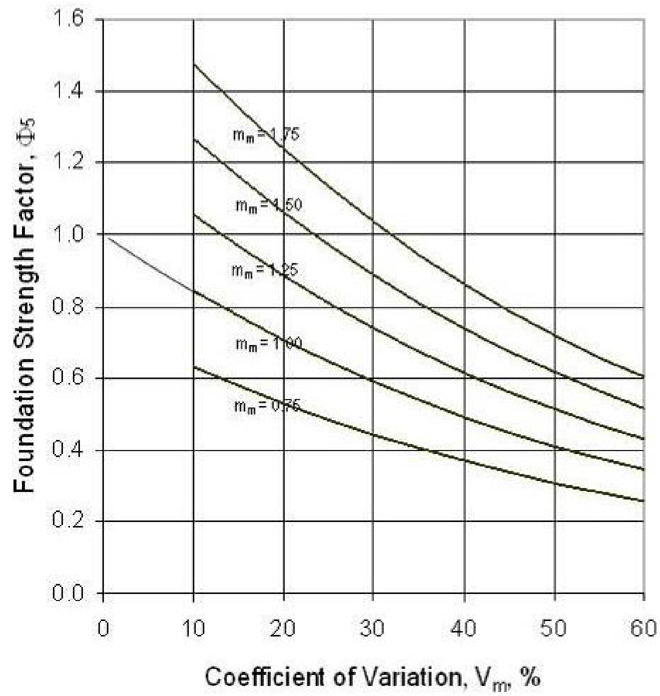


Figure A.12
Foundation Strength Factor (φ_5) versus Design Model Coefficient of Variation, V_m

Figure A.12 can be used in the following manner. If the coefficient of variation (V_m) of a design model is 30% and the slope (m_m) of the least square fit line for the design model is 1.00, a strength factor (φ_5) of 0.59 is obtained from Figure A.12. Rounding φ_5 to 0.6, the design capacity (R_5) of foundations designed by the calibrated model this method is given by:

$$R_5 = \phi_5 * R_n = 0.6 * R_n$$

Alternately, the value of ϕ_5 can be computed as follows:

$$\phi_5 = m_m [1-0.01 (1.64-0.00925*V_m)*V_m]$$

$$\phi_5 = 1.0 [1-0.01 (1.65-0.00925(30))*30] = 0.59$$

Section A.4 presents the results of calibrating FAD drilled shaft and direct embedded pole design models against the results of full-scale foundation load tests for the determination of a strength factors, ϕ_5. Section A.4 also summarizes recommended strength factors for design models where no full-scale foundation load tests are available.

A.4. RBD Calibration of FAD Tools Design Modules

Resistance factors used in RBD analysis (ϕ_5) have been calculated as discussed in Section A.3 for all FAD Tools modules developed after Version 5.0. This process, called "model calibration" is presented herein.

A.4.1. RBD Calibration of MFAD

MFAD was calibrated for use in RBD analysis for compatible return interval and reliability with the applied load. As noted in Section A.2, theoretical models were modified via an empirical process to provide a best-fit of the full-scale foundation test results to create the FAD modules. The variability observed after this process, can be analyzed to statistically determine resistance factors for the RBD calibration. The steps used in the calibration process were as follows:

1. Assemble full-scale foundation load test data for drilled shaft and direct embedded poles tested in soil and/or rock subsurface profiles for moment, lateral shear, and compression loads.
2. Based on the field test data for drilled shafts and direct embedded poles, determine the interpreted test moment capacity (R_T). For drilled shafts, use the capacity measured at a ground line displacement of 2 degrees rotation for R_T. For direct embedded poles, use the maximum capacity measured in the test for R_T. The D/B ratio for all tests was less than or equal to 10.
3. Develop in-situ nominal geotechnical parameters at each test site as discussed in Section A.6.
4. Use MFAD 5.1 to predict the nominal ultimate moment capacity (R_N) of each test.
5. Plot the data developed in Steps 2 and 4 on a graph of interpreted test moment capacity (R_T) versus predicted ultimate nominal moment capacity (R_N).
6. Perform a constant coefficient of variation least square fit to the data plotted in Step 5 to establish the slope (m_m) of the least square fit line and the coefficient of variation (V_m) of the design model about the least square fit line.
7. Determine the slope of the 5% lower exclusion limit (LEL) line which is the 5% lower limit resistance factor, ϕ_5.

A.4.1.1. MFAD RBD Calibration Results

Figure A.13 presents the results of calibrating MFAD 5.1 against the results of full-scale laterally loaded drilled shafts in soil and/or rock.

Figure A.13 shows that MFAD has a resistance factor (ϕ_5) of 0.63 for the design of drilled shafts in soil and/or rock. This resistance factor is based on an m_m value of 0.99 and a design model coefficient of variation (V_m) of 23.1%.

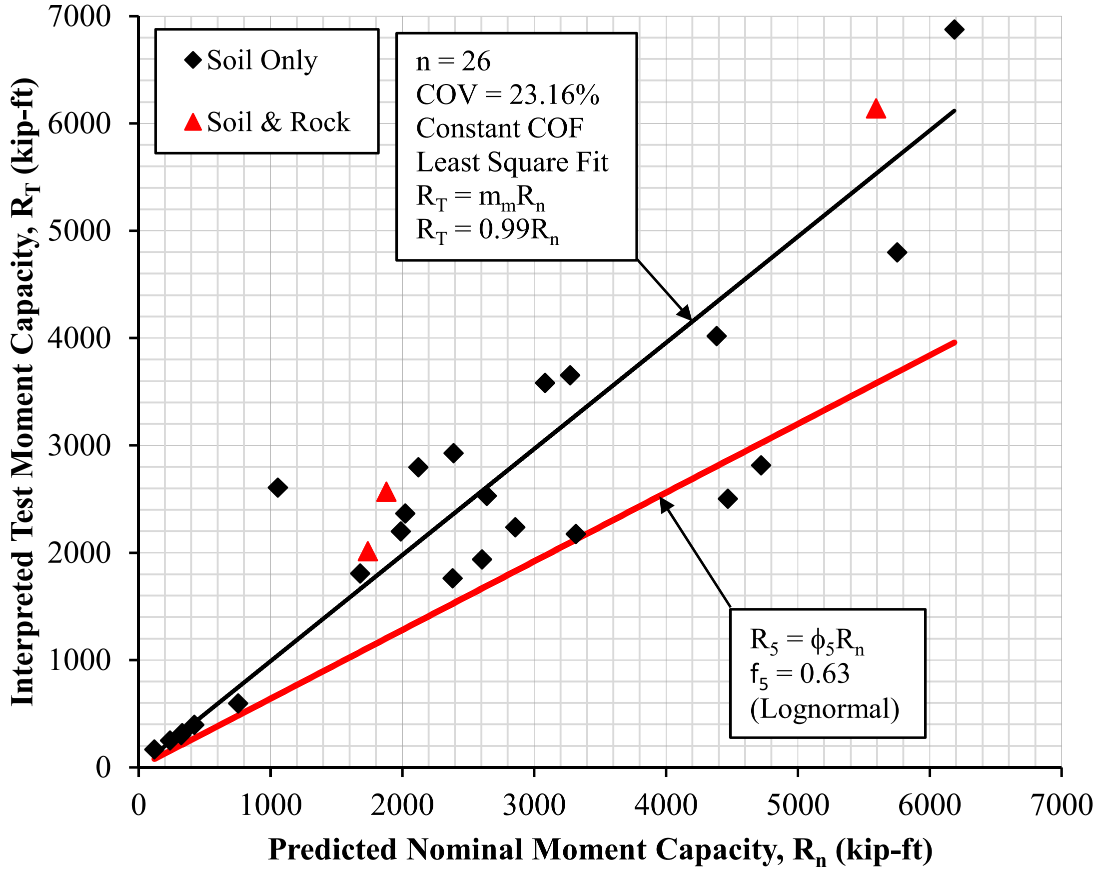


Figure A.13
MFAD Predicted Nominal Ultimate Moment Capacity (R_n) Versus Interpreted Test Moment Capacity (R_T) for Drilled Shafts in Soil and/or Rock

Figure A.14 presents the results of calibrating MFAD against the results of full-scale laterally loaded direct embedded poles in soil and/or rock. Figure A.14 shows that MFAD has a resistance factor (ϕ_5) of 0.63 for the design of direct embedded poles in soil and/or rock. This resistance factor is based on an m_m value of 1.25 and a design model coefficient of variation (V_m) of 38.4%.

Based on the above data, it is recommended that MFAD be used with a resistance factor of 0.63 for both drilled shafts and direct embedded poles in soil and/or rock to achieve the 5% LEL. The 0.63 resistance factor has been incorporated in the MFAD 5.1 code.

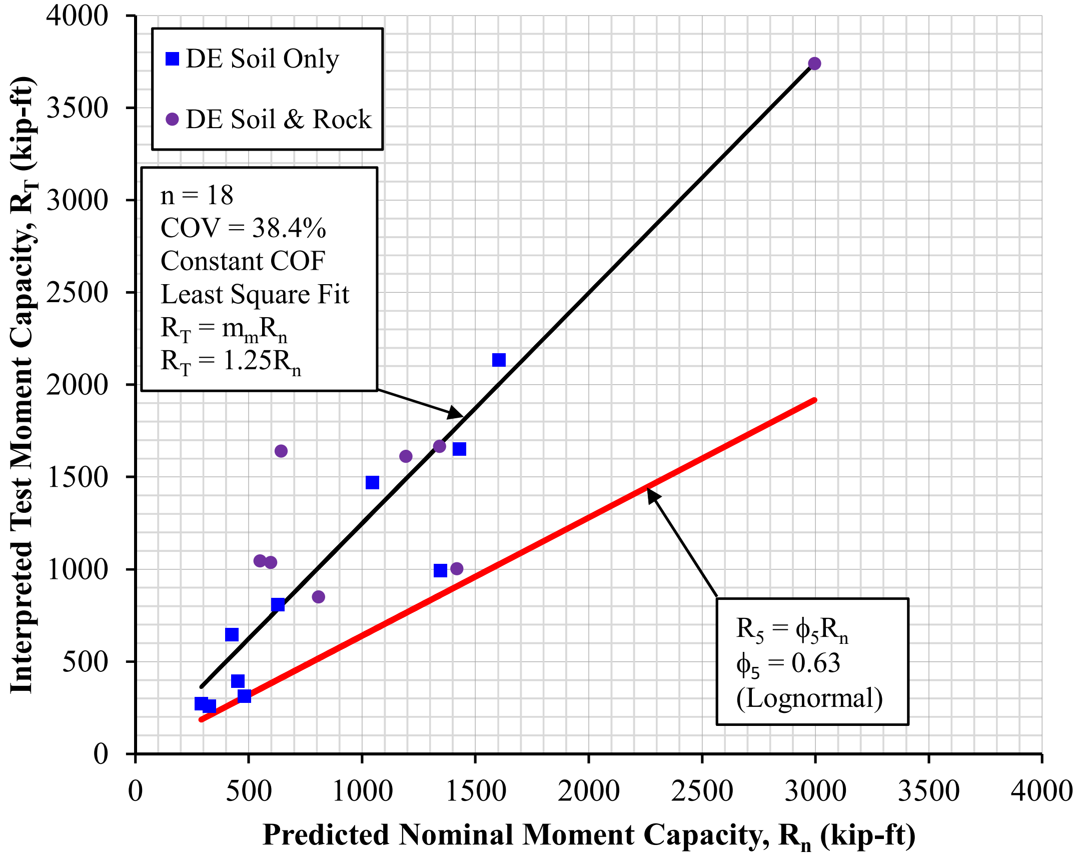


Figure A.14
Predicted Nominal Ultimate Moment Capacity (R_n) Versus Interpreted Test Moment Capacity (R_T) for Direct Embedded Poles in Soil and/or Rock

A.4.2. RBD Calibration HFAD & TFAD

The HFAD and TFAD cylindrical side shear design model was calibrated for RBD analysis by comparing the program results to the results of full-scale uplift foundation load (EPRI 1984, EL-3771). The steps used in the calibration process as follows:

1. Assemble foundation uplift load test data for drilled shafts in granular and cohesive soil subsurface profiles.
2. Choose the uplift test capacity (R_T) at each site as the maximum applied test load. Limit the test database to a depth of embedment to diameter (D/B) ratio of 10 or less.
3. Develop in-situ nominal geotechnical parameters at each test site as discussed in Section A.6, use HFAD 5.1 to compute the predicted nominal geotechnical load capacity (R_N) for each test.
4. Plot the data developed in Steps 2 and 3 in a graph of interpreted test capacity (R_T) versus predicted nominal ultimate capacity (R_N).
5. Perform a constant coefficient of variation least square fit to the data plotted in Step 4 to establish the slope (m_m) of the least square fit line and the coefficient of variation (V_m) of the design model about the least square fit line.
6. Determine the slope of the lower 5% exclusion limit line which is the lower 5% exclusion limit resistance factor, ϕ_5.

Limited full-scale tests in uplift and compression can be found in the literature (EPRI 1984, EL-3771). Since no full-scale foundations load tests have been performed for several combinations of mode of loading, foundation type, design models and subsurface profile, assumed strength factors for various combinations of the above variables were incorporated into the HFAD and TFAD programs.

A.4.2.1. Drilled Shafts and Direct Embedded Poles in Soil and/or Rock and Subject to Moment and Lateral Shear Loads

A resistance factor of 0.63 was assigned to the calculated lateral capacity in HFAD and TFAD for both drilled shaft and direct embedded poles based on the MFAD calibration analysis presented in the previous section.

A.4.2.2. Drilled Shafts in Granular Soils and Subjected to Uplift Loads

Figure A.15 presents the results of RBD calibrating the cylindrical shear design model in HFAD and TFAD using the results of 11 full-scale drilled shaft uplift load tests conducted in granular soils (EPRI 1984, EL-3771). This figure shows that the granular soil cylindrical shear design module has a resistance factor (ϕ_5) of 0.56, based on an m_m value of 1.12 and a design module coefficient of variation, V_m of 38.6%.

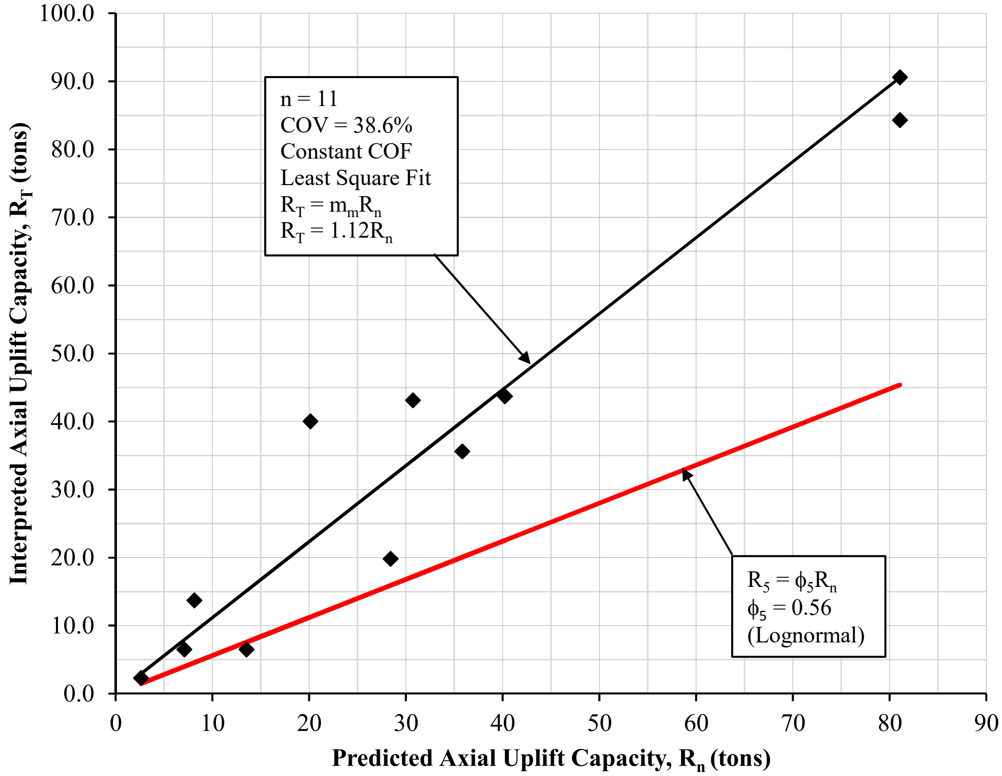


Figure A.15
Cylindrical Side Shear Design Model Predicted Nominal Ultimate Uplift Capacity (Rn) Versus Interpreted Test Uplift Capacity (RT) for Drilled Shafts Embedded in Granular Soils (D/B < 10)

A.4.2.3. Drilled Shafts in Cohesive Soils and Subjected to Uplift Loads

Figure A.16 presents the results of RBD calibrating of the cylindrical shear design model in HFAD and TFAD against the results of 71 full-scale drilled shafts uplift load tests conducted in cohesive soils (EPRI 1984, EL-3771). Figure A.16 shows that the cohesive soil cylindrical shear design model has a resistance factor (ϕ_5) of 0.65. This resistance factor is based on an m_m value of 1.05 and a design model coefficient of variation (V_m) of 24.6%.

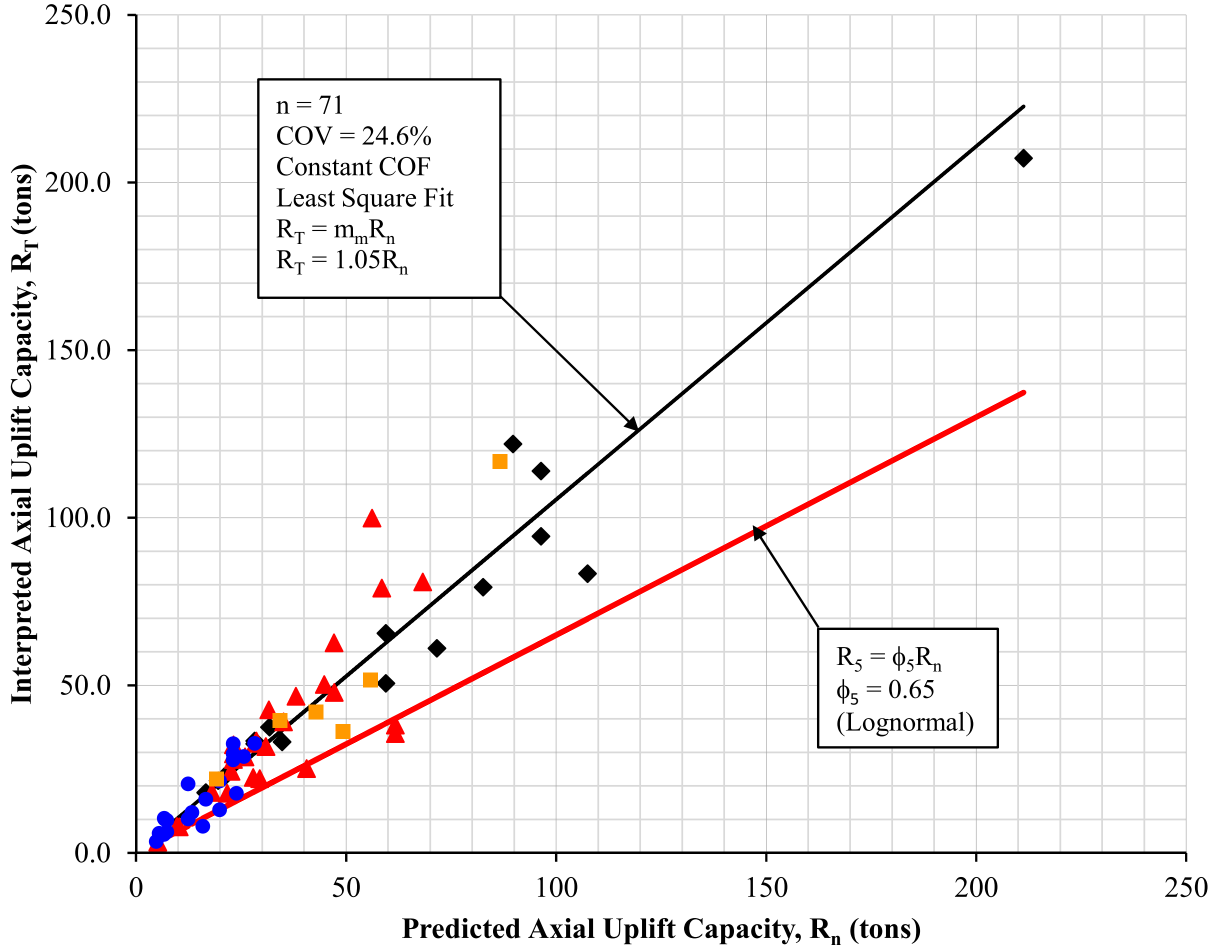


Figure A.16
Cylindrical Side Shear Design Model Predicted Nominal Ultimate Uplift Capacity (Rn) Versus Interpreted Test Uplift Capacity (RT) for Drilled Shafts Embedded in Cohesive Soils (D/B < 10)

A.4.2.4. Drilled Shafts Subjected to Compression Loads

A limited number of full-scale foundation compression load tests are available for the calibration of HFAD and TFAD for applicable foundation dimensions (Depth/Diameter ≤ 10) (EPRI 1984, EL-3771). Based on engineering judgment, resistance factors in compression are assumed to be similar to the resistance factors in uplift.

A.4.2.5. Resistance Factors for Remaining HFAD & TFAD Design Models

Table A-2 and Table A-3 present a summary of the recommended resistance factors incorporated into HFAD and TFAD for uplift and compression design models. The recommended values are based on either professional judgment, similarity of resistance model to existing calibrations, or resistance factor data available from AASHTO publications.

Table A-2
Recommended Resistance Factors (ϕ5) for HFAD 5.1 for the Cylindrical Shear Design Model and Uplift Loads (AASHTO 2004)

Mode of Loading	Foundation Type	Design Model	Soil/Rock Type	Recommended ϕ_5	Remarks
Uplift	Drilled Shaft / Direct Embedded Pole	Cylindrical Side Shear	Granular	0.56	Calibrated
Uplift	Drilled Shaft / Direct Embedded Pole	Cylindrical Side Shear	Cohesive	0.65	Calibrated
Uplift	Drilled Shaft / Direct Embedded Pole	Cylindrical Side Shear	Rock	0.50	Prof. Judgement
Uplift	Drilled Shaft	Foundation Weight	-	0.9	Prof. Judgement

Table A-3
Recommended Resistance Factors (ϕ_5) for HFAD 5.1 for the Cylindrical Shear and End Bearing Design Models and Compression Loads (AASHTO 2004)

Mode of Loading	Foundation Type	Design Model	Soil/Rock Type	Recommended ϕ_5	Remarks
Compression	Drilled Shaft / Direct Embedded Pole	Cylindrical Side Shear	Granular	0.56	Calibrated with Prof. Judgement
Compression	Drilled Shaft	Vesic End Bearing	Granular, N_γ and N_q Terms	0.45	AASHTO
Compression	Drilled Shaft / Direct Embedded Pole	Cylindrical Side Shear	Cohesive	0.65	Calibrated with Prof. Judgement
Compression	Drilled Shaft	Vesic End Bearing	Cohesive N_c Term	0.55	AASHTO
Compression	Drilled Shaft / Direct Embedded Pole	Cylindrical Side Shear	Rock	0.50	Prof. Judgement
Compression	Drilled Shaft	Vesic End Bearing	Rock, N_c Term	0.55	AASHTO
Compression	Drilled Shaft	Vesic End Bearing	Rock, N_γ and N_q Terms	0.45	AASHTO
Compression	Drilled Shaft	Foundation Weight	-	1.1*	Prof. Judgement

* Foundation Weight is added to the applied loads.

A.5. Foundation Design Process

A.5.1. Introduction

Although a number of industry guidelines describe the fundamental design principals for electric transmission line foundation types, there is no comprehensive document which relates all the elements needed to properly characterize loads imposed by electrical transmission line structures on foundations. The current practice for designing foundations for transmission line structures is quite variable. The purpose of Section A.5 is to recommend a specific and consistent reliability-based process for use with the FAD program for foundation design (see EPRI 2012, EL-1024138). Figure A.17 presents a flow diagram of the Foundation Design Process. The goal of the recommendations in this section is to provide foundations for all the structures of a given transmission line that have been optimized and have a relatively uniform level of reliability.

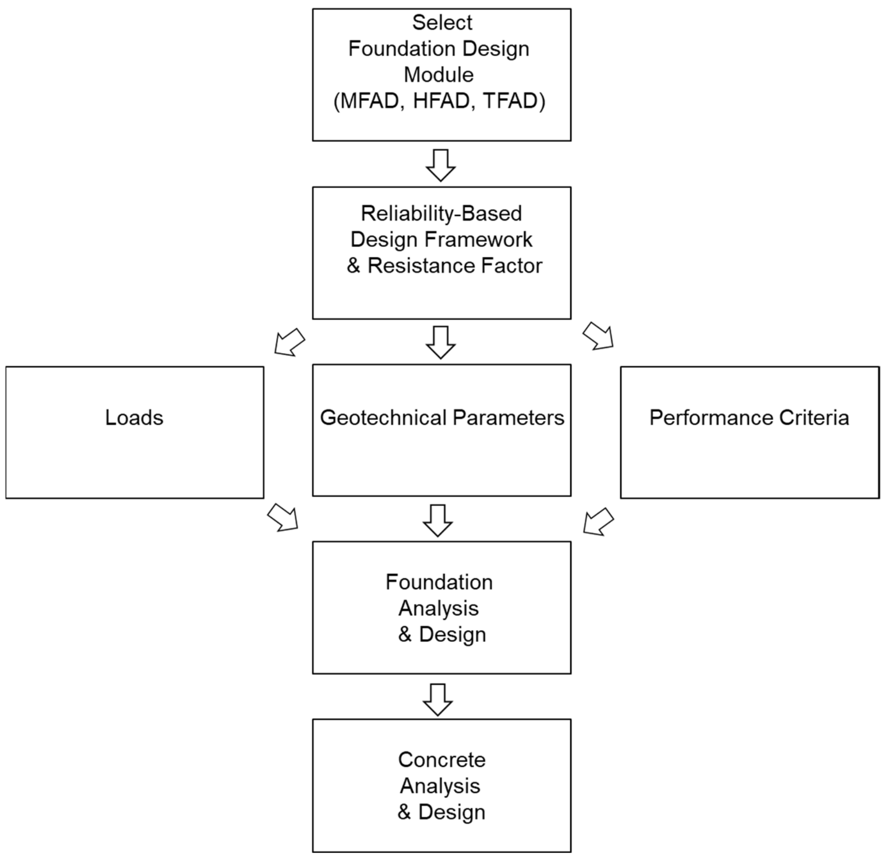


Figure A.17
Foundation Design Process Flow Diagram

The foundation design process incorporates a RBD format and consists of the following steps:

1. Determine the factored foundation design loads. Load cases for numerous line conditions, prepared by an engineer are used to design new structures or to redesign existing structures. The need to check for numerous line conditions results in a tabulation of loads to be used to design foundations.
2. Establish the nominal geotechnical (soil and rock) design parameters at each boring location and at structure locations between borings. This is a critical step and requires well trained and experienced geotechnical engineers and engineering geologists.
3. Establish foundation performance criteria for laterally loaded drilled shafts in terms of total and non-recoverable top of concrete displacement and rotation (step not needed for HFAD or TFAD).
4. Using the information obtained in Steps 1-3, design foundation(s) for each structure location using MFAD, HFAD, TFAD.

A.5.2. Reliability-Based Design Framework

Section A.3 presents a recommended RBD framework. The recommended foundation design equation is as follows:

$$R_{DES} = \phi_5 R_N \geq \text{Maximum Foundation Loads}$$

Where

R_{DES} = the design capacity,

ϕ_5 = the 5% lower exclusion limit strength factor, and

R_N = the nominal resistance capacity.

The FAD Tools foundation design modules (MFAD, HFAD and TFAD) compute the nominal resistance, R_N, for each trial design and automatically multiply R_N by the appropriate ϕ_5 to establish a trial R_{DES}. The FAD program is calibrated for RBD as described in Section A.4, for the compatibility of applied load and design capacity. If R_{DES} is less than the critical applied load, the size of the foundation can be increased incrementally until an adequate design is achieved.

MFAD also checks that the foundation, designed to resist maximum foundation design loads, also satisfies the established foundation performance criteria. If not, the size of the foundation can be increased incrementally until an adequate design is achieved.

A.5.3. Foundation Design Loads

The load cases developed for the design of transmission line foundations fall into the following categories:

- Weather related loads,
- Construction and maintenance loads,
- Failure containment loads, and
- Legislated loads.

The loads include applicable load factors for RBD of the transmission structure. The ground line or top of foundation loads (including factors) are entered in to the FAD program as applied loads (Figure A.12). MFAD allows for up to nine load cases to be entered; HFAD and TFAD allow for four load combinations to be entered. Each of the FAD modules determines the critical loading condition from the entered applied load cases and evaluates the design capacity for the specified foundation embedment and subsurface conditions as described in section A.5.2. See Section A.3.2 for a discussion on the relationship between applied load and design capacity within the RBD calibration of the MFAD models.

Although the utility industry has not directly addressed a probabilistic-based method to assess combined structure and environmental loads on foundations, guide documents developed by other agencies and professional organization can be used to better understand how these can be incorporated with transmission line foundation design. These groups have developed load factors that vary depending on specified strength, extreme event and service load cases. These include:

- ASCE/SEI Standard 7-10 (ASCE 2010) – Probabilistic method of assessing variable load factors for combined dead, live, roof, wind and earthquake loads on structures;
- NCHRP 489 (Ghosn et al. 2003) - Probabilistic method of assessing variable load factors for combined dead, traffic, wind, collision and earthquake loads on bridge structures. Probabilistic foundation scour depth factors are also given for various extreme event load cases; and
- AASHTO LRFD Highway Bridge Specifications (AASHTO 2012) - Probabilistic method of assessing variable load factors for combined loads from components/attachments, traffic and other live loads, wind on bridges, water on piers, ice on piers, collisions and earthquakes.

Note all loads are entered as positive values. Within HFAD and TFAD, the program internally corrects the sign convention for uplift or compression.

Within FAD, for all foundations with stickup (reveal), the entered applied reactions *at top of shaft* are converted to applied reactions *at groundline*. The *applied moment* will increase proportionally to the *applied shear* at top of shaft by the length of the *stick up* while the *applied shear* and *applied axial* loads remain the same. All calculations of *design capacity* and *nominal capacity* are at groundline.

A.5.4. Geotechnical Design Parameters (Section A. 6)

The most critical step in the implementation of the Design Process is the development of geotechnical design parameters that reflect the nominal subsurface conditions at each foundation site. Thus, the initial step in this process is to layout a subsurface exploration program that collects the geotechnical data needed by the foundation designer for the foundation design models to be used in the project, i.e. MFAD, HFAD or TFAD. The geotechnical information needed by the FAD program is as follows:

- Layer Type, as defined as soil or rock;
- Depth to Bottom, of soil/rock layers;
- Design Groundwater Level;
- Total Unit Weight (pcf);
- Deformation Modulus (ksi), as defined by pressuremeter testing;
- Friction Angle (degrees);
- Undrained Shear Strength or Rock Cohesion (ksf); and
- Rock-Concrete Bond Strength (ksf).

The FAD program requires the determination of realistic parameters for each subsurface layer, also referred to as nominal properties. During MFAD full-scale foundation testing, a site-specific subsurface investigation was conducted at each test foundation that included in-situ testing (standard penetration testing (SPT) and pressuremeter modulus testing (PMT)) and extensive laboratory testing (unit weight, water content, grain size distribution, plasticity index, unconfined compressive strength tests, triaxial shear tests (unconsolidated undrained, consolidated undrained with pore pressure, and consolidated drained tests) (EPRI 1982, EL-2197; EPRI 2012, TR-1024138). Resulting subsurface properties were then used to develop idealized profiles representing nominal soil properties for calibrating the various MFAD models. In lieu of such direct measurement of subsurface properties, estimated values for various parameters are frequently obtained from empirical correlations (see Appendix C). Regardless of the technique used to define the subsurface conditions, an idealized profile should be developed consisting of layer boundaries and material properties for each layer.

Section A.6 gives recommended procedures for establishing geotechnical design parameters for soil and rock layers. The implementation of the procedures described in Section A.6 is critical in achieving foundation designs having a uniform level of reliability. Laboratory test data, when available, should always be used in lieu of or to supplement the correlation methods discussed herein.

A.5.5. Foundation Performance Criteria (Section A. 7)

Performance criteria are established for the design of safe and economical foundations. This requires a thorough understanding of failure, damage and service limits by the foundation and structure designers. Currently, foundation performance criteria are only input for MFAD. The displacement and rotation at the top of concrete for drilled shafts and at the ground line for direct embedded poles are relatively small when compared to displacements at conductor attachment points which are due to the bending of a tubular steel pole under the design load case and to the foundation displacement and rotation. Thus, care should be exercised in not selecting overly stringent foundation performance criteria. Recommended practices are given in Section A.7.

A.5.6. Foundation Design Models and Resistance Factors (Section A.2 & 4)

FAD Tools foundation design models are described in Section A.2, where nominal foundation capacity is calculated using resistance factors given in Section A.4 to reduce nominal resistance to design values. Each of the FAD modules (MFAD, HFAD and TFAD) will produce foundation designs having relatively uniform levels of reliability as long as compatible applied loads (Section A.5.3), nominal geotechnical design parameters (Section A.5.4), and performance criteria (Section A.7) are input. See Figure A.18 for the idealized relationship between load, resistance, and performance.

A.6. Development of Geotechnical Design Parameters

A.6.1. Introduction

Ideally, geotechnical design parameters should be assigned based on the results of in-situ and laboratory testing of undisturbed samples for soil and rock for which stress histories are appropriately accounted (as was done for the full-scale testing of the FAD models). However, in lieu of such tests the user may consider estimating these parameters from correlations with SPT blow counts (N). SPT blow count correlations are commonly used in geotechnical design as they are abundant and relatively inexpensive to obtain. It is stressed that, all correlations contain uncertainties and must be considered within the context of stress history.

Numerous references are available for correlating SPT blow counts to various soil properties. The 2012 EPRI *Transmission Structure Foundation Design Guide* provides correlations to density, undrained shear strength and deformation modulus for un-corrected blow counts (EPRI 2012, TR-1024138). Other references to property estimates based on field consistency correlations include EPRI Report EL-6800 “Manual on Estimating Soil Properties for Foundation Design” (EPRI 1990) and FHWA Geotechnical Engineering Circular No. 5, “Evaluation of Soil and Rock Properties” (FHWA 2012). These documents provide a comprehensive reference for estimating engineering soil parameters from field and laboratory test data. Users are recommended to also consider available regional-specific correlations when developing geotechnical design parameters.

A.6.2. Development of Nominal Values

FAD Tools RBD methodology calibrates resistance factors (Φ_5) to specific mechanistic models using high quality full-scale test data with nominal resistance (R_N) dependent upon predicted loads and capacities. Hence, variability in the actual field data must be combined with engineering judgment when selecting nominal geotechnical resistance to prevent conservative or unconservative design where lower quality data exists in typical design work. The foundation designer has the challenge of reviewing subsurface information from laboratory and field tests to provide this estimate, typically based on professional experience. If low-bound geotechnical resistance values are used in design in lieu of nominal values, a different load-deflection relationship develops and the RBD model as described in Section A.3 and A.4 may no longer be valid.

A.6.3. Geotechnical Design Parameters - Soil

For MFAD, HFAD and TFAD, the soil strata material, strength and deformation properties input include:

- Undrained shear strength (c),
- Friction angle (ϕ),
- Deformation modulus (E_p),
- Depth to water (below ground surface), and
- Total unit weight (γ).

The use of only one of the strength parameters (undrained shear strength or friction angle) is required in FAD Tools foundation design. In cemented or overconsolidated unsaturated soils, the use of both strength parameters may be warranted, but the user is cautioned to verify that the model corresponds to the expected behavior of the subsurface condition. This is particularly important for calculation of the side shear moment spring, base moment spring, base shear spring, and bearing capacity calculations.

FAD version 5.1 and later include internal calculation of shear strength reduction factor (α_r) relating to adhesion between the foundation and drilled shaft side wall strata (see EPRI 1982, EL-2197 vol. 1, Figure 3-5).

The deformation modulus used in the FAD design models corresponds to the modulus of deformation determined from field pressuremeter testing (E_p). The manner in which the pressuremeter loads the soil is similar to the manner in which the pier loads the soil. Thus, the modulus of deformation determined in this fashion is thought to be more relevant to pier behavior than a modulus of elasticity determined from a laboratory test of a vertically loaded sample. A more detailed discussion on pressuremeter testing and computation of E_p values is presented in the EPRI research report (EPRI 1982, EL-2197, vol. 2, sect. 3).

The effective unit weight is internally calculated in all FAD modules. The default depth to groundwater is set to zero or ground line. All increments of subsurface layers below the depth to groundwater use the effective unit weight for calculation of foundation capacity.

$$\gamma'_i = \gamma_{Total,i} - 62.4 \left(\frac{lbf}{ft^3}\right), below\ groundwater\ table$$

The moist (bulk) unit weight for soils may be used above the groundwater table, but these soils typically have low degrees of saturation and are based on extensive field testing. The total unit weight value must be greater than the unit weight of water for the program to properly function.

The FAD program expects input of realistic subsurface parameter values. Zeroing out or inputting values lower than can exist in the real world may cause unexpected behavior in the program.

Up to ten layers of subsurface soil or rock may be utilized and a single depth to groundwater is assumed.

A.6.4. Geotechnical Design Parameters - Rock

For MFAD, HFAD and TFAD the rock strata material, strength and deformation properties input include:

- Rock-concrete bond strength,
- Rock cohesion (c),
- Friction angle (ϕ),
- Deformation modulus (Ep),
- Depth to water (below ground surface), and
- Total unit weight (γ).

In order to use the FAD modules to predict the behavior of laterally and axially loaded drilled shafts in rock, the user must enter the nominal strength and deformation parameters of the rock mass. The theoretical ultimate capacity model requires both the Mohr-Coulomb strength parameters of the rock mass and the rock-concrete bond strength.

When a layer is identified as being rock, the user entered values for ϕ' and c' for the rock layer are used to calculate the ultimate lateral capacity (MFAD, HFAD and TFAD). For calculation of side shear capacity, the FAD program does not use the entered ϕ' and c' values, but instead substitutes rock-concrete bond strength value as the unit side shear resistance (HFAD and TFAD) and vertical side shear moment spring (MFAD).

The strength and deformation parameters needed for rock are more difficult to determine than with soil. In the original EPRI research for the development or rock-socketed foundations, the quantity and quality of subsurface data tended to vary due to geologic conditions, different drillers and equipment, and in-situ equipment variability. As a result, the same in-situ and laboratory test data could not be used consistently at each load test site to assess the rock properties needed to calibrate the MFAD models. In order to best match the program design results with the full-scale foundation results and perform calibrations, a consistent method of estimating rock properties was required. For this reason, the Geomechanics Classification System and RMR_{76} value of Bieniawski (1976) were used to estimate the strength and deformation properties of rock. It is recommended that this approach be used to determine strength and deformation parameters of rock layers for design and analysis of rock-socketed foundations in the FAD software. Section C presents the recommended approach that is consistent with the approach that was used in full-scale foundation correlation work (see EPRI TR-108254 for details on the evaluation of rock parameters for the FAD software).

The load-deflection behavior predicted by MFAD is based on the deformation modulus (E_p) for each rock layer in the rock mass and the overlying soil layers. Users can enter soil layers below rock layers, but this may produce inconsistencies in the model. The FAD program does not consider the cracking moment of the foundation when the foundation is embedded within rock. The user must perform independent checks if there is a need to validate this assumption.

A.6.5. Design Parameters – Annulus Backfill

MFAD and HFAD require the input of backfill annulus properties for direct embedment analysis. Backfill material strength and deformation properties input are as follows:

For soil backfill material:

- Annulus thickness,
- Total unit weight (γ),
- Deformation modulus (E_a),
- Undrained shear strength (c), and
- Friction angle (ϕ).

For concrete backfill material:

- Annulus thickness,
- Total unit weight (γ),
- Deformation modulus (E_a),
- Concrete strength (f'c), and
- Effective Shear Strength.

The models assume the annulus is filled with either concrete or well-compacted cohesive/granular backfill placed in thin lifts. Attempting to model the annulus with poorly-compacted backfill or low strength cementitious slurry backfill possibly will result in an inaccurate load-deflection response.

Research suggests a relationship between granular aggregate backfill density with both internal friction angle and modulus of elasticity. Both geotechnical parameters increase as density increases and vary based on particle size and particle distribution (EPRI 1989, El-6309). EPRI performed a series of laboratory direct shear and triaxial test in the late 1980's that documented this phenomenon (EPRI 1989, El-6039) and additional testing was later performed (EPRI 1997, TR-108254). The user is encouraged to review the literature and perform laboratory tests in the development of appropriate design parameters for the specific annulus backfill to be used in construction.

The MFAD and HFAD modules evaluate three different failure modes for direct embedment foundations under lateral loading:

1. At the pole-annulus interface,
2. Within the annulus material (combination of pole-annulus-subsurface), and
3. At the annulus-subsurface interface.

And two failure modes under axial loading:

1. At the pole-annulus interface, and
2. At the annulus-subsurface interface.

Variations in foundation dimensions, subsurface properties, and annulus properties may change the controlling mechanism and produce different capacities.

A.7. Performance Parameters

Performance parameters are employed within MFAD to limit pole rotation due to foundation movement and to keep foundation deflections within reasonable limits under service load application. When using an RBD approach, performance of the foundation in terms of top of pier rotation and deflection rarely controls final foundation embedment depth as the methodology assumes resulting loads and resistance occur in the elastic range of motion. Deflection and rotation limits, though, should be checked to insure working or services loads perform within acceptable limits.

A.7.1. Load-Deformation Response

The goal of the engineer is to design a foundation that performs as expected under the anticipated range of applied loads. At a conceptual level, the mechanics of materials dictates a relationship between stress and strain as a function of soil-structure interaction. The non-linear nature of the load-deformation response for typical transmission line foundation types is well documented from ERPI full-scale testing, laboratory scale tests and most foundation design models in both axial and lateral load modes (EPRI 1982, EL-2197; EPRI 1983, EL-2870; DiGioia and Rojas-Gonzalez 1994).

Figure A.18 provides an understanding of how MFAD interprets various loads or resistances relating to foundation performance.

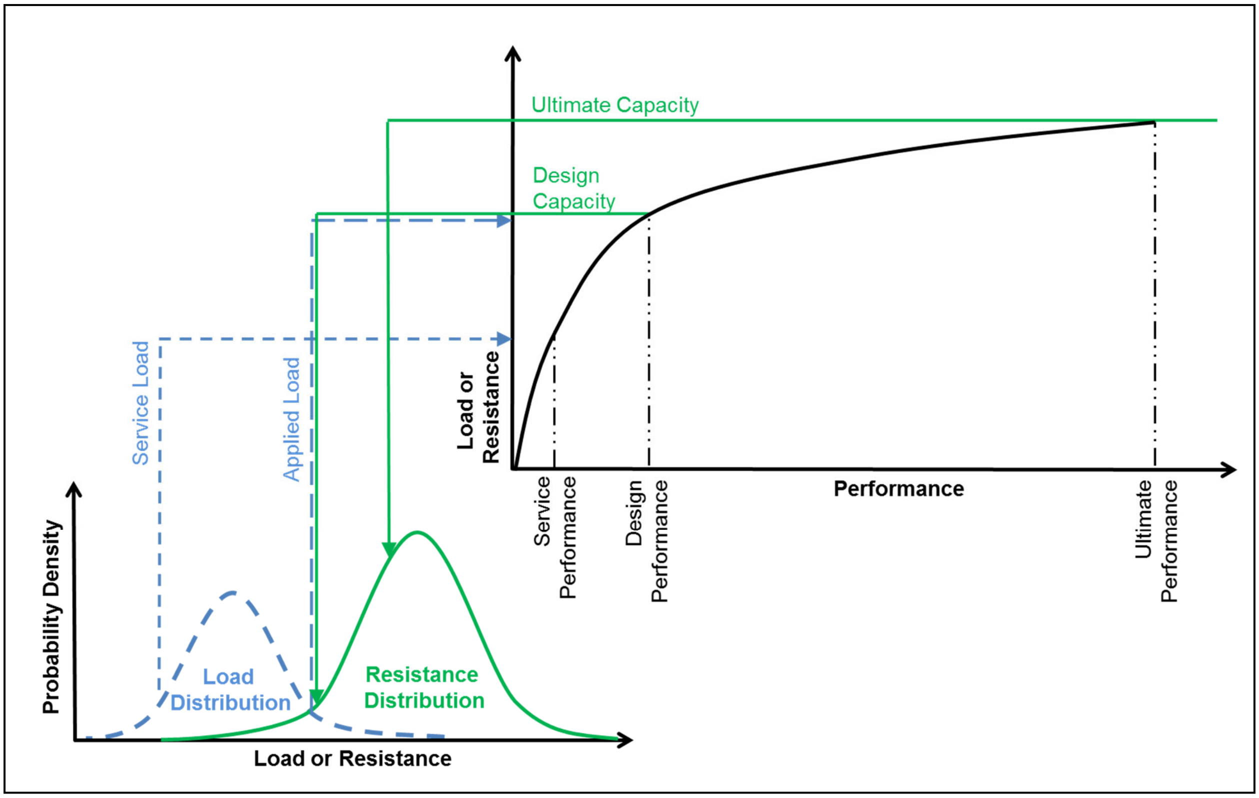


Figure A.18
Relationship of Load and Resistance Probability to Performance Parameters

A.7.2. Parameter Selection

MFAD 5.1 includes the following performance parameter inputs:

- Maximum allowable ground line deflection (δ),
- Maximum allowable ground line rotation (θ),
- Maximum non-recoverable ground line deflection (δ'), and
- Maximum non-recoverable ground line rotation (θ').

Full-scale foundation lateral load tests performed by EPRI found a strong relationship between top of pier rotation and geotechnical failure of short rigid shafts, with maximum sustainable load occurring at or after 2 degrees of rotation (EPRI 1982, EL-2197). In these original MFAD studies, non-elastic (plastic) deformation was well developed after 2 degrees of rotation.

As such, MFAD was calibrated with ultimate capacity defined at 2 degrees or more the rotation using nominal geotechnical properties. But as shown in Figure A.18, top of shaft performance limits must also relate to the applied load (A_{PPL}) on the load-deflection curve to achieve a compatible load-deflection relation for design.

Limited research has been done to evaluate reasonable non-recoverable deflection and rotation values for use in MFAD. Limits have been generally thought as related to aesthetics and owner preference. In practice, designers set non-recoverable values at 50% of the allowable values. See EPRI EL-2197 Volume 2 for further discussion.

Note that the development of FAD Tools 5.1 included updated algorithms to more accurately model full-scale foundation load test results performed during the original development of the model (FAD 4.0 and earlier). The end result of this re-calibration is a slightly softer deformation response than seen in earlier MFAD versions, where the same soils and load parameters result in an increased deflection on the order of 8% to 9% with the newer version (see Figure A.19).

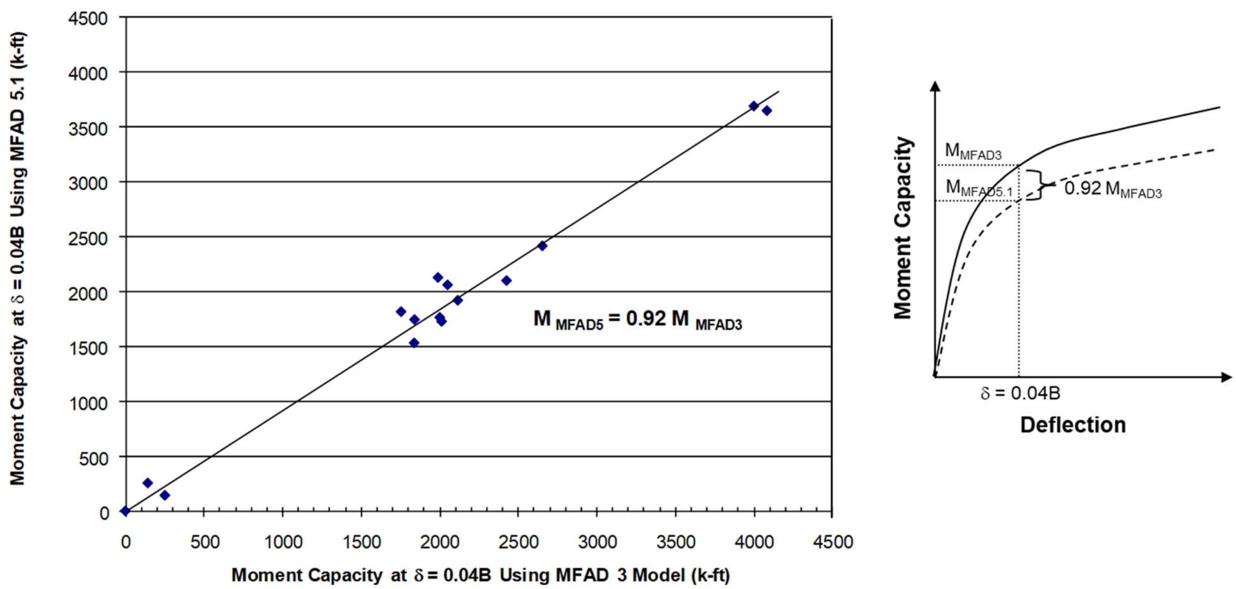


Figure A.19
EPRI Full-scale Foundation Tests Predicted Moment Capacity at δ = 0.04B (Kandaris 2011)

A.8. Drilled Shaft Concrete Design

A.8.1. Introduction

The purpose of the concrete design module of FAD is to determine the steel reinforcement for concrete drilled shafts designed to resist combined axial, moment and shear loads calculated using the FAD modules (MFAD, HFAD and TFAD). In MFAD, the concrete design is performed for the load case that controls geotechnical design. In HFAD and TFAD, the concrete design accounts for all input modes of loading.

The concrete design methodology within FAD adheres to the strength requirements of sections of the ACI 318-14 Code, hereafter referred to as the ACI code. Although drilled shafts for transmission structures are typically not within the scope of this document (ACI Section 1.4.6), it serves as the reference code for design of steel reinforcement and structural concrete for drilled piers in the electric transmission line industry. The number of longitudinal bars is determined to resist the maximum bending moment in the shaft along with the corresponding axial force. The program verifies that the number of bars and the bars' spacing are within the requirements of the ACI code and verifies that the required amount of steel does not exceed the maximum allowed by ACI code.

The concrete module also determines the required spacing of shear reinforcement tie hoops along the entire depth of the shaft to resist the applied shear loads and soil pressures. When shear reinforcement is not required by analysis, rebar spacing is calculated using minimum shear reinforcement requirements of ACI code.

A.8.2. Methodology

The FAD concrete module follows a Load and Resistance Factor Design (LRFD) approach where combinations of factored loads are less than, or equal to, the design capacity which is calculated as the nominal strength multiplied by strength factors. The FAD concrete module assumes that the input loads already include appropriate load factors. It is noted that the strength factors listed in the ACI are encoded in the concrete model as described in the following sections.

A.8.3. Concrete Design Input

The drilled shaft is assumed to consist of a cylindrical concrete straight-sided shaft with constant diameter. Reinforcing consists of longitudinal bars arranged in a circular pattern and shear reinforcement (tie-bars) transverse to the longitudinal axis of the shaft.

The input used for concrete reinforcement design is a combination of data already existing in FAD modules (MFAD, HFAD and TFAD) and from the geotechnical design calculations, and data that is input directly by the user.

<u>Data already entered in the foundation analysis section</u>

- Shear forces as a function of depth, kips. (internal shear from foundation analysis report)
- Bending moments as a function of depth, kip-ft. (internal moment from foundation analysis report)
- Shaft weight as a function of depth, kips. (calculated by the program using the input diameter and an assumed concrete unit weight of 0.15 kcf)
- Applied vertical load, kips. (defined by user input)

<u>Required additional data for concrete reinforcement design</u>

- Cover provided for shear tie reinforcement, in.
- Concrete compressive strength (f'_c), ksi.
- Yield strength of steel longitudinal reinforcement (f_y), ksi.
- Yield strength of steel shear reinforcement (f_y), ksi.

- Bar size to be used for longitudinal reinforcement for bending and axial loads.
- Bar size to be used for shear reinforcement as circular ties.
- Selection of method for calculating the minimum longitudinal steel.
- Selection of method for calculating concrete shear strength.

Full length anchor bolts (optional check)

- A new section has been added for the special case of full-length anchor bolts. This section is optional and provides a check of the minimum foundation diameter required if an anchor bolt circle diameter is specified.

A.8.4. Combined Bending and Axial Loading

The following considerations are made when calculating strength for combined uniaxial bending and axial load:

a. Cross sectional strength is calculated based on satisfying the equilibrium of stresses and the compatibility of strains (ACI Section 22.2.1).
a. The strain is directly proportional to the distance from the neutral axis (ACI Section 6.7.1.3).
b. The maximum usable strain at the extreme concrete compression fiber is equal to 0.003 (ACI Section 22.2.2.1).
c. In compliance with ACI Section 20.2.2.1, the tensile or compressive stress (f_s) in each steel reinforcement bar is calculated as:

$$f_s = E_s \varepsilon_s$$

where:

E_s is the modulus of elasticity of the steel, taken to be 29,000,000 psi, in agreement with ACI Section 20.2.2.2 and ε_s is the strain in each steel reinforcement bar.

d. When the absolute value of f_s is greater than the specified yield strength, f_y, the magnitude of the steel stress is set equal to f_y, with the sign of the corresponding strain.
e. The concrete compressive stress versus strain relationship is represented by an equivalent distribution, as prescribed in ACI Sections 22.2.2.3 and 22.2.2.4. Following ACI Sections 22.2.2.4.1 and 22.2.2.4.2, the uniform stress in the compression zone is equal to:

$$f_c = 0.85\, f'_c$$

where:

f_c = concrete stress in the same units as f'_c

f'_c = the concrete unconfined compressive strength

The compression zone extends over a zone bounded by the compression edge of the cross section and a straight line located parallel to the neutral axis at a distance *a* from the concrete fiber under maximum compression strain (0.003). In agreement with ACI Section 22.2.2.4, the distance *a* is calculated as follows:

$a = \beta_1$ c

$\beta_1 = 1.05 – 0.05$ f'c

$0.65 \leq \beta_1 \leq 0.85$

where:

c = distance from the point of maximum compressive strain to the neutral axis, in.

f'_c = the concrete unconfined compressive strength, ksi.

f. The tensile strength of concrete is neglected (ACI Section 22.2.2.2).

g. The program calculates the longitudinal steel reinforcement ratio required to resist the maximum applied moment and associated axial force. The steel reinforcement ratio is calculated assuming that the longitudinal steel is distributed as 36 equal lumped areas of steel separated by 10 degrees thereby distributing them evenly throughout the drilled shaft. Comparisons of the strength of circular concrete sections shows that this assumption is applicable for cross sections that use as few as 8 longitudinal bars.

h. The longitudinal steel design is conducted at the drilled shaft section where the maximum bending moment occurs.

i. The acting compressive axial force is calculated as the sum of the applied axial load, with uplift loads being negative, plus the weight of concrete above the depth of the design section. The unit weight of concrete is taken equal to 150 pounds per cubic foot.

For MFAD:

$$P_a = P_{appl} + 150 * (D_{foundation} + l_{stick}) * Atan(1) * B^2$$

For HFAD and TFAD:

$$P_{a_{uplift}} = -P_{appl_{uplift}} + 150 * (D_{foundation} + l_{stick}) * Atan(1) * B^2$$

$$P_{a_{comp}} = P_{appl_{comp}} + 150 * (D_{foundation} + l_{stick}) * Atan(1) * B^2$$

j. In agreement with Section 21.2.2 of the ACI code, the concrete strength reduction factor (ϕ) is calculated as follows for combined axial and bending resistance:

$\phi = 0.65$, for $\varepsilon_t \leq 0.002$

$\phi = 0.90$, for $\varepsilon_t \geq 0.005$

Otherwise:

$\phi = 0.65 + 250\ (\varepsilon_t – 0.002)/\ 3$

Where:

ε_t = net tensile strain in the extreme tension steel.

A.8.5. Minimum Longitudinal Steel

FAD Tools 5.1 provides three methods for calculating the minimum amount of longitudinal steel by selecting either the 0.5% Minimum Longitudinal Steel ($\rho_{min} = 0.5\%$), the ACI Column Method ($0.5\% \leq \rho_{min} \leq 1.0\%$) or a custom value ($0.0\% \leq \rho_{min} \leq 8.0\%$). The ACI Column Method calculates the minimum required area of longitudinal steel based on the requirements of ACI Sections 10.6.1.1 and 10.3.1.2. Additionally, the user may enter a different steel strength for longitudinal steel and shear steel bars. The following procedure is used to determine minimum steel requirements.

<u>Calculation of Longitudinal Reinforcing when using the ACI Column Method</u>
To obtain results compatible with previous versions of FAD (5.1.0 to 5.1.19) select the <u>ACI column method</u> ($0.5\% \leq \rho_{min} \leq 1.0\%$) for the minimum longitudinal reinforcement ratio. This method assumes a basic minimum reinforcement ratio of 1% but then calculates a reduction of the minimum steel ratio when the cross section is greater than required by analysis per ACI Section 10.3.1.2.

a. The design moment capacity of the drilled shaft (ϕMn) is calculated at the design section for the applied axial load assuming the minimum allowable reinforcing ratio of 1% (Section 10.6.1.1). If ϕMn is less than the maximum internal moment, then the amount of longitudinal reinforcing is controlled by strength considerations and the reinforcing ratio is increased until a satisfactory design is achieved. If ϕMn is greater than the maximum internal moment, then the cross section is considered to be larger than required by considerations of loading and the longitudinal reinforcing area is reduced per Section 10.3.1.2.

b. The minimum longitudinal steel is calculated by incrementally reducing the drilled pier diameter and re-calculating the design moment capacity until the smallest circular concrete section required to resist the maximum applied moment is found. The area of longitudinal steel in the reduced section is calculated as 1% of the reduced gross concrete area.

c. The minimum required longitudinal steel area for the full cross section is taken as the steel area in the reduced cross section from step b, however, the reinforcing ratio is limited to 0.5% of the gross concrete area of the full section depending on the method selected. Therefore, the actual minimum reinforcement ratio is a foundation independent value that will range between 0.5% and 1.0% of the gross area:

$$0.5\% \leq \rho_{min} \leq 1.0\% \text{ following the ACI column method}$$

Note that the ACI Column Method ($0.5\% \leq \rho_{min} \leq 1.0\%$)described above is an interpretation of ACI Sections 10.6.1.1 and 10.3.1.2 that was introduced in FAD Tools 5.1. Note that the ACI Column Method ($0.5\% \leq \rho_{min} \leq 1.0\%$), may calculate a larger reinforcement ratio when compared to previous FAD versions, for shafts where the required reinforcement ratio is less than 1%.

Calculation of Longitudinal Reinforcing when using the 0.5% Minimum Longitudinal Steel Method

In previous versions, the 0.5% Minimum Longitudinal Steel ($\rho_{min} = 0.5\%$), the minimum reinforcement ratio was assumed to be 0.5% based on the full diameter of the shaft and then incrementally increased until an acceptable amount of steel was achieved. This method is consistent with recommendations provided in the FHWA Drilled Shafts Manual (2002) and historical drilled shaft design.

Definition of Longitudinal Reinforcing when the engineer introduces a custom value

The engineer is allowed to introduce a custom value between 0.0% and 8.0%. FAD will issue an error message if the custom value is larger than 8.0% and will stop the analysis. This upper limit of 8% is based on ACI 318-14 Section 10.6.1.1. FAD issues also a warning message for values smaller than 0.5% but the analysis is allowed to continue if the engineer chose to do that.

A.8.6. Shear Loading

The FAD concrete module performs the shear design for the entire depth of the drilled shaft, at 1.0-ft intervals. The user can select between two methods for calculating the nominal concrete shear capacity (V_c) as either the FAD Method ($3.5\sqrt{f'_c}$) or the ACI Method ($2\sqrt{f'_c}$). Additionally, the user may enter a different steel strength for longitudinal steel and shear steel bars.

To obtain results compatible with previous versions of FAD (5.1.0 to 5.1.19) select the FAD Method ($3.5\sqrt{f'_c}$) for the concrete shear stress method.

a. The user selects the method of analysis for shear tie calculation.

$$V_c = 3.5 * \sqrt{f_c'} * B * d, \text{ for the FAD Method}$$

$$V_c = 2.0 * \sqrt{f_c'} * B * d, \text{ for the ACI Method}$$

Where:

V_c = shear carried by concrete, lbs.

f'_c = concrete compressive strength, psi.

B = diameter of the drilled shaft, in.

d = distance from extreme compressive fiber to the centroid of longitudinal tension reinforcement in inches; taken equal to 0.8*B per ACI Section 22.5.2.2.

The FAD Method ($3.5\sqrt{f'_c}$) was developed for the shear tie design of drilled piers for transmission structures to be used in the PADLL program. The concrete shear strength was based on quarter scale drilled shaft tests presented in EPRI EL-2197 (1982) with zero to minimal shear reinforcement and subjected to load distributions similar to that imposed by lateral soil pressures on a pier. The EPRI funded study was undertaken with recognition that typical utility practice at the time, which had not led to numerous shear failures, was to provide adequate shear reinforcement to tie the cage together or to resist the applied shear at the top of the pier regardless of the magnitude of the below ground shear.

b. The FAD concrete module conservatively ignores any increase in concrete shear strength due to compressive stresses but does decrease the concrete shear strength for drilled shafts in uplift. For shafts in uplift, V_c is decremented by the equation below which is consistent with ACI 318 Section 22.5.7.1.

$$V_{c_{uplift}} = V_c * \frac{1 - N_u}{500 * A_g}$$

Where:

N_u = axial uplift force, lbs.

A_g = Gross concrete area, in^2.

c. In agreement with Table 21.2.1 of the ACI code, the strength factor for shear is $\phi = 0.75$. It is noted that this value is lower than the strength factor of 0.85 that was incorporated in previous versions of the ACI Code and in MFAD version 4.0 and earlier.

d. There are a number of spacing limits as defined by the ACI code, each of which are evaluated in the FAD concrete module.
   - Section 9.6.3.1 defines cases where area of shear steel is not required.
   - Section 9.7.6.2 defines spacing as a function of foundation diameter. In previous versions this function was limited only be the 24 in maximum spacing requirement (per ACI 318-11 Section 11.4.5). In accordance with ACI 318-14 section 9.7.6.2, the 12 in maximum spacing requirement is also included in FAD 5.1.19 or newer versions.
   - Section 9.7.6.4.2, 9.7.6.4.3, and 25.7.2.1 defines spacing requirements as a function of bar size.
   - Section 10.6.2.1 and 10.6.2.2 defines minimum of area of shear reinforcement.
   - Section 22.5.1.2 defines cross sectional dimensions and Section 22.5.10.5.3 defines the relationship between spacing and steel area requirements.

e. The concrete output report tabulates the calculated shear strength of the concrete (ϕV_c), the required shear strength to be provided by the hoop steel (ϕV_s), and the maximum tie bar spacing based on considerations of strength and minimum spacing requirements.

When the required steel strength (ϕV_s) is zero, then the tie bar spacing is controlled by the minimum spacing limits listed previously in Section A.8.5.d.

A.9. Limitations

The following are a list of key limitations for consideration by the user. The list should not be considered comprehensive, but does identify limitations documented to date. FAD Tools 5.1 specific limitations are also discussed in Section B.7 as part of warnings included in the software. Additional details on limitations are discussed in EPRI EL-2197 (EPRI 1982).

- Because of their very nature, the dimensions of the foundation and the strength properties of the soil and rock layers must have positive values. In addition, the depth of the layers is considered positive downwards. Since the thickness of one layer cannot be negative, the depth of each layer must be larger than the depth of the layer above. The maximum number of layers has been set to 10.
- As a rule, geometrical properties are accepted with one significant figure (one tenth) in the English system. For the types of foundations being analyzed and designed it is unrealistic to consider more accurate figures.
- FAD Tools is limited to short rigid shaft design where the bending stiffness is constant along the full length of the shaft, as observed when performing the full-scale load tests. Therefore, the ratio of foundation depth (L) to drilled shaft diameter (B) as recommended by the program developers should be equal to or less than 10. This limitation gives reasonable assurance that the shaft will behave essentially as a rigid body. The bending flexibility of drilled shafts can be a factor in foundations with L/B higher than 10. For direct embedded poles, the ratio of foundation depth (L) to pole diameter (B) should be equal to or below 10. Also, the ratio of foundation depth to diameter should be equal to or greater than 2. When drilled shafts are outside this limit, the designer must consider using an alternate foundation design model that incorporates a point of fixity and inflection points within the shaft (intermediate or long pier design).
- In previous FAD versions, the designer was required to enter foundation flexural rigidity parameters such as modulus of elasticity and moment of inertia of reinforced concrete. Full-scale foundation tests demonstrate these parameters to provide minimal influence for short rigid shafts and are not required in FAD 5.1 or later versions.
- Drilled shaft diameter is limited to a maximum of 15 feet.
- The program is not designed to incorporate (a) repetitive load cycling that results in degradation of soil resistance, (b) sustained high loading beyond the normal working range where creep effects may be encountered and (c) seismic and blast-type loading. Although the program will yield results for combined uplift and lateral forces, the accuracy of these predictions is untested and unknown.
- In general, FAD is designed to be used for foundations within the normal range of working load conditions as follows:
    - Axial loads input range of 0 - 250 kips,
    - Moment input range of 0 - 30,000 kip-ft,

  - Shear (lateral) loads input range of 0 - 300 kips.
- FAD has been developed for foundations where lateral forces and overturning moments are the primary loading mode. The effects of significant vertical loads have not been considered in the MFAD model for drilled shafts and direct embedded poles. Only compressive forces are allowed in MFAD for axial loads. MFAD is intended to be used for single pole foundations only and does not consider group effects. When axial loads dominate, HFAD or TFAD models should be used to perform foundation design. Bearing capacity and settlement are not calculated by the FAD program. Effects of torsion are not evaluated by the program.
- Only lateral deflection and pier rotation are calculated in MFAD. HFAD and TFAD models do not account for the complex interaction of combined axial and lateral loading conditions. As such calculations of lateral deflection and rotation are not included in the HFAD and TFAD models.
- FAD has been calibrated for RBD. The user is encouraged to use the reduction factors provided in the program. However, it is up to the engineer of record to verify the load and performance compatibility.
- The FAD Tools models are calibrated based on full-scale testing which uses nominal geotechnical parameters based on extensive field and laboratory testing (EPRI 1982, EL-2197). Therefore, the user is encouraged to maintain usage of nominal parameters unless special circumstances warrant a deviation(s) from this approach.
- The use of only one of the strength parameters (undrained shear strength or friction angle) is considered in FAD foundation design. In cemented or overconsolidated unsaturated soils, the use of both strength parameters may be warranted, but the user is cautioned to verify that the model corresponds to the expected behavior of the subsurface materials.
- Only one groundwater depth may be assumed per geotechnical parameter data file.
- Previous FAD versions require soil-shaft adhesion reduction factors (referenced as “alpha factor”) as input. These reductions for both cohesive and cohesionless strata have been included within the MFAD 5.1 and later versions.
- Cracking moment of the concrete foundation is not evaluated in the program and must be checked independently if the user deems necessary.
- FAD limits rock socket depths to a maximum of 5 diameters.
- FAD does not evaluate the effects of bedding planes or other discontinuities with rock mass strength. As such, recommended minimum embedment depth of one diameter may or may not be sufficient depending on specific subsurface material. The user must independently verify that sufficient embedment into rock has been provided to prevent local failure.

B. STEP-BY-STEP PROGRAM GUIDE

B.1. Welcome to FAD

FAD Tools (FAD) is comprised of three modules: MFAD, HFAD, and TFAD. This section provides instructions on the step-by-step use of the FAD program. Additional resources can be found in Section A of this document and FAQ List provided on the FAD Tools website.

B.1.1. MFAD Architecture

- Designs drilled shaft and direct embedment foundations for single pole structures.
- Relatively low axial loads. Overturning loads are resisted by a combination of lateral pressure, vertical shear forces, base shear and moment.
- Models the soil-structure interaction based on RBD methodology.
- Models multi-layered soil and rock subsurface conditions.
- Uses a four-spring model to resist the design loads.
- Springs can be turned on/off to model various soil–structure interaction conditions.
- Results include nominal and design capacities.
- Includes performance criteria of total rotation and deflection and non-recoverable rotation and deflection.
- Is calibrated with full-scale load test of both direct embedment and drilled shaft foundations.

B.1.2. HFAD Architecture

- Designs drilled shaft and direct embedment foundations for H-frame pole structures.
- Models a foundation subjected to a combination of large overturning loads and large uplift, compression and shear loads.
- Uses four design models to resist four design load cases.
- Models the soil-structure interaction based on RBD methodology.
- Models multi-layered soil and rock subsurface conditions.
- Results include nominal and design capacity.

B.1.3. TFAD Architecture

- Designs drilled shaft foundations for lattice tower structure legs.
- Models a foundation subjected to a combination of lateral shear under uplift and compression loads.
- Uses four design models to resist four design load conditions.
- Models the soil-structure interaction based on RBD methodology.
- Models multi-layered soil and rock subsurface conditions.
- Results include nominal and design capacity.

- Cylindrical shear model calibrated with full-scale uplift load tests.

B.2. Installing FAD

B.2.1. System Requirements

FAD Tools is supported on Windows 11 and 10. The minimum hardware requirements include: Pentium 300-megahertz (MHz) processor or faster; at least 128 megabytes (MB) of RAM; at least 40 megabytes (MB) of available space on the hard disk; Keyboard and a Mouse or some other compatible pointing device; Video adapter and monitor with Super VGA (800 x 600) or higher resolution.

Note: Users have encountered issues with screen resolution, please adjust the screen resolution if there are “missing” buttons.

B.2.2. Installing FAD Tools

FAD is distributed electronically and has an easy-to-use common Windows installation procedure. All modules (MFAD, HFAD, and TFAD) use the same user interface and are installed at the same time. Only those modules that a license has been purchased will be accessible when using FAD. To install FAD Tools, exit all programs, including anti-virus protections, and click on the installation file and follow the prompts. .

B.2.3. Installation Procedure

The installation will copy all necessary files to your computer and place the FAD Tools Icon on the Desktop. FAD uses a database to store all program information (extension fadt). During installation, this database is installed in the FAD Tools folder on the local computer.

- If you want to install FAD to the default folder, click “Next”. This is the recommended location for FAD. If you want to override the default, click “Browse”, select a folder, and then click “OK”.
- Note that the default folder will also be the location of the default database file (extension fadt). When opening FAD, make sure that the user has read/write access to the database file location selected. The user may need to create a new database file in a location with read/write access (see instructions in Section B.3).

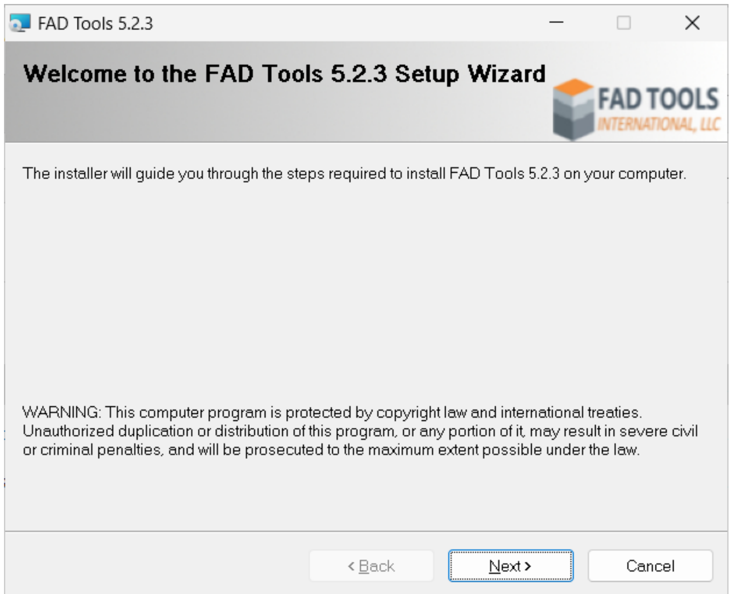


Figure B.1
FAD Tools Installation Window

FAD is uninstalled using Windows Add or Remove Programs. Note that uninstalling FAD Tools will remove all the modules (MFAD, HFAD, and TFAD). Click "Start" and select Control Panel. Click "Add or Remove Programs" and select FAD Tools. Folders and files that contain saved reports or have been revised by the user will not be deleted during the uninstall process. Save any files, including reports, to an alternate location and manually delete the FAD Tools folder to delete all remaining folders and files.

If you experience difficulties accessing the application after standard installation, please consult your IT department personnel to have proper access permissions setup for your use. If the problem cannot be resolved, please visit www.fadtools.com for support contact information, or email support@fadtools.com.

B.2.4. Contacting Technical Support

If you have technical questions, please contact a Technical Support Representative at FAD Tools International. Our Technical Support personnel are available to answer your questions and will respond to your inquiries within two business days.

E-mail your questions or comments to our e-mail address: support@fadtools.com
For more information please visit the FAD Tools website at www.fadtools.com.

B.3. Starting FAD

B.3.1. Opening the Program

To open FAD, click the icon on the desktop or do the following:

- Click “Start”
- Select All Programs
- Select and Launch FAD
    - On the Tool Selection box, select MFAD (See Figure B.2 below.) Only the modules that are purchased will be available for selection. If the trail period has expired or you would like to purchase additional modulus please contact technical support.

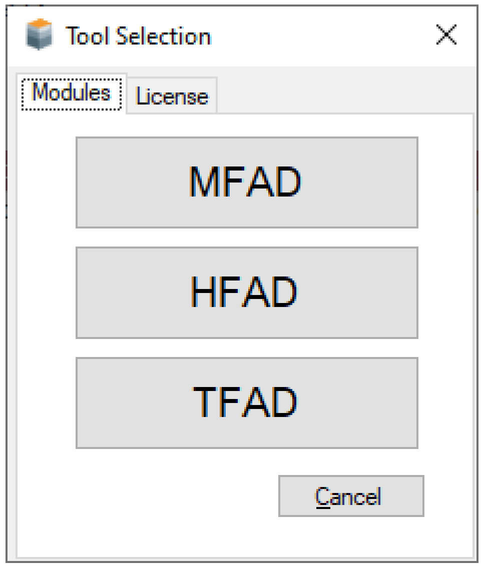


Figure B.2
FAD Tools Selection Window

B.3.2. Adding Licenses

There are three ways to add licenses to FAD:

- Online activation: This method requires an internet connection.
- Offline activation or manual activation: This method does not require an internet connection.
- Specifying a license file location: This method can be used if you have a license file that was created by another user.

To add a license, click the Add License button in the License tab of the selection tool window (see Figure B.3)

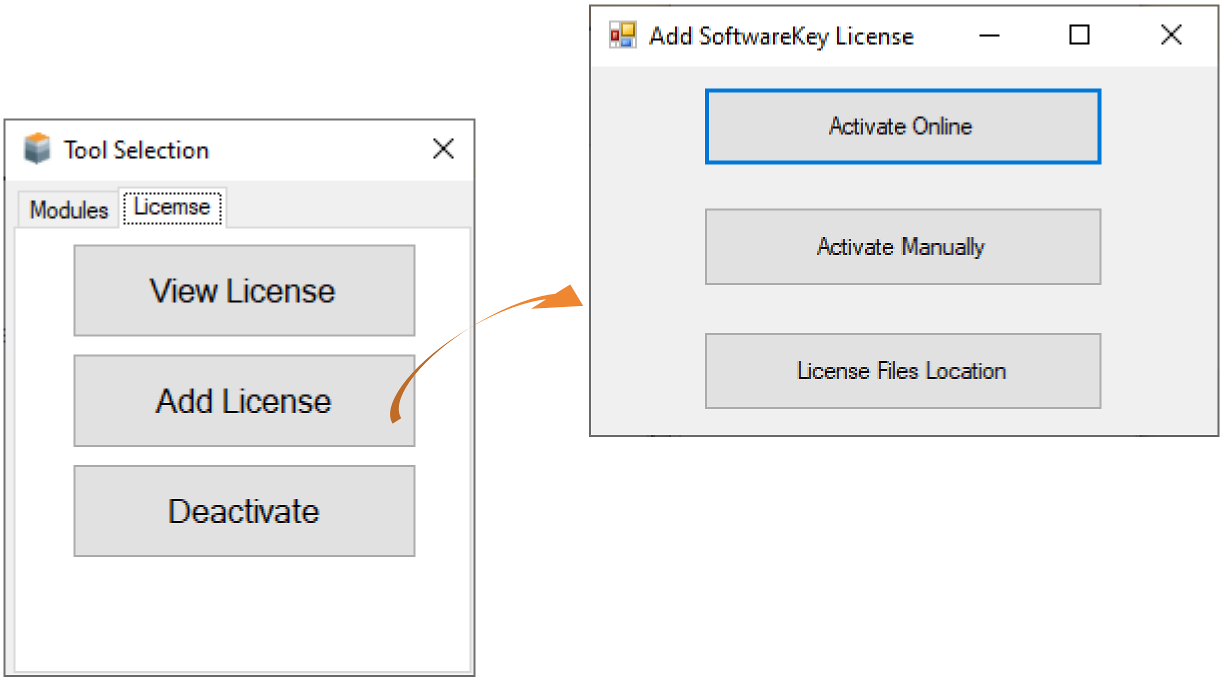


Figure B.3
FAD Options to add Licenses.

B.3.2.1. Online Activation

Online activation is the easiest and quickest way to add a license to FAD. To do this, follow these steps:

- Click "Activate Online" (see Figure B.4).
- Obtain your License ID and Password from the License Portal (see Figure B.5).
- Enter your License ID and Password in the online activation form and click "Activate" (see Figure B.4).

Note that this option is available when you have an internet connection and access to our server (e.g. no firewall blocking the connection).

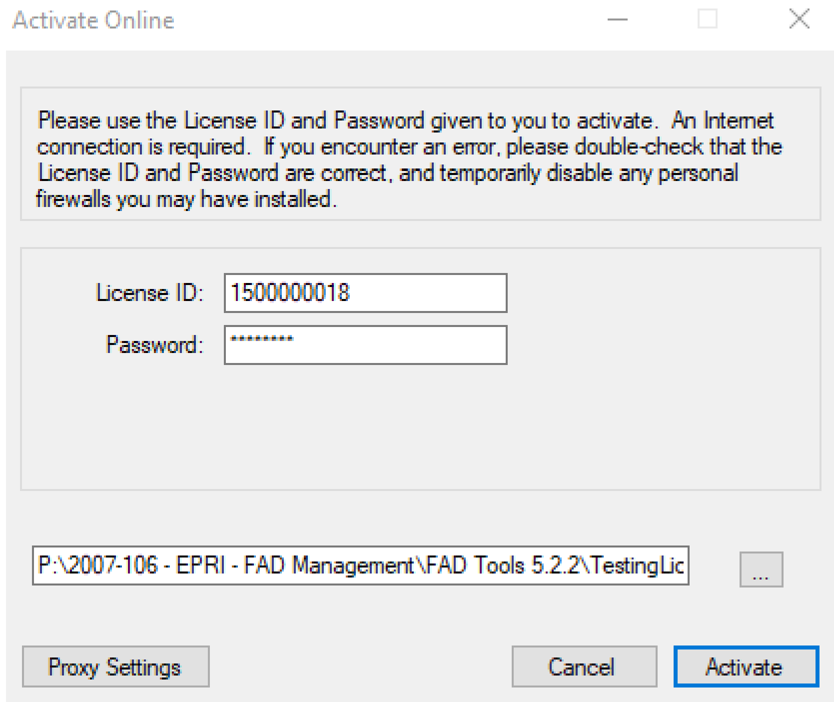


Figure B.4
Online Activation of Licenses.

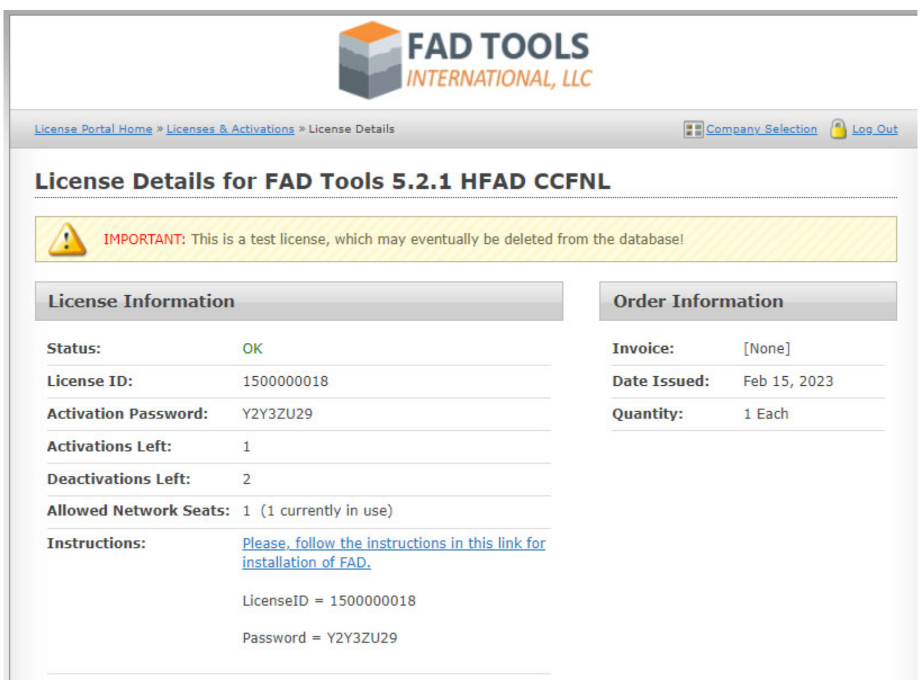


Figure B.5
License Portal.

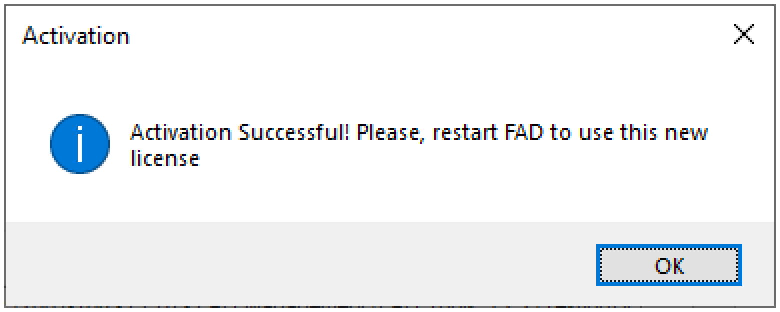


Figure B.6
Successful activation.

B.3.2.2. Offline activation or manual activation.

Offline activation is available for users who do not have an internet connection or access to the FAD server. Depending on the situation use one of these sets of instructions:

For Licensees with connection to internet but without access to the FAD sever, follow these steps:

1- Click the button “Activate Manually” in Figure B.3.
2- The manual activation form will open.
3- Enter your License ID and Password, which can be obtained as explained in the previous section.
4- Click “Generate”.
5- Click “Copy” at step 2 on Figure B.7.
6- Click on “Open Activation web page” on Step 2 of Figure B.7. This will open the webpage shown in Figure B.8.
7- Paste the request from step 5 on the “Copy and Paste Request” box.
8- Click submit and the webpage from Figure B.9 will appear.
9- Click copy.
10- Return to form from Figure B.7 and click paste on Step 3.
11- Press “activate” on Figure B.7, if successful, the notification shown in Figure B.10, will appear.

For licensees without an internet connection on the device using FAD:

1- Click 'Activate Manually' on Figure B.3.
2- Enter your License ID and Password on the manual activation form (Figure B.7).
3- Click 'Generate'.
4- Save the generated text as an activation request file (click 'Save Activation Request file', top left corner, on Figure B.7).
5- Move the saved activation request file to a computer with internet access. Open the following URL: "https://secure.fadtools.com/solo/customers/ManualRequest.aspx". You'll see the webpage depicted in Figure B.8.

6- Choose 'Choose file' bellow 'Upload Request file,' select the saved activation request file, and upload it.
7- Submit the uploaded file. When finished, click on 'Download Activation Response file' (lower half of Figure B.9) and move that downloaded file over to the original device where FAD software is installed.
8- Go back to Figure B.7 and find the button labelled 'Open Activation response file' in the bottom right corner of the window under Step 2. Select this option.
9- After completing Step 8, press 'Activate' on Figure B.7. An alert like Figure B.10 appears after a successful activation process.

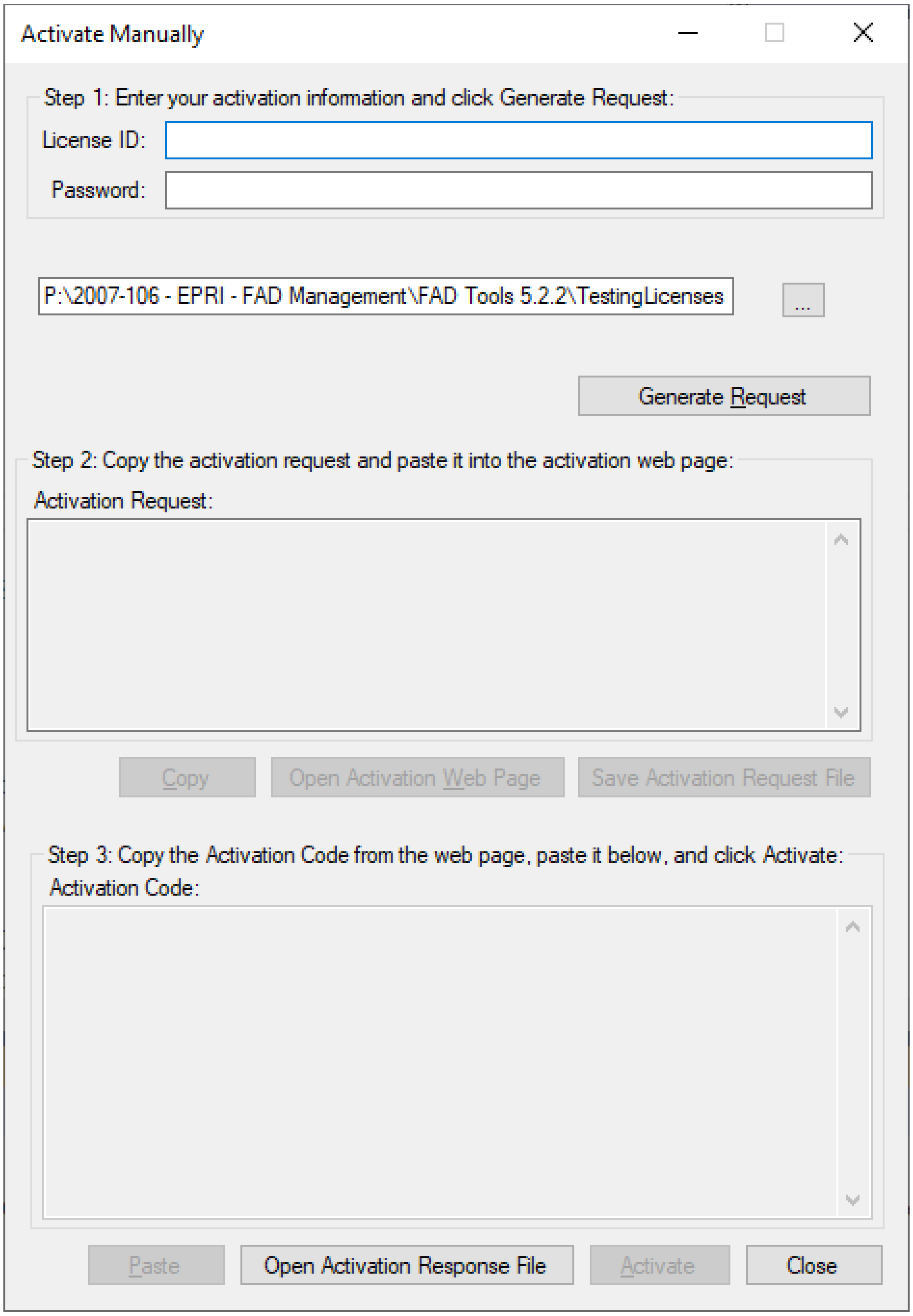


Figure B.7
Form for Manual Activation.

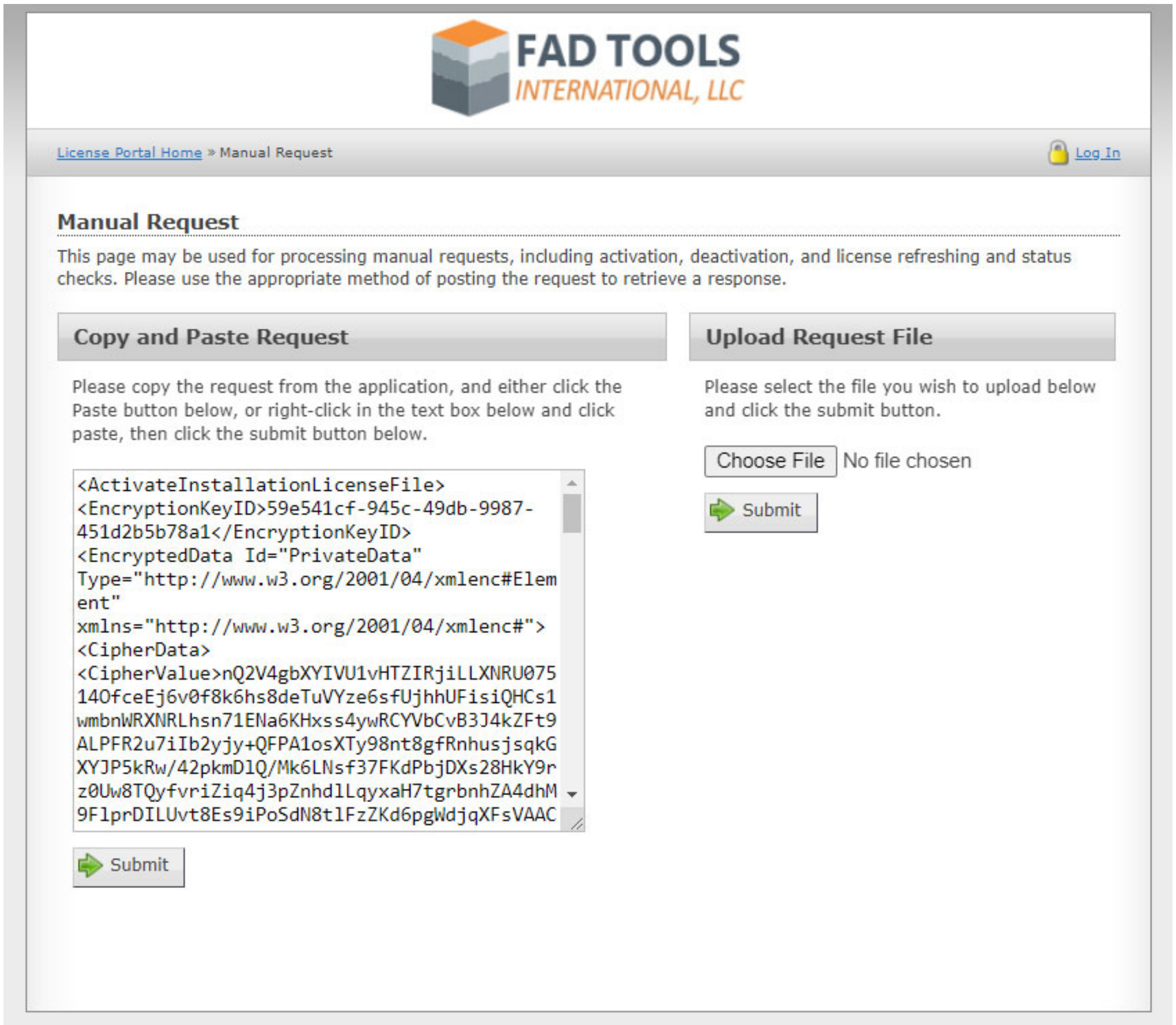


Figure B.8
Submitting request for activation in webpage.

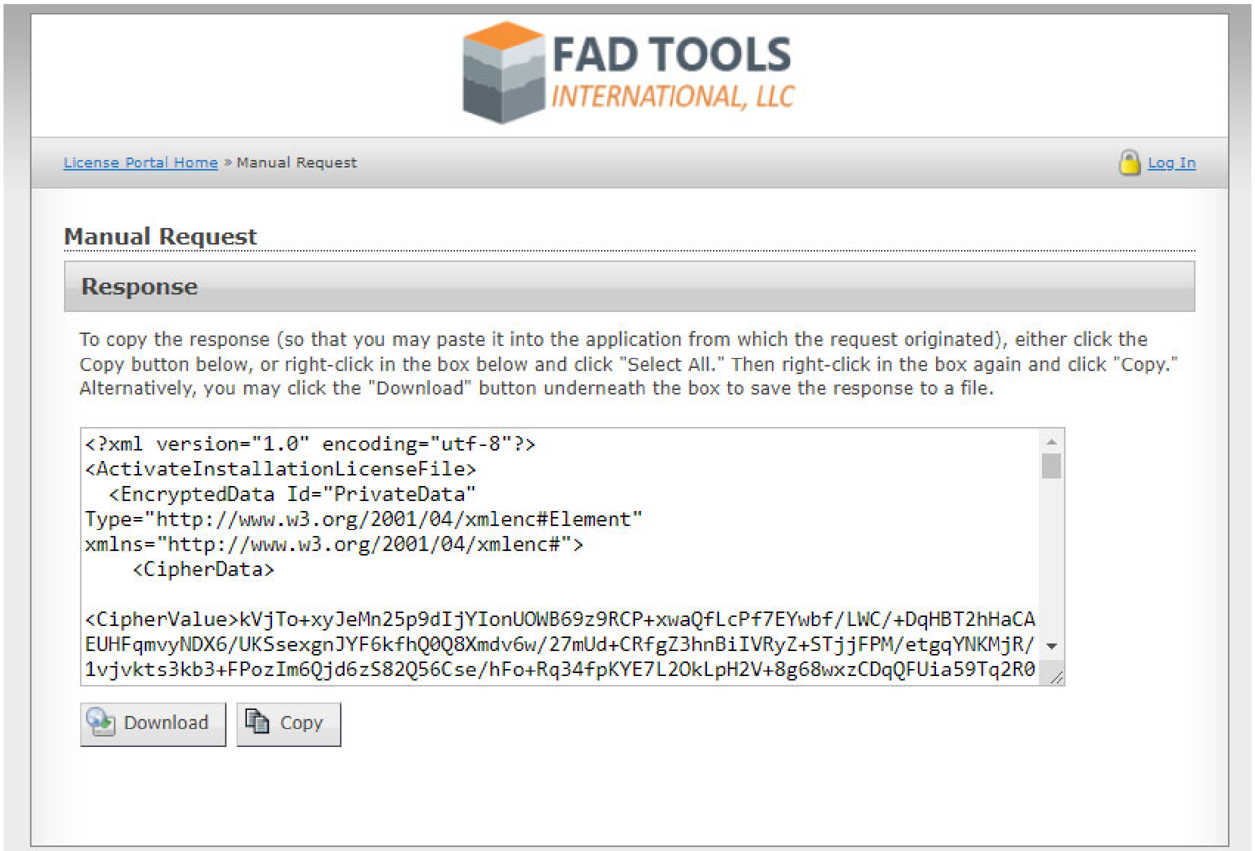


Figure B.9
Getting response from webpage for activation.

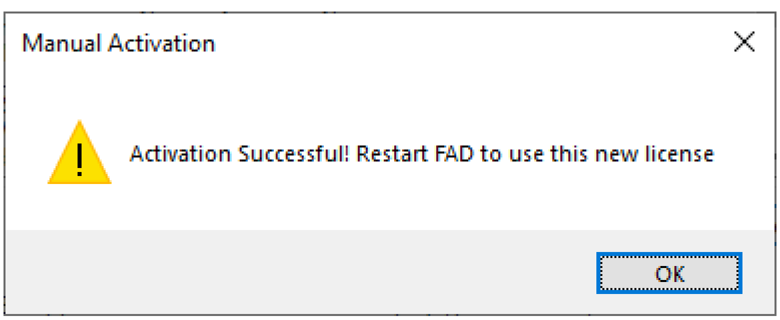


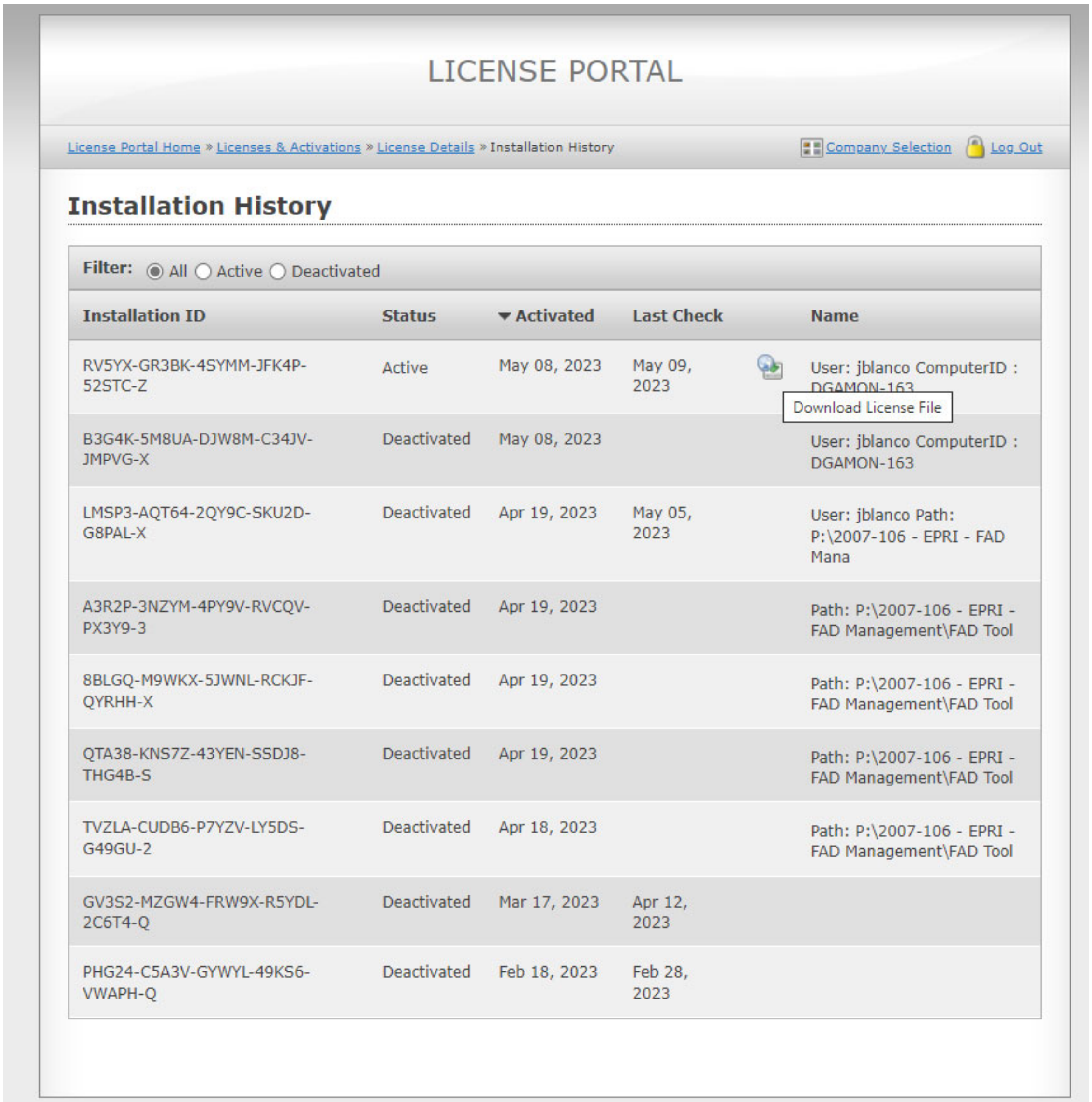
Figure B.10
Successful Manual/offline activation.

B.3.2.3. Transferring License to different computers.

Licenses that are not tied to a computer like Cloud Controlled Floating Licenses can be transferred from computer to computer by copying/pasting the license file and telling FAD where it is. That is:

- Transfer the License file (.e.g #.lfx) from another computer or download it from license Portal (see Figure B.11)

- Specify the new folder location as indicated in Figure B.12.



LICENSE PORTAL

License Portal Home » Licenses & Activations » License Details » Installation History   Company Selection   Log Out

Installation History

Filter: (•) All ( ) Active ( ) Deactivated

Installation ID	Status	▼Activated	Last Check		Name
RV5YX-GR3BK-4SYMM-JFK4P-52STC-Z	Active	May 08, 2023	May 09, 2023	Download License File	User: jblanco ComputerID : DGAMON-163
B3G4K-5M8UA-DJW8M-C34JV-JMPVG-X	Deactivated	May 08, 2023			User: jblanco ComputerID : DGAMON-163
LMSP3-AQT64-2QY9C-SKU2D-G8PAL-X	Deactivated	Apr 19, 2023	May 05, 2023		User: jblanco Path: P:\2007-106 - EPRI - FAD Mana
A3R2P-3NZYM-4PY9V-RVCQV-PX3Y9-3	Deactivated	Apr 19, 2023			Path: P:\2007-106 - EPRI - FAD Management\FAD Tool
8BLGQ-M9WKX-5JWNL-RCKJF-QYRHH-X	Deactivated	Apr 19, 2023			Path: P:\2007-106 - EPRI - FAD Management\FAD Tool
QTA38-KNS7Z-43YEN-SSDJ8-THG4B-S	Deactivated	Apr 19, 2023			Path: P:\2007-106 - EPRI - FAD Management\FAD Tool
TVZLA-CUDB6-P7YZV-LY5DS-G49GU-2	Deactivated	Apr 18, 2023			Path: P:\2007-106 - EPRI - FAD Management\FAD Tool
GV3S2-MZGW4-FRW9X-R5YDL-2C6T4-Q	Deactivated	Mar 17, 2023	Apr 12, 2023		
PHG24-C5A3V-GYWYL-49KS6-VWAPH-Q	Deactivated	Feb 18, 2023	Feb 28, 2023		

Figure B.11
Downloading License File from License Portal.

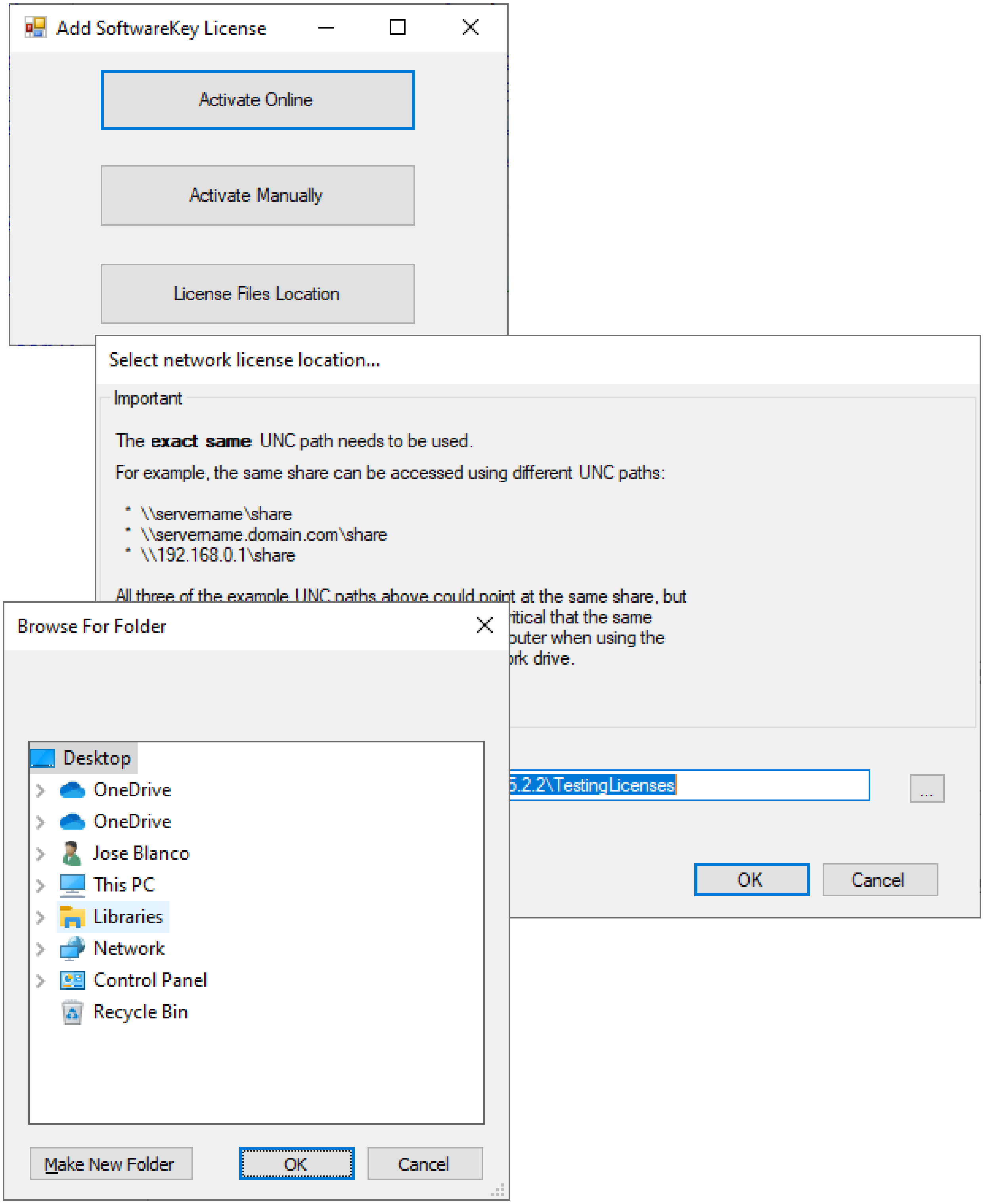


Figure B.12
Saving a new location of the license file in a computer.

B.3.2.4. Deactivating a license

Licenses that are tied to a single computer like PC license, cannot be used in other computers. In these cases, licenses need to be deactivated in the computers first and then activate it back into another computer. This can be done as shown in Figure B.13.

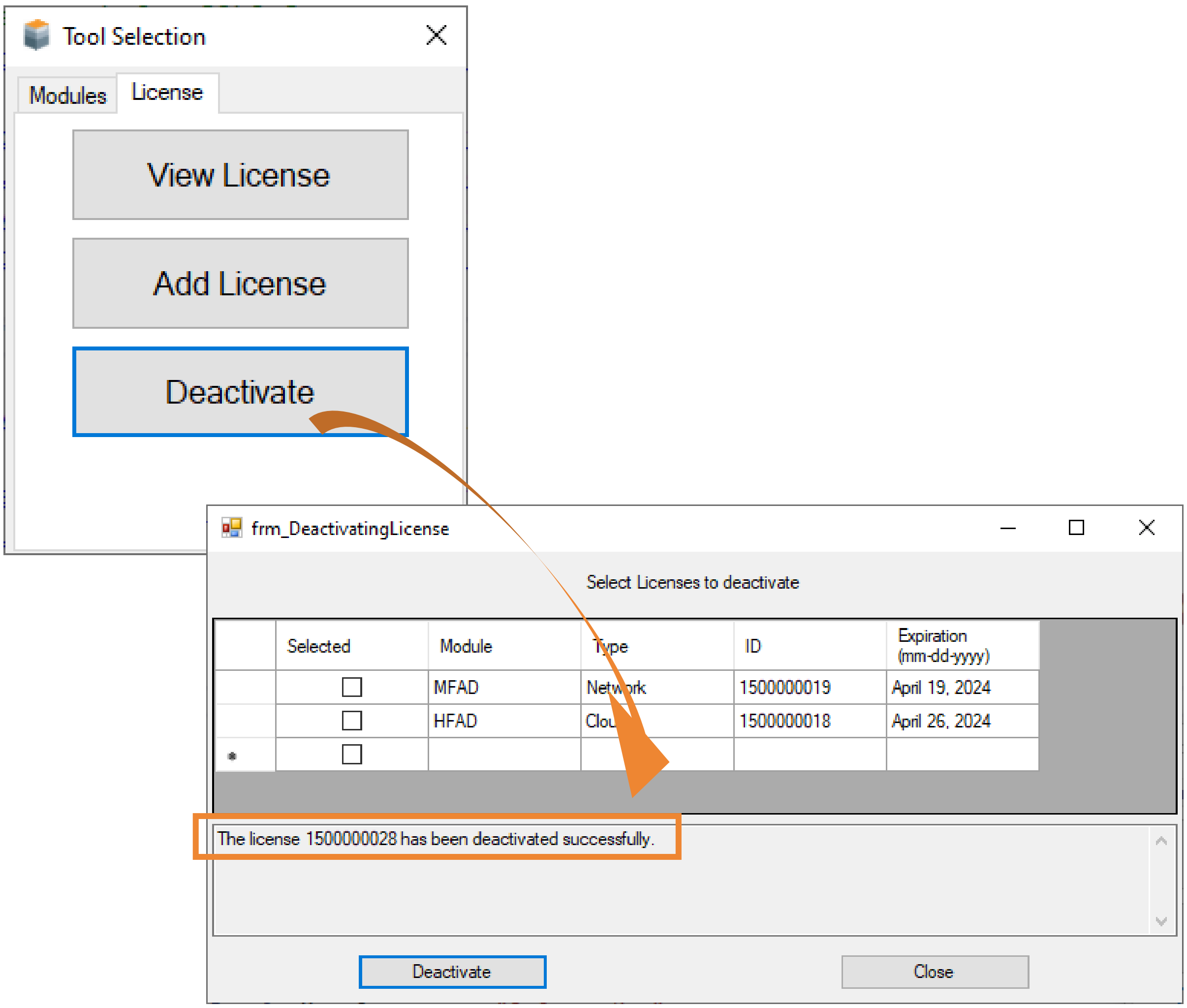


Figure B.13
Online Deactivation.

B.3.3. Open File Window

To use FAD, the user must select a database file to open or create a new database file (see Figure B.14). The user can create a new database file by selecting the desired file location and typing the desired name and selecting Open. Make sure to save the database file to a location that has read/write privileges. The default file location for the database file is stored in the installation file location.

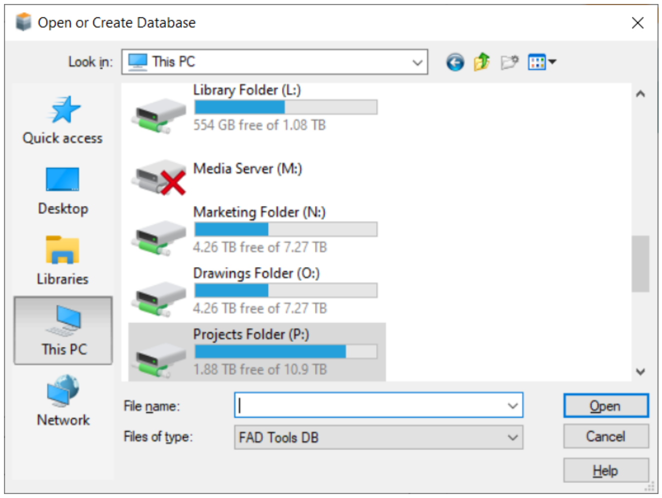


Figure B.14
File Selection Window

B.3.4. Menu Bar

The Menu Bar contains the following selections:

- File,
- Run,
- Options, and
- Help.

Each selection is described below. The Report function has been removed, as reports can be opened from their saved locations and saved in a variety of format types.

B.3.4.1. FILE

The File menu contains the following selections:

- Open option that allows the user to open an existing database file (see Figure B.15).
- New option that allows the user to create a new database file (see Figure B.15).
- “Save As” option allows the user to save the database file with a different name.
- Recent option lists the last saved database files for the user.
- Switch Tool option is a new feature that allows the user to switch between MFAD, HFAD and TFAD modules without being required to close the program or to select a different project.
- Exit option allows the user to close the program.

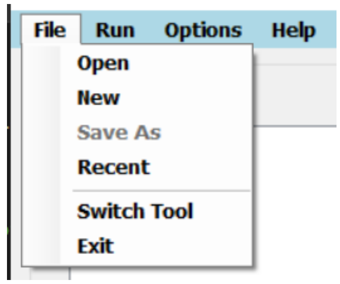


Figure B.15
File Menu Options

B.3.4.2. RUN

The Run menu allows the user to initiate an analysis. The user first must select and activate a Case. See further discussion below for Run Analysis Options. As a new feature, the user can now double click a case to run an analysis or to right click a case and select run analysis.

B.3.4.3. OPTIONS

The options menu item allows the user to set Design Settings for FAD. Click "Options", then "Design Setting". This opens the Design Settings window (Figure B.16).

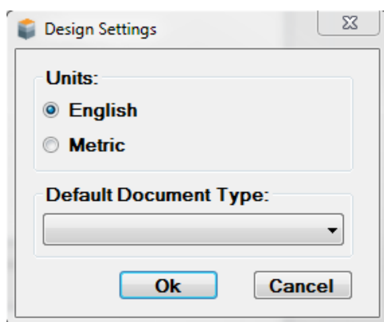


Figure B.16
Design Settings

This window allows the designer to set the Units for the program. By selecting English or SI, the program will default analysis inputs and outputs to the selected units. All reports and graphs will also default to the selected units. Units can also be changed on each data entry window, but units for reports and graphs can only be selected through the Design Settings. Note: the database location option has been removed and replaced with the File, Open option.

New to FAD is the Default Document Type option. This feature lets the designer select the default report format for all reports within a project. The designer can also select the file type from the Report, Save menu. File types include PDF (*.pdf), HTML (*.htm, *.html), Word (*.doc and *.docx), Rich Text Format (*.rtf), and Plain Text (*.txt).

B.3.4.4. HELP

The help menu contains a link to the FAD Tools User Guide, Check for Updates, Technical Support, View Licensing Information, and information About FAD.

B.4. Project Explorer

B.4.1. Project Explorer

FAD includes a Project Explorer interface that allows the designer to organize foundation design projects. The Project Explorer is composed of the Projects window and Libraries window (Figure B.17).

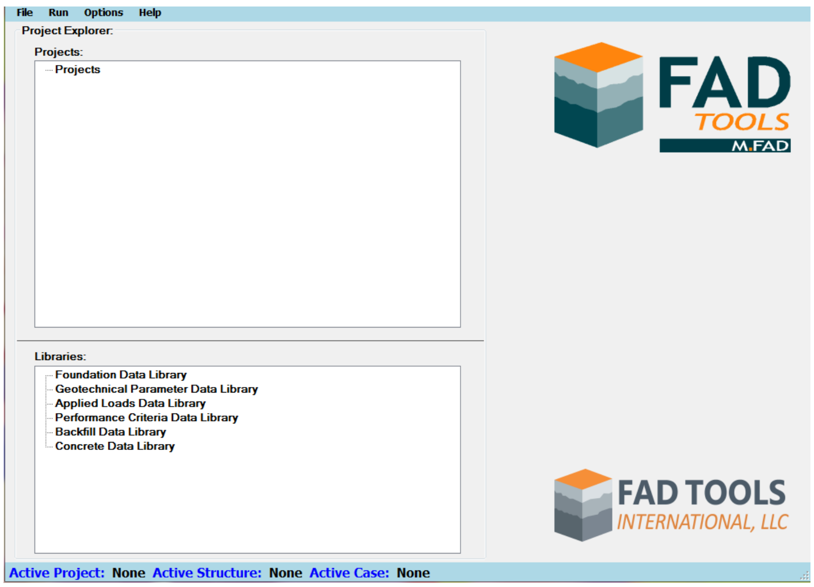


Figure B.17
MFAD 5.2.3 Project Explorer

The Project Explorer items (Projects, Project Name, Structure ID, Case Description, and Libraries) all contain Context Menus, that when right-clicked a menu of options is available. See section on Context Menus for more details. The Projects window is used to create, edit, design, and analyze foundation projects and consists of the project name, structure ID, and case description. The Libraries window can be used to create data files and will store data files in corresponding libraries. Data stored in the libraries can be used for multiple cases.

B.4.2. Libraries

As part of the Project Explorer, FAD allows the designer to create data libraries for information used in the Case window to analyze foundations (Figure B-7). This allows the designer to enter data into the library and use it in multiple foundation cases. The libraries include the Foundation

Data, Geotechnical Parameters, Applied Loads, the Performance Criteria Data, Backfill Data, and Concrete Data. The designer can enter data into each library prior to creating a Project, Structure, or Case. New libraries have been added for backfill and concrete data in the latest FAD version.

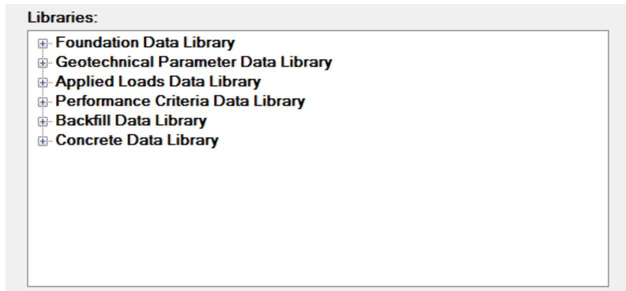


Figure B.18
Project Explorer Data Libraries

Entering data into the Data Libraries is performed similarly to entering data in the Case window. There is a new Import feature that allows the user to copy and paste data from either excel or text-based programs in comma separated form or tab delimited form.

B.4.3. Context Menus

The Project Explorer items (Projects, Project Name, Structure ID, Case Description, and Data Libraries) all contain Context Menus. When an item is right-clicked, a menu of options is available. The menus change depending upon what item is clicked. Options typical of all items include:

- New,
- Open, and
- Delete.

Depending upon what item is right-clicked, selecting New, Open, or Delete applies to a Project, Structure ID, Case, Foundation, Geotechnical Parameters, Applied Loads, and Performance Criteria Data Library attached to a case. Context menus specific to individual project explorer items are discussed in the following sections.

B.4.4. Case - Context Menus

B.4.4.1. Set Active

The Set Active menu item can be accessed by right-clicking a Case (Figure B-8). By default, a Case is Set Active when created or opened. When the FAD program opens, there is no Active Case. To set the Active Case, right-click the Case to be analyzed and select Set Active. This can be done at any time to Set Active the case for analysis. See the Run section under the FAD Menu Bar for more details on performing a Run Analysis.

The selected active case is listed at the bottom of the window.

A new feature of FAD allows the user to double click a Case to set it as the Active Case and to Run the analysis.

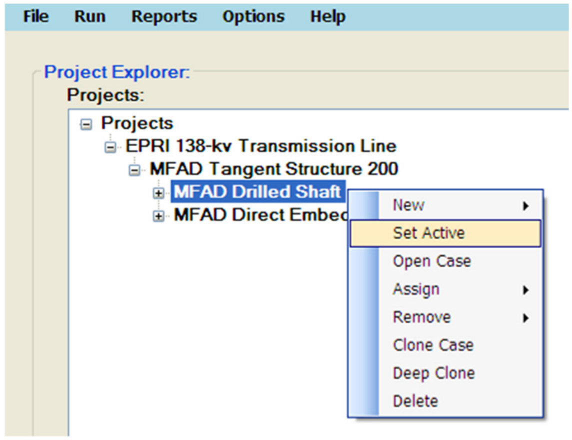


Figure B- 1
Right-Click Case to Set Active

B.4.4.2. Set Active & Run Analysis

Run analysis can now be performed by double-clicking a Case. The case must have all associated parameters. The user can still right-click to set the active case.

B.4.4.3. Assign Case

The Assign menu item can be accessed by right-clicking a Case. This item will allow the user to assign a Foundation, Geotechnical Parameters, Applied Loads, and Performance Criteria from the Project Explorer Library to the selected Case.

B.4.4.4. Remove Case

The Remove menu item can only be accessed by right-clicking a Case, Foundation, Geotechnical Parameters, Applied Loads, and Performance Criteria Data Library attached to a case. This item will allow the user to remove a Foundation, Geotechnical Parameters, Applied Loads, and Performance Criteria from the selected Case.

B.4.4.5. Clone Case

The Clone menu item can be accessed by right-clicking a Foundation, Geotechnical Parameters, Applied Loads, and Performance Criteria Data Library attached to a case or in the Project Explorer Library. This item will allow the user to create a copy of the selected Foundation, Geotechnical Parameters, Applied Loads, or Performance Criteria. The Clone Case menu item can be accessed by right-clicking a Case. The Clone Case item will allow the user to create a copy of the selected case and maintain the associated libraries attached to the case.

B.4.5. Data – Context Menus

B.4.5.1. Import Feature

Previous versions of FAD required manual entry of all parameters. FAD now allows for copy and paste from the clipboard to automatically fill out each Case parameter, under Import. Case parameters can be copied and pasted from either excel or text-based programs in comma separated form or tab delimited form.

For each Case Parameter (e.g., Foundation Data), select New and then on the pop-up screen select Import (Figure B.19). Alternatively, in the Library Window of Project Explorer on the Main Screen, in the Libraries section, the user can right click the Foundation Data Library and create a new foundation data file and select Import (Figure B.20). The format for importing data is specific to each Case Parameter and is described in the following sections.

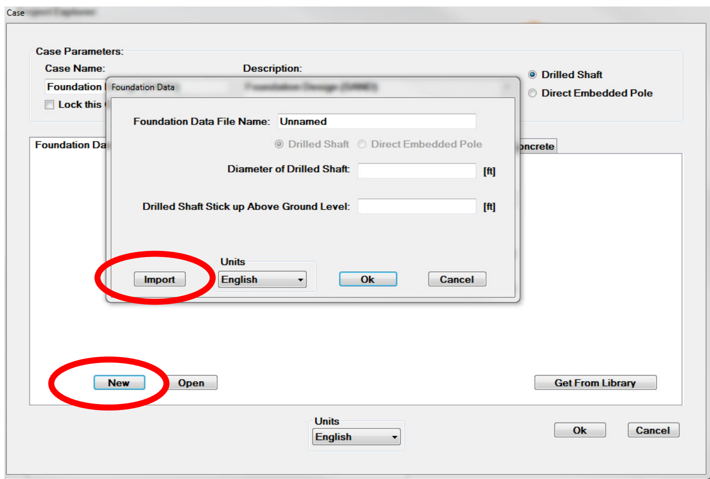


Figure B.19
Import Window

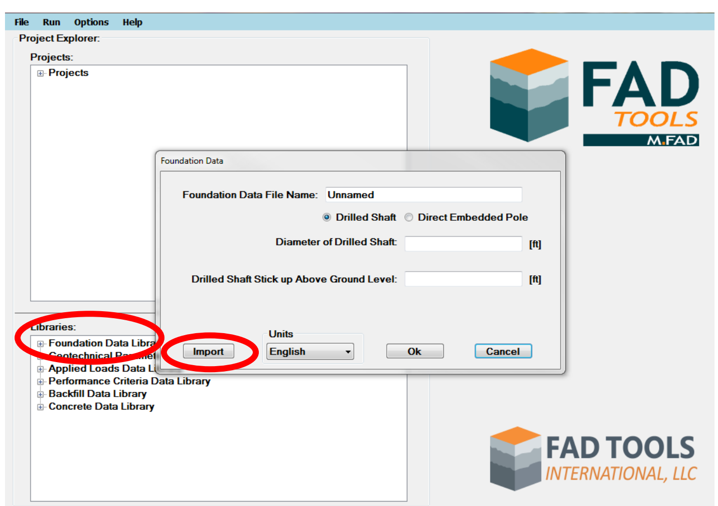


Figure B.20
Import Window

B.4.6. Project Explorer

As previously discussed in Section B.4.1, the Projects window allows the designer to create foundation design projects. Each project consists of a project name, structure IDs, and cases (Figure B.21).

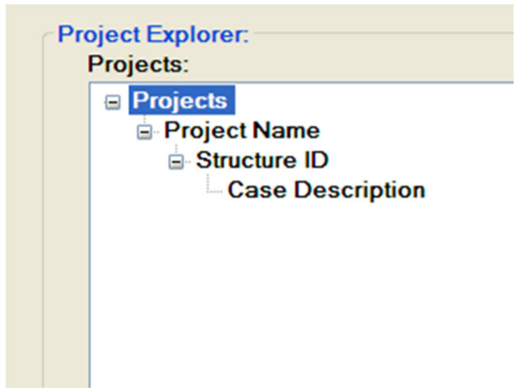


Figure B.21
Projects Window

The project information presented in the following discussion can be used to create a new project and complete associated input screens in FAD. All fields are completed by the designer and all name fields have the ability to be flexible to the designer. A project must be composed of at least one project name, one structure, and one case.

B.4.6.1. Projects:

To create the project, right-click on Projects and select New Project. See Figure B.22.

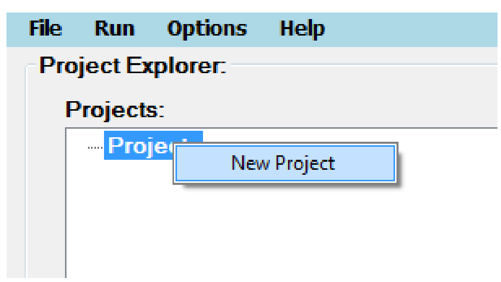


Figure B.22
Right-Click Project to Create a New Project

This opens the New Project window. See Figure B.23.

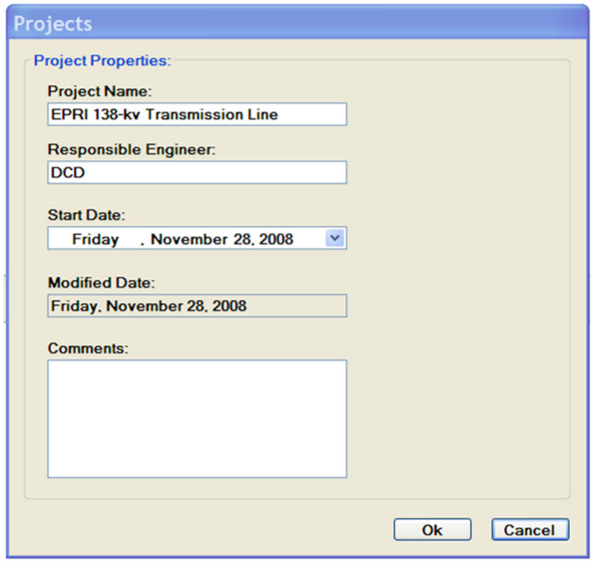


Figure B.23
New Project Window

Enter the Project Name, Responsible Engineer, and any applicable Comments. The date is automatically entered. Click "Ok" when finished.

The designer who performs the MFAD analysis should enter their initials in the Analysis window. Depending on state or governmental requirements, the Responsible Engineer is typically the engineer of record who is a licensed professional.

B.4.6.2. Structure

To create a Structure, right-click on the project created and select New, then Structure. See Figure B.24.

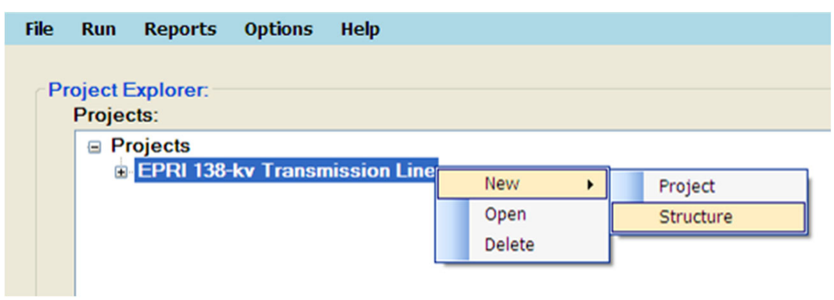


Figure B.24
Right-Click Project to Create a New Structure

This opens the New Structure window. See Figure B.25.

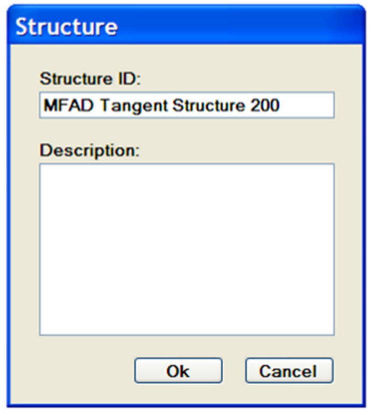


Figure B.25
New Structure Window

Enter the Structure ID. This can be a name, number or any descriptive text for the structure being analyzed. Enter a Description and click “Ok” when done. Repeat the process for all unique structures being designed.

B.4.6.3. Case

To create a Case, right-click on the structure created and select New, then Case. See Figure B.26.

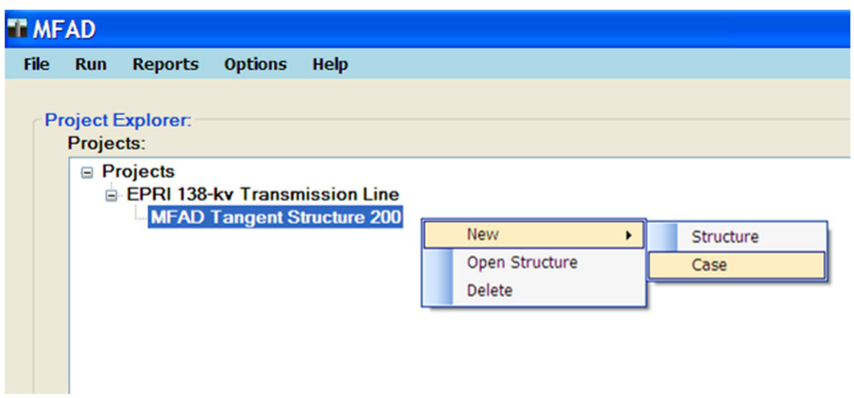


Figure B.26
Right-Click Structure to Create a New Case

This opens the New Case window. See Figure B.27.

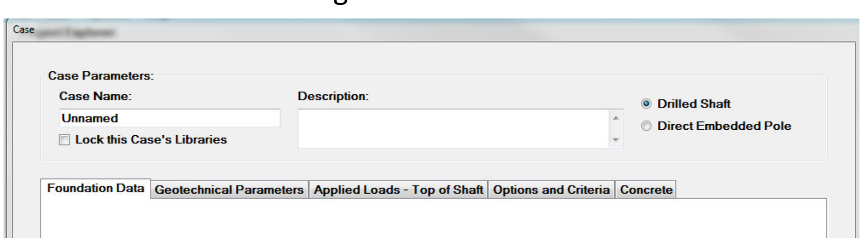


Figure B.27
New Case Window

Enter a Case Name, Description, and select a Drilled Shaft or a Direct Embedded Pole. The Case window is also where the data necessary to analyze a given foundation is entered. There are tabs for the following data: Foundation Data, Geotechnical Parameters, Applied Loads, Options and Criteria, Annulus Backfill Properties (Direct Embedded Pole only), and Concrete (Drilled Shaft only).

Data can be entered from the Case window and will be automatically added to the data libraries in the form of a data file or entered into the data libraries from the Libraries window of Project Explorer and retrieved from the library from the Case window.

The Lock this Case's Libraries will notify users that the data library files used for this case are locked and should not be edited. When a data library file is used in more than one case, the user is notified prior to allowing editing of the data library file items even if the Lock this Case's Libraries is not selected.

B.5. Entering Data in FAD

B.5.1. Foundation Data

The Case Foundation Data tab allows the designer to enter foundation data to the case. See Figure B.28.

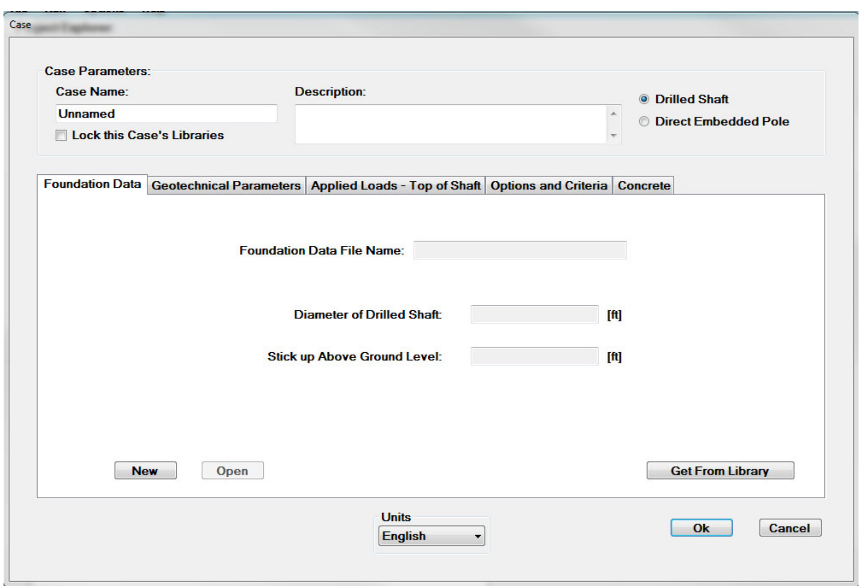


Figure B.28
Case Foundation Tab

Click the New button to open the Foundation Data window. (See Figure B.28). Click on "Get from Library" if the data was previously entered in the Foundation Library directly. See the Libraries section for more detail on creating data library files for foundations. The Open button can be used after the foundation has been created to make changes to the data file.

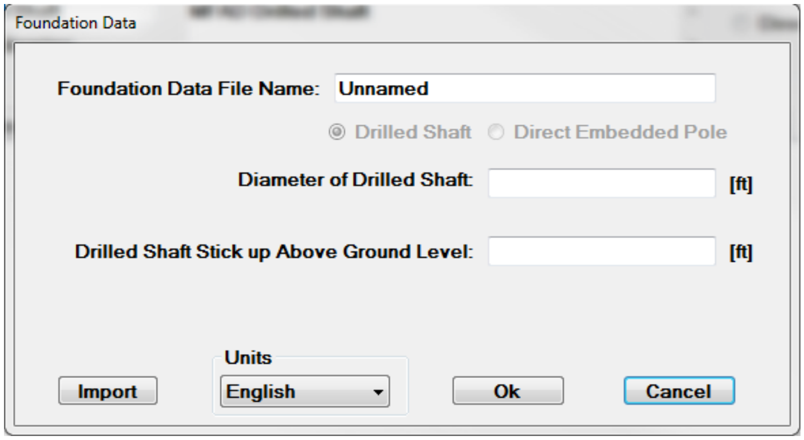


Figure B.29
Foundation Data Window – Drilled Shaft

Enter a name in the Foundation Data File Name to identify the foundation. By default, this data will be saved in the Foundation Data Library. When the Foundation Data window is initiated from the Case window, the selection of Drilled Shaft or Direct Embedded Pole is made in the Case window. When creating a Foundation Data file from the foundation data library, the selection of Drilled Shaft or Direct Embedded Pole is activated. For a Drilled Shaft enter the Diameter of Drilled Shaft and Drilled Shaft Stick up Above Ground Level. For a Direct Embedded Pole enter the Outside Base Diameter of Pole. (See Figure B.29).

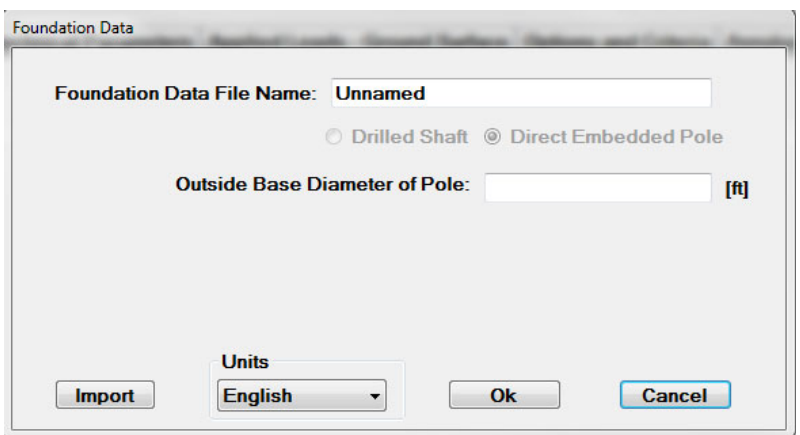


Figure B.30
Foundation Data Window – Direct Embedded Pole

There is no Stick up for a Direct Embedded Pole. For both Drilled Shaft and Direct Embedded Poles the depth of embedment will be determined through the Run Analysis procedure.

The Import Type Selector screen requires the user to specify if the imported data will be from the Clipboard or a CSV File (new to the FAD Import option). The data to be imported must contain the Foundation Data File Name (Name), whether the foundation is a drilled shaft (Drilled Shaft) or a Direct Embed (Direct Embedded Pole), foundation diameter (diameter), and the reveal height for a drilled shaft foundation (stick up).

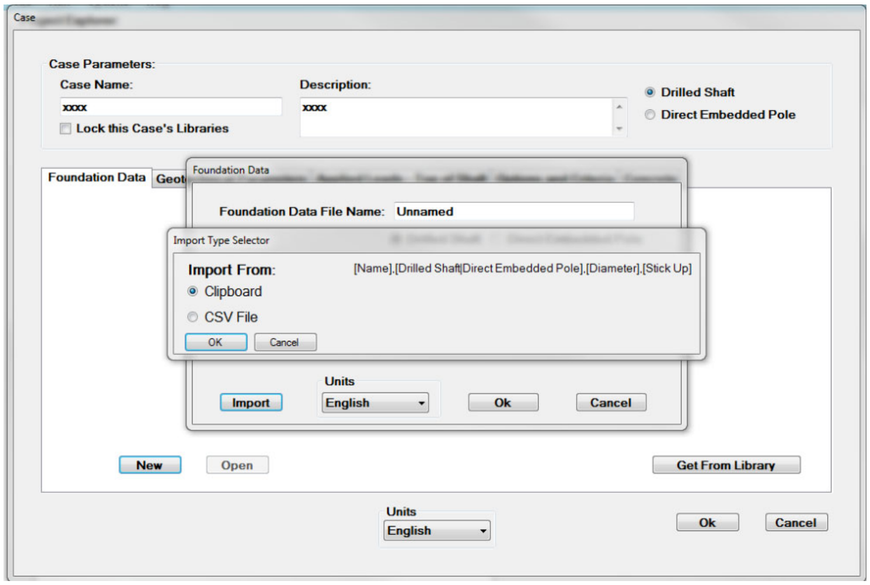


Figure B.31
Import Feature

B.5.2. Geotechnical Parameters

The Geotechnical Parameters tab allows the designer to assign geotechnical parameters to the case. (See Figure B.32). For more detail on assigning parameters see Section A.6.

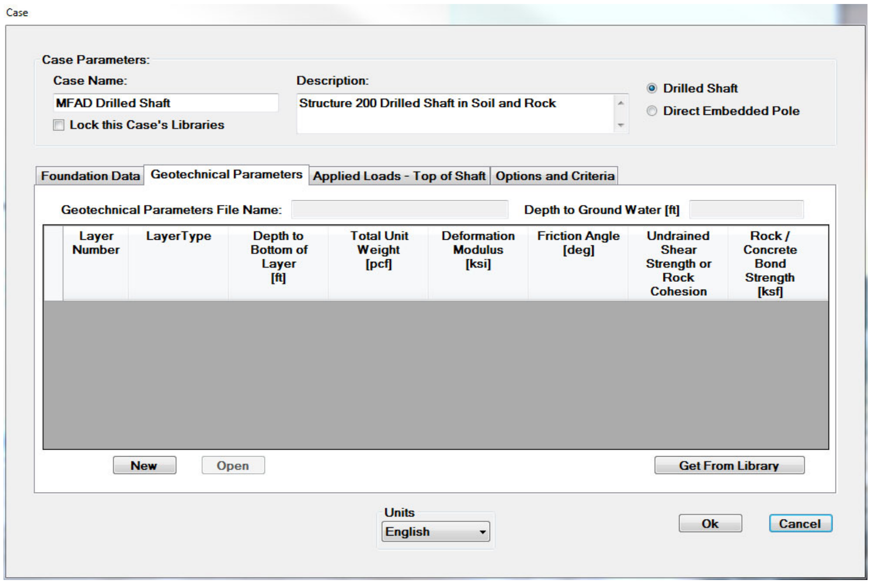


Figure B.32
Case Geotechnical Parameters Tab

Click the New button to add data to the Geotechnical Parameters Data window (See Figure B.33). To retrieve Geotechnical Parameters data from the library, click on "Get From Library". See the Libraries section for more detail on creating data libraries for geotechnical parameters. The Open button can be used after the geotechnical parameters have been created to edit the data.

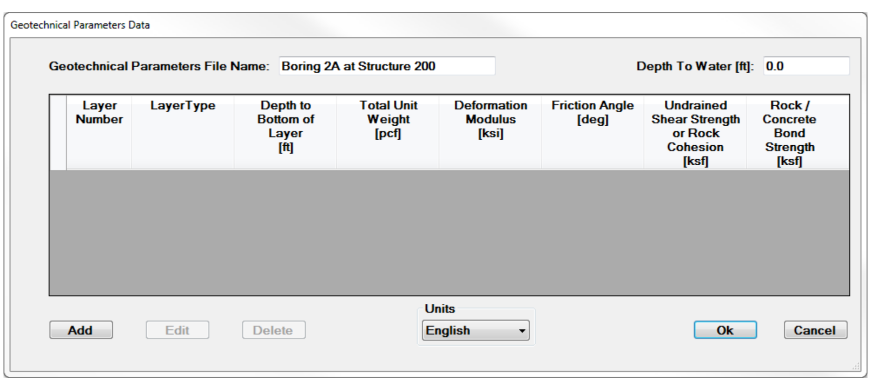


Figure B.33
Geotechnical Parameters Data Window

If the user selects New, the Geotechnical Parameter Window opens requiring the user to enter a name in the Geotechnical Parameters File Name to identify the parameters. This can be the Boring number or label that identifies the parameters. By default, this data will be saved in the Geotechnical Parameters Data Library. Enter the Depth to Ground Water. Click on the Add button to open the layer dialog window. After layers are entered you can click on Edit to make changes to a layer or Delete to eliminate a layer (See Figure B.34).

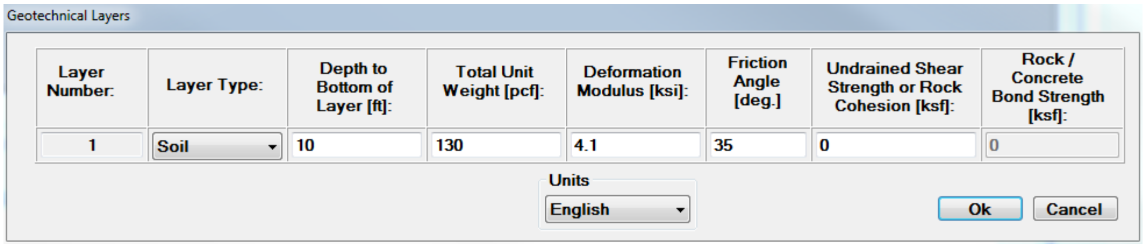


Figure B.34
Add Geotechnical Layer Window

Enter the Layer Type, Depth to Bottom of Layer, Total Unit Weight, Deformation Modulus, Friction Angle, Undrained Shear Strength or Rock Cohesion, and Rock/Concrete Bond Strength. For soil layers the Rock/Concrete Bond Strength is set to zero. Click "Ok". Continue to add layers until all geotechnical parameters are entered. The number of layers is limited to ten (10) layers.

The Import Type Selector screen requires Data in the Clipboard or the CSV File to contain the Geotechnical Parameters File Name (Name) on the first row/layer, Depth to ground water on the second row /layer(depth to water), and then up to 9 rows/layers of subsurface properties.

For each row/layer, the user will select soil or rock, depth to bottom of layer, total unit weight, deformation modulus, friction angle, shear strength, and rock/concrete bond strength (See Figure B.35).

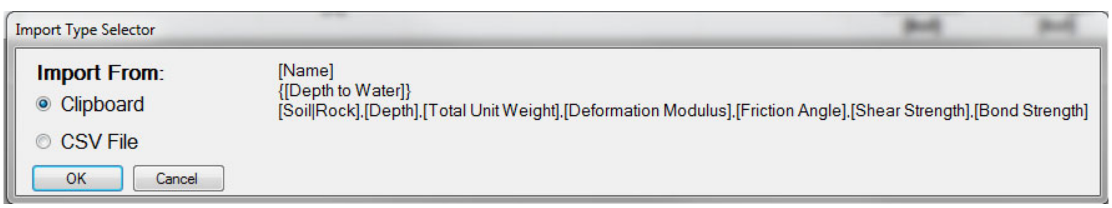


Figure B.35
Geotechnical Import Screen

B.5.3. Applied Loads

B.5.3.1. MFAD Loads

The Applied Loads – Top of Shaft tab allows the designer to assign the applied loads to the case. There can be up to 10 applied loads for each case. MFAD will determine the controlling load case during the analysis of the foundation and will only generate output for the controlling load case. (See Figure B.36).

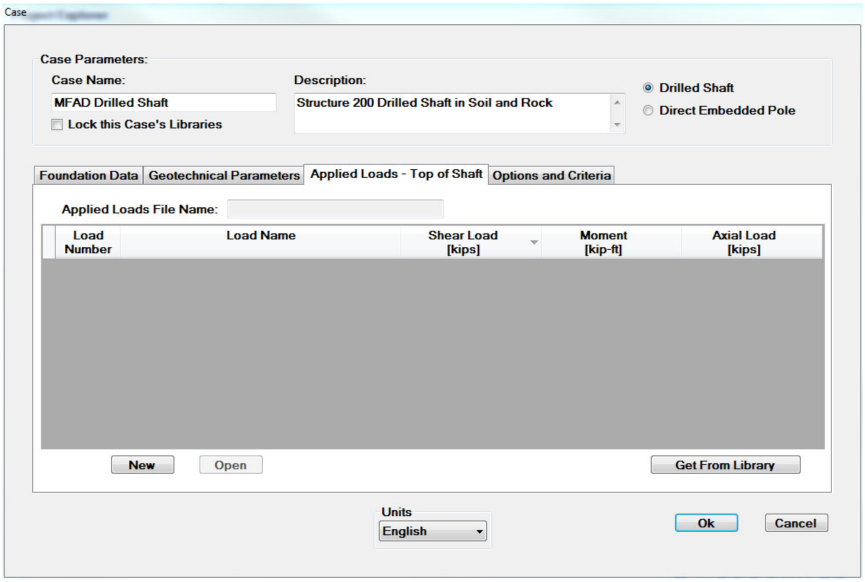


Figure B.36
MFAD Case Applied Loads Tab

Click the New button to add data to the Applied Loads Data window(See Figure B.37). To retrieve Applied Loads data from the Applied Loads Data library, click on "Get From Library". See the Libraries section for more detail on creating data libraries for applied loads. The Open button can be used after the Applied loads have been created to make changes to the data.

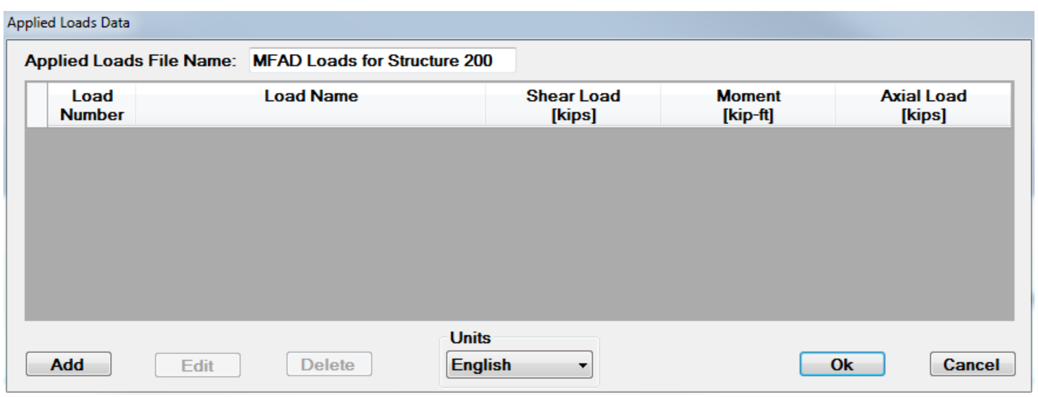


Figure B.37

MFAD Applied Loads Data Window

If the user selects New, the Applied Loads Data Window opens requiring the user to enter a name in the Applied Loads File Name to describe the loads. By default, this data will be saved in the Applied Loads Data Library. Click the Add button to open the Applied Load dialog window. Enter the Load Name, Shear Load, Moment, and Axial Load. Click "Ok". Continue to add loads until all loads are entered. There can be up to 10 applied loads for each case. After load cases are entered you can click on Edit to make changes to a load or Delete to eliminate a load case (See Figure B.38).

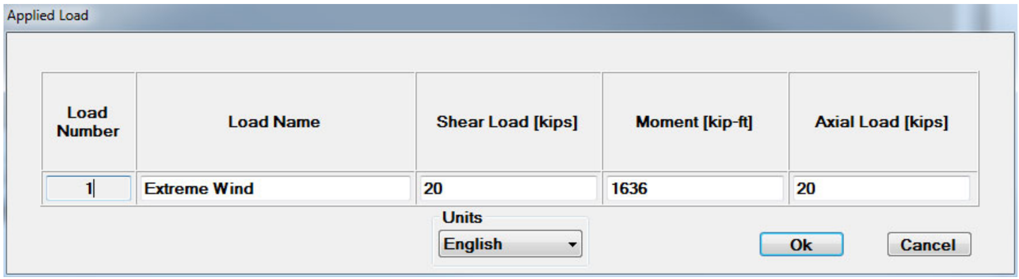


Figure B.38
MFAD Add Applied Load Window

The Import Type Selector screen requires data in the Clipboard or the CSV file to contain the applied load file name (load name) and up to 9 load cases for MFAD. For each load case the user can import the load case name (layer name) followed by the shear load (shear load), moment load for MFAD and HFAD (Moment) and axial load (Axial Load). (See Figure B.39).

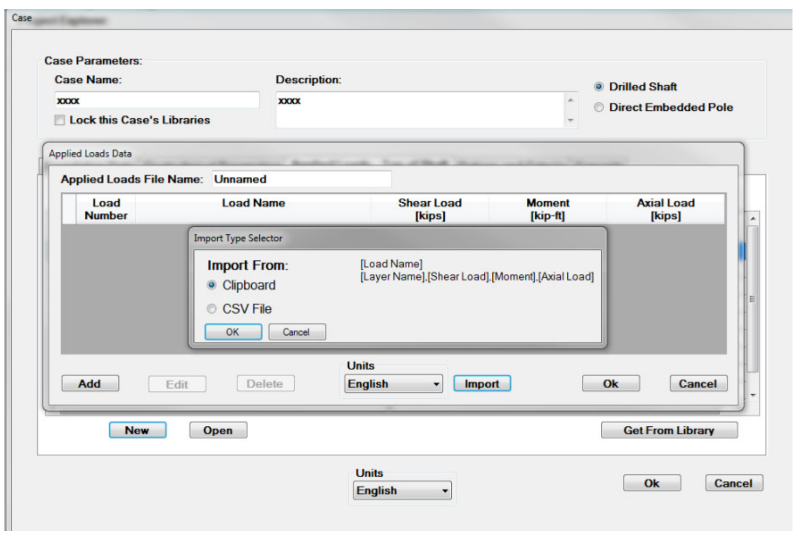


Figure B.39
MFAD Load Import Screen

B.5.3.2. HFAD Loads

The Applied Loads – Top of Shaft tab allows the designer to assign the applied loads to the case. (See Figure B.40).

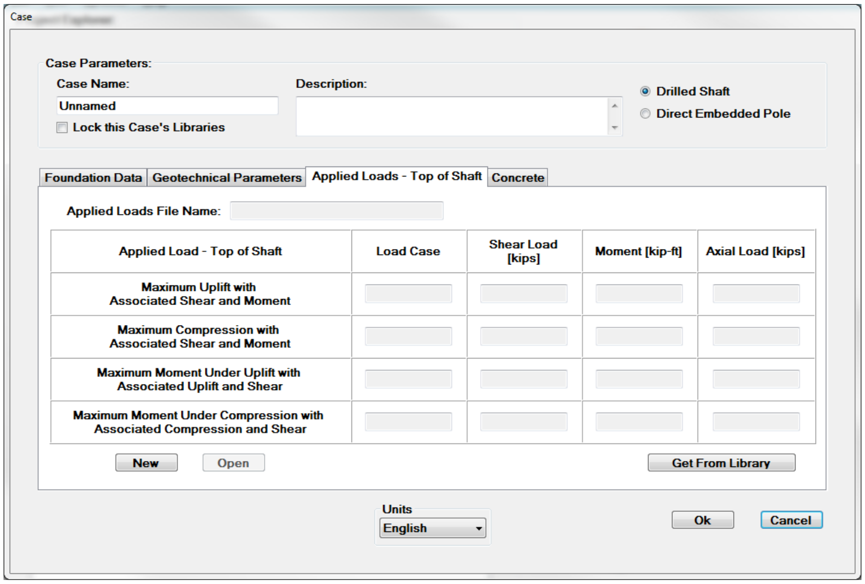


Figure B.40
HFAD Case Applied Loads Tab

Click the New button to add data to the Applied Load Data window (See Figure B.41). To retrieve Applies Loads data from the Applied Loads Data library click on “Get From Library”. See the Libraries section for more detail on creating data libraries for applied loads. The Open button can be used after the Applied loads have been created to make changes to the data.

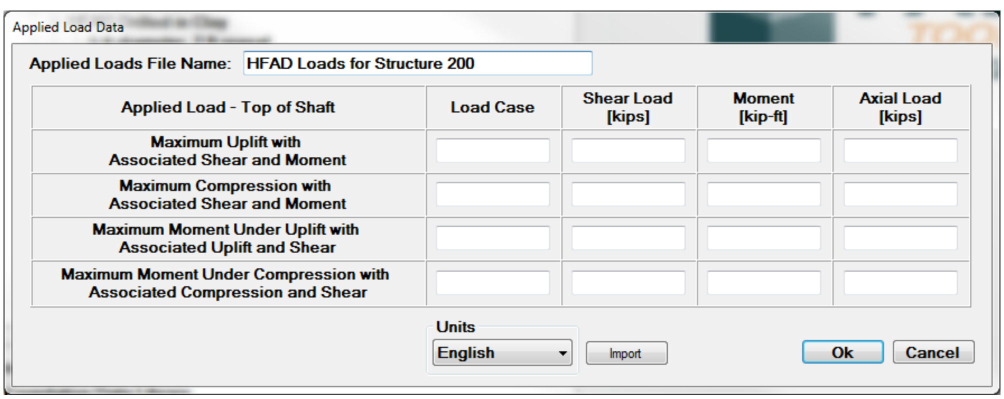


Figure B.41
HFAD Applied Loads Data Window

If the user selects New, the Applied Loads Data Window opens requiring the user to enter a name in the Applied Loads File Name to describe the loads. By default, this data will be saved in the Applied Loads Data Library. Enter values for the Axial, Shear, and Moment loads and enter a Load Case name for each mode of loading.

The Import Type Selector screen requires data in the Clipboard or the CSV file to contain the applied load file name (load name) and up to 4 load cases for HFAD. For each load case the user can import the load case name (layer name) followed by the shear load (shear load), moment load (Moment) and axial load (Axial Load). (See Figure B.42).

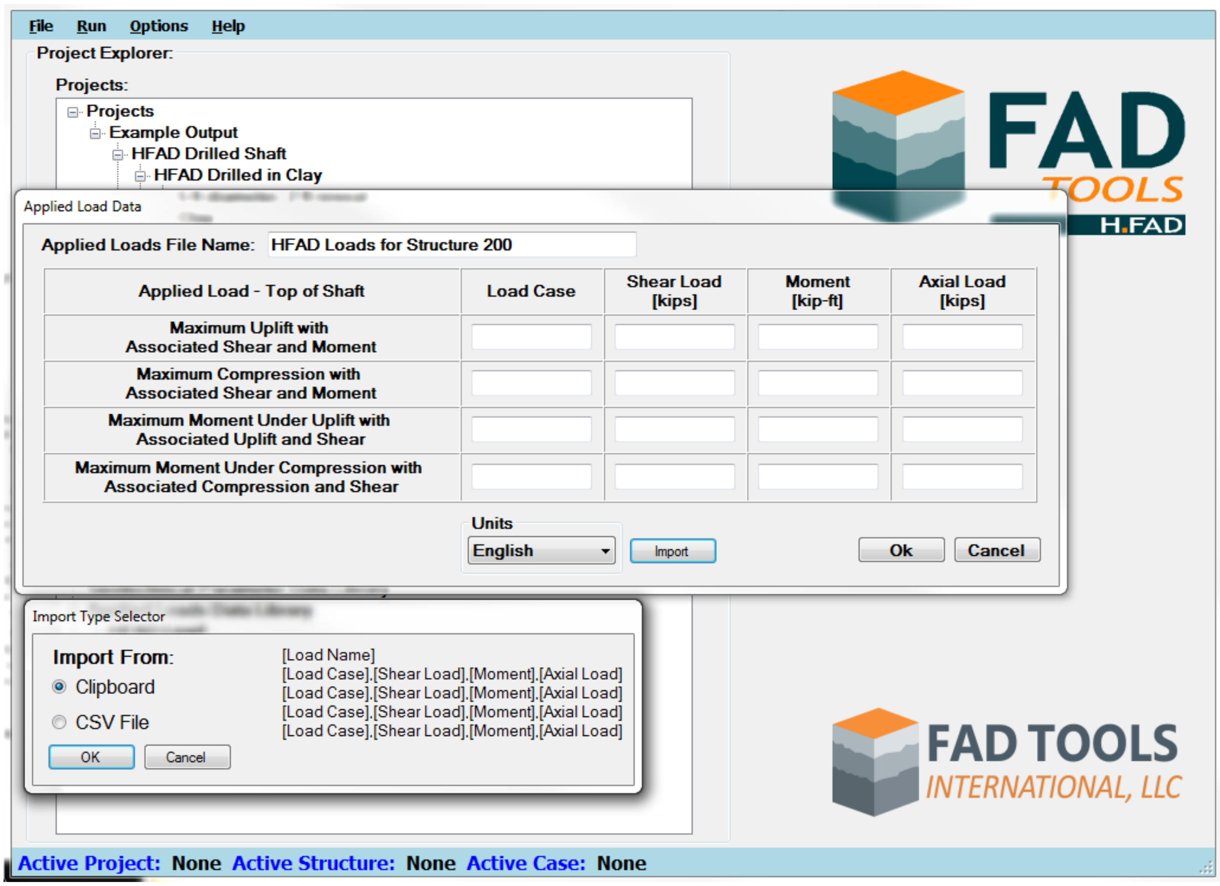


Figure B.42
HFAD Loads Import Window

B.5.3.3. TFAD Loads

The Applied Loads – Top of Shaft tab allows the designer to assign the applied loads to the case. See Figure B.43.

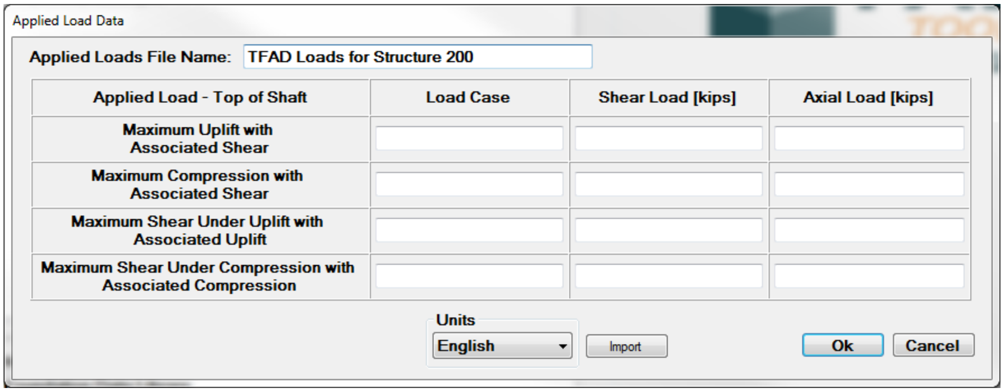


Figure B.43
Applied Loads Data Window

Enter a name in the Applied Loads File Name to describe the loads. Enter values for the Axial, Shear, and Moment loads and enter a Load Case name for each mode of loading.

The Import Type Selector screen requires data in the Clipboard or the CSV file to contain the applied load file name (load name) and up to 4 load cases for TFAD. For each load case the user can import the load case name (layer name) followed by the shear load (shear load), and axial load (Axial Load). See Figure B.44.

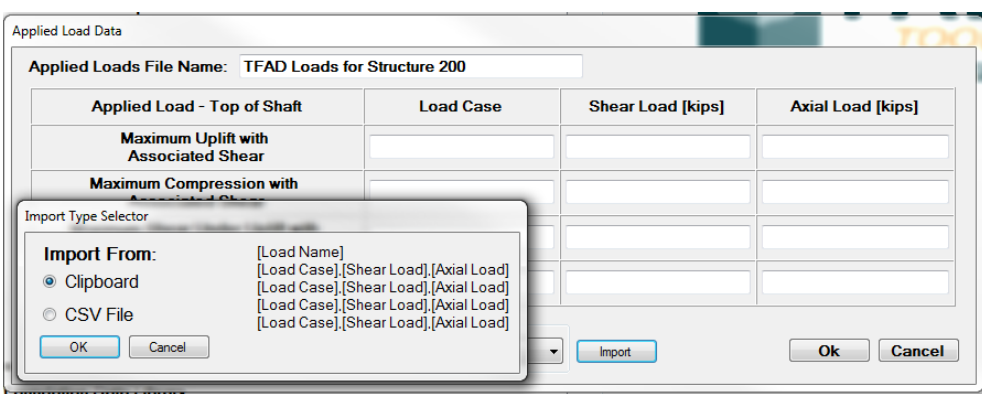


Figure B.44
TFAD Loads Import Window

B.5.4. Options and Criteria

The Options and Criteria tab is composed of model options and performance criteria. Model options include the Side Shear Spring, Base Shear Spring, and the Base Moment Spring. The MFAD Drilled Shaft model is designed to use all three springs. Therefore, for a drilled shaft design, all three springs are typically turned on (see Section A.2.8.1 for background information on MFAD springs). See Figure B.45.

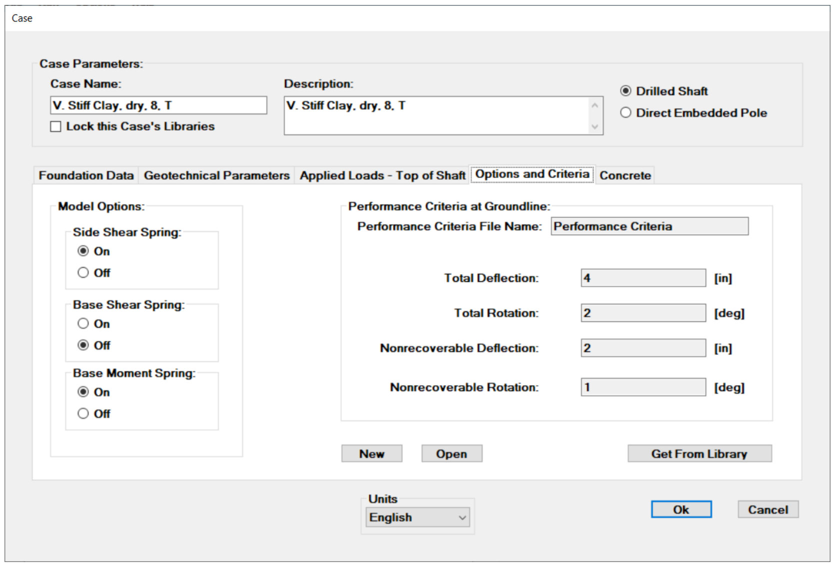


Figure B.45
Case Options and Criteria Tab for Drilled Shaft

The MFAD Direct Embedded Pole model is designed to use the Side Shear Spring only. Therefore, for a direct embedment pole, the Side Shear Spring is typically selected On. See Figure B.46.

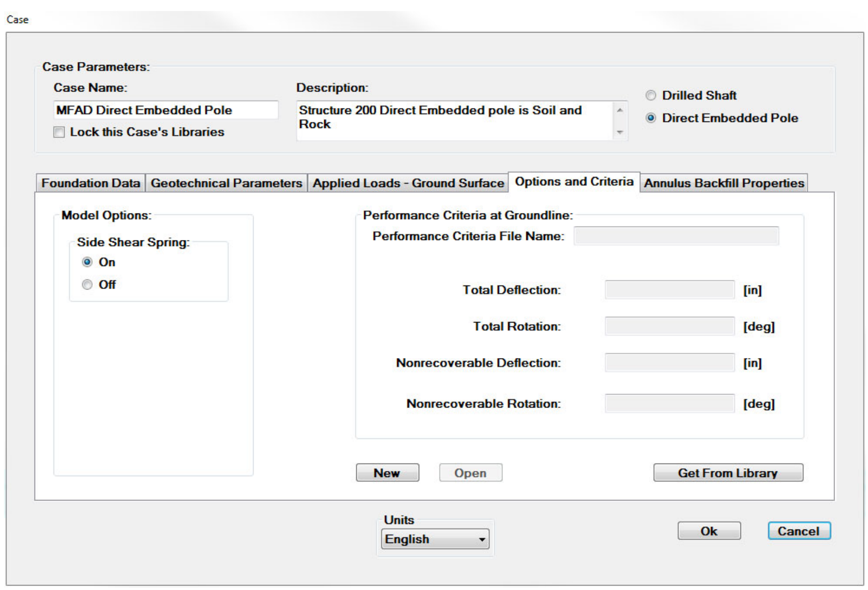


Figure B.46
Case Options and Criteria Tab for Direct Embedded Pole

The Performance Criteria window allows the designer to enter limits for Total Deflection, Total Rotation, Total Nonrecoverable Deflections, and Total Nonrecoverable Rotation. These values are used by the designer to compare the FAD output in order to achieve a foundation design that meets these performance criteria.

Click the New button to add data to the Performance Criteria Data window (See Figure B.47). To retrieve Performance Criteria data from the Performance Criteria Data library, click on "Get From Library". See the Libraries section for more detail on creating data libraries for performance criteria. The Open button can be used after the performance criteria has been created to make changes to the data.

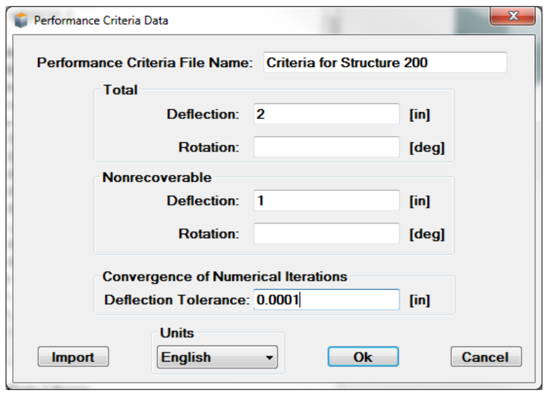


Figure B.47
Performance Criteria Data Window

If the user selects New, the Performance Criteria Data Window opens requiring the user to enter a name in the Performance Criteria File Name to describe the criteria. By default, this data will be saved in the Performance Criteria Data Library. Enter the desired Total Deflection, Total Rotation, Total Nonrecoverable Deflection, and Total Nonrecoverable Rotation. The user only needs to input deflection or rotation values for performance verification as the non-entered criteria will be calculated in the report.

The Import Type Selector screen in MFAD requires data in the Clipboard or the CSV file to contain the performance Criteria File Name (Name), Total Deflection, Total Rotation, Nonrecoverable Deflection (NR deflection), and nonrecoverable rotation (NR rotation) (See Figure B.48).

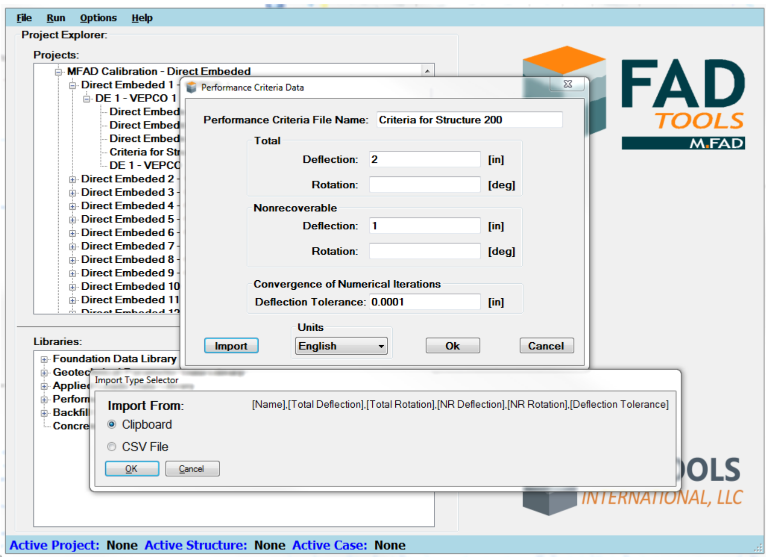


Figure B.48
Performance Criteria Import Screen

B.5.5. Annulus Backfill Properties

The Annulus Backfill Properties tab is only used for a Direct Embedded Pole. Select Concrete or Soil Backfill and enter the appropriate geotechnical properties for concrete or soil backfill. When selecting Concrete, the Friction Angle is set to zero and the Effective Shear Strength is set to 1/2 of the Concrete Strength. Clicking "Save as Default Backfill" will use the current values for all new cases created. See Figure B.49 below.

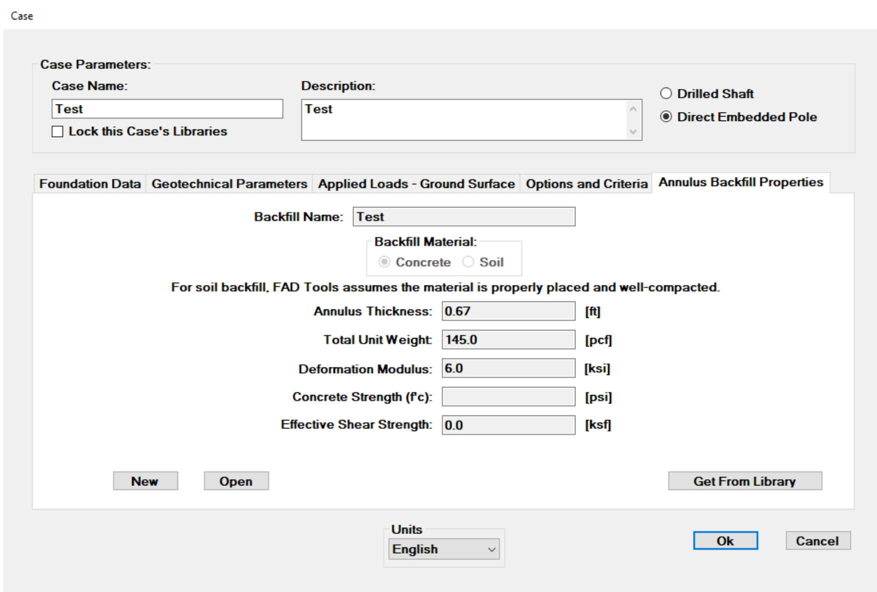


Figure B.49
Case Annulus Backfill Properties Tab for Direct Embedded Pole

The Import Type Selector Screen Backfill parameters requires the data in the Clipboard or the CSV file to contain Backfill Name, Material, Unit Weight, shear strength (undrained for soil and effective for concrete), concrete strength (concrete only), deformation modulus, and friction angle (soil only). See Figure B.50 and Figure B.51.

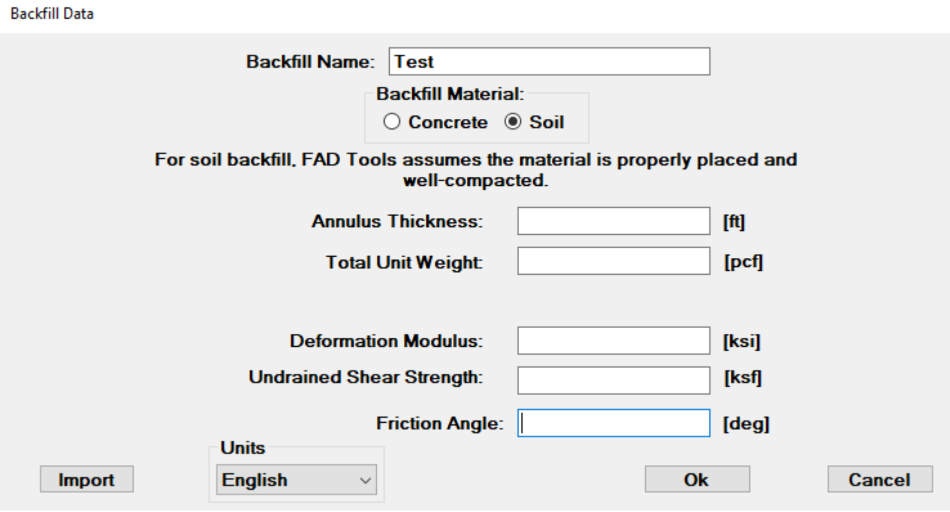


Figure B.50
Backfill Import for Soil

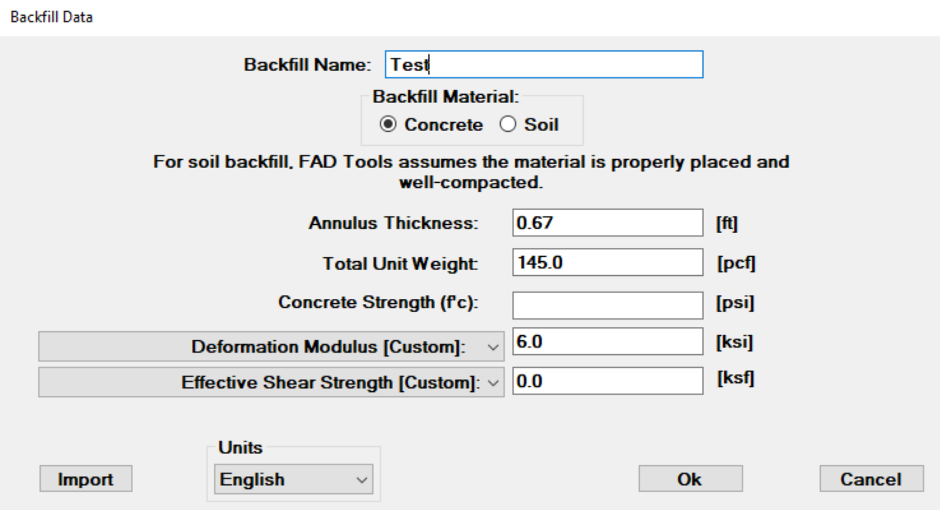


Figure B.51
Backfill Import for Concrete

Previous versions of FAD internally calculated the undrained shear strength and deformation modulus of concrete backfill. FAD now allows users to define the deformation modulus and effective shear strength in various ways, as outlined:

- Deformation modulus (custom), for user defined value.
- Deformation modulus (ACI 318.14, 19.2.2.1.b), calculated from concrete strength.

$$E = 57\sqrt{f'_c}$$

- Effective shear strength (custom) for user defined value.
- Effective shear strength (Gardner & Phoon 1976), calculated from concrete strength.

$$\tau = 0.22({f'_c}^{0.67})$$

- Effective shear strength (Mohr circle), calculated from concrete strength, from earlier versions of FAD.

$$\tau = 0.5(f'_c)$$

B.5.6. Concrete Design

If designing a Drilled shaft, the designer has the option of generating a concrete design for the drilled shaft. This menu is now associated with each Case and can be entered from the Case menu or in the Concrete Data Library section. Click on Concrete tab to open the concrete design window. See Figure B.52.

If importing a database from FAD 5.1.18 or older, the default concrete case will be blank. The user will be asked to enter values in the case window or associate data file from the Concrete Data Library before running the concrete design.

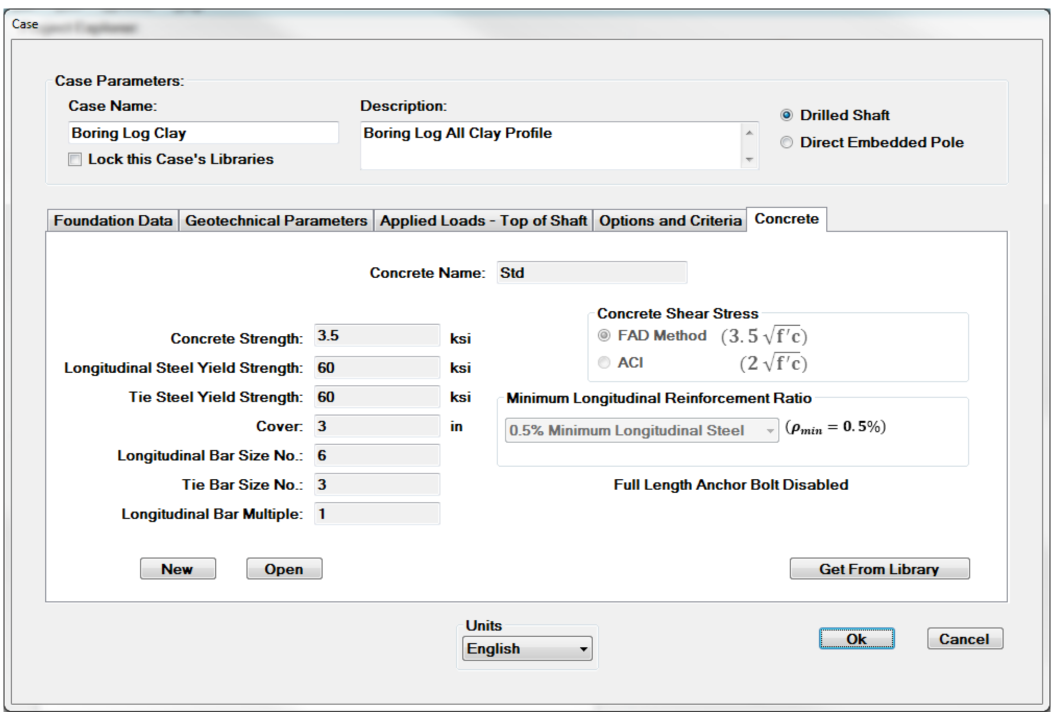


Figure B.52
Concrete Design Window

To create a new concrete for the project, select the New button. Enter the Concrete Name, Concrete Strength, Steel Yield Strength for both longitudinal steel and tie steel, Cover, Longitudinal Bar Size No., and Tie Bar Size No, desired multiple of longitudinal bars and select the Concrete Shear Stress method for shear design and the Longitudinal Reinforcement method for design.

New options for concrete shear stress method and minimum longitudinal reinforcement ratio are included in the latest FAD version. To obtain results compatible with previous versions of FAD (5.1.0 to 5.1.19) select the FAD Method ($3.5\sqrt{f'_c}$) for the concrete shear stress method and the ACI column method ($0.5\% \leq \rho_{min} \leq 1.0\%$) for the minimum longitudinal reinforcement ratio.

There is an option for full length anchor bars (new to FAD 5.2.1), which performs a check that the foundation diameter meets the minimum spacing requirements for the specified center to center anchor bolt diameter. This is only a check and does not impact the design of the foundation. Additionally, a check is performed to verify that the number of anchor bolts specified meets the minimum requirements.

In the Analysis window, run a case for a specified depth. After creating the Report, user can select to run concrete design (only for drilled shaft foundations). A separate window will open that contains the Concrete Design Report. Click on Save. The last Design Run with the selected Depth of Embedment is automatically saved for the case being analyzed. This will allow the user to open the case at a future time and review the analysis. The Generate Plot, Generate Reports, and Concrete Design buttons will all be active eliminating the need for sequencing through the buttons. See Figure B.52.

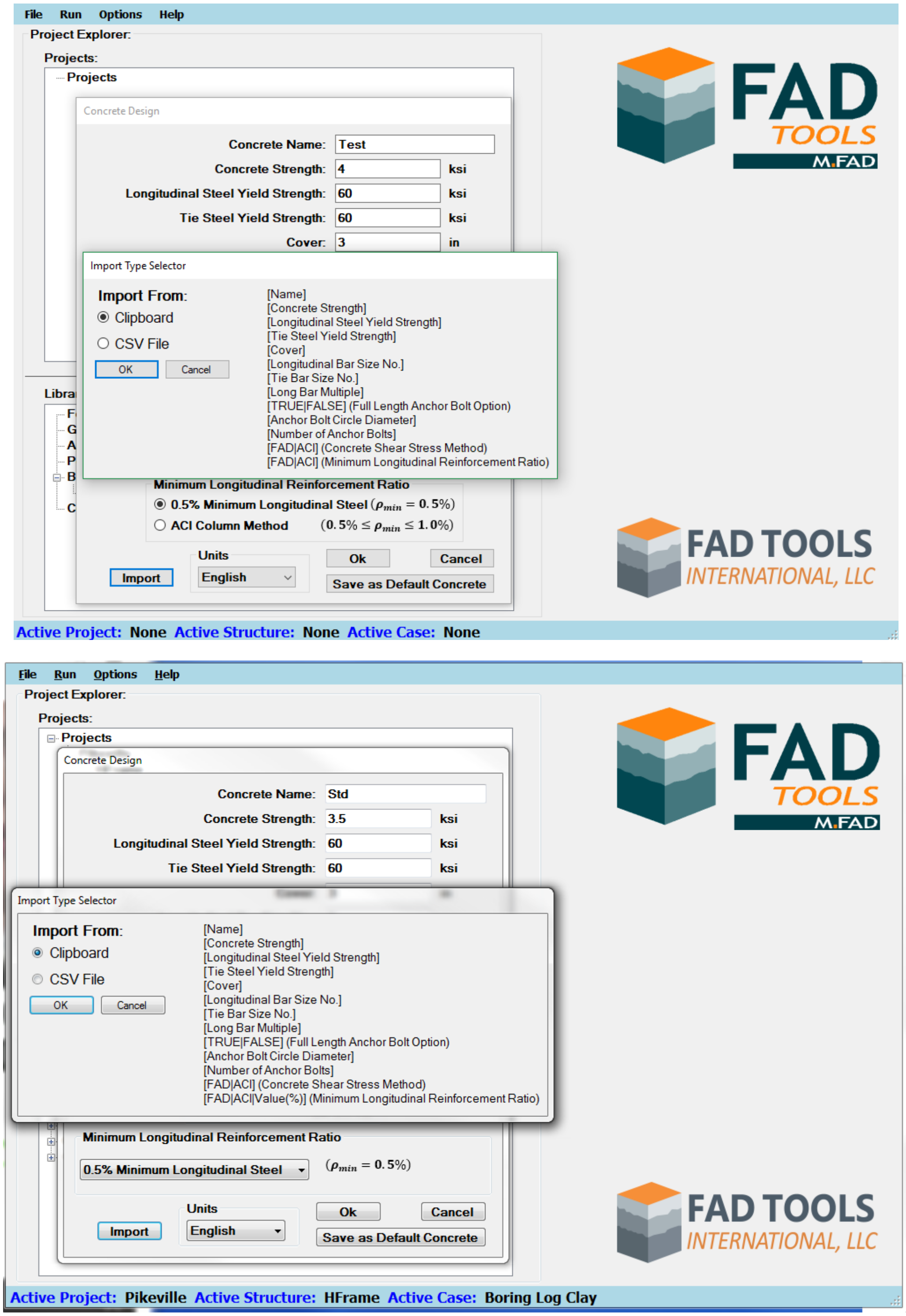


Figure B- 2
Concrete Import Screen

B.6. Running Analysis

B.6.1. Set Case Active & Run

The user can either double click a case or right click and select Set Active & Run to initiate the Run Analysis screen. See Figure B.53. The Run Analysis screen allows the user to enter Depth of Embedment and displays the foundation data, controlling load case, analysis message, capacity verification, performance verification, and buttons to allow the designer to Run Analysis, Generate plot, Generate Report, and Generate Concrete.

The latest version of FAD has updated the look of the Analysis Menu.

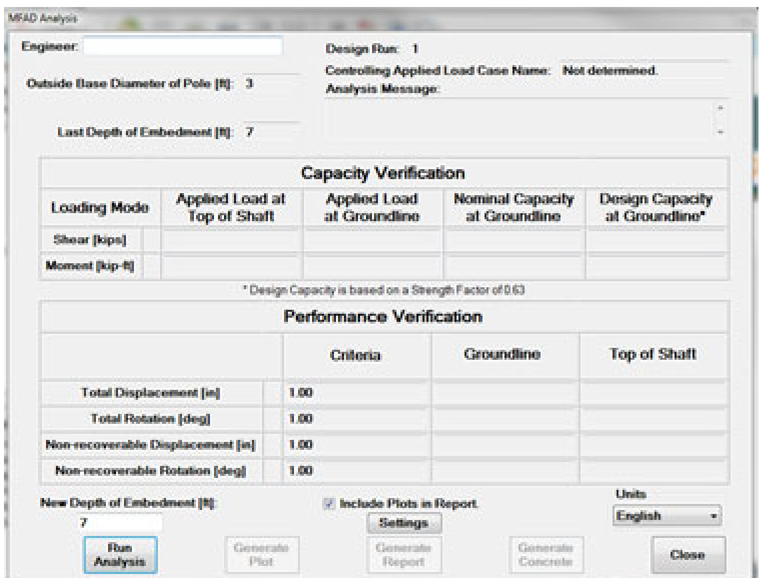


Figure B.53
Run Analysis Screen in MFAD before Run Analysis (Prior to executing Design Run 1)

The run screen allows the designer to determine appropriate depth of embedment for a Drilled Shaft or Direct Embedded Pole. The appropriate depth is typically the depth for which the Design Capacity at Groundline equals or exceeds the applied load at the top of shaft and Groundline and Top of Shaft Deflections are within the Performance Criteria. The foundation data entered for the active case is reported at the top. The controlling applied load is not determined at this time and the rest of the screen is incomplete. The designer needs to run the analysis by clicking on the Run Analysis button. By default, the value of the initial depth of embedment is set to two (2) times the diameter of the foundation.

After the designer clicks Run Analysis, the run screen changes from Design Run 1 to Design Run 2 and so on, until a sufficient embedment is reached and reports the controlling load case along with the Capacity Verification and Performance Verification data. See Figure B.54.

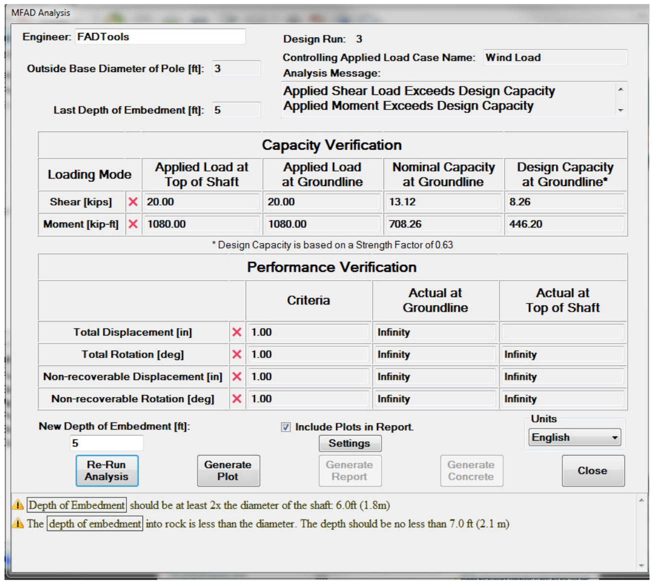


Figure B.54
Run Analysis Screen in MFAD after Run Analysis (Design Run 3)

The Analysis Message area will note if the applied load exceeds the design capacity for the given depth of embedment, both in Analysis Message section, and with green checks or red crosses beside all failure conditions, and with associated warning below the window. The designer should review all the data and determine if the design meets the capacity needs and performance criteria established. If not, the designer should enter a new depth of embedment and click Re-Run Analysis. After the initial Run Analysis, the designer can click on Generate Plots to view plots for Deflection, Shear, Moment, and Lateral Pressure. See Figure B.55.

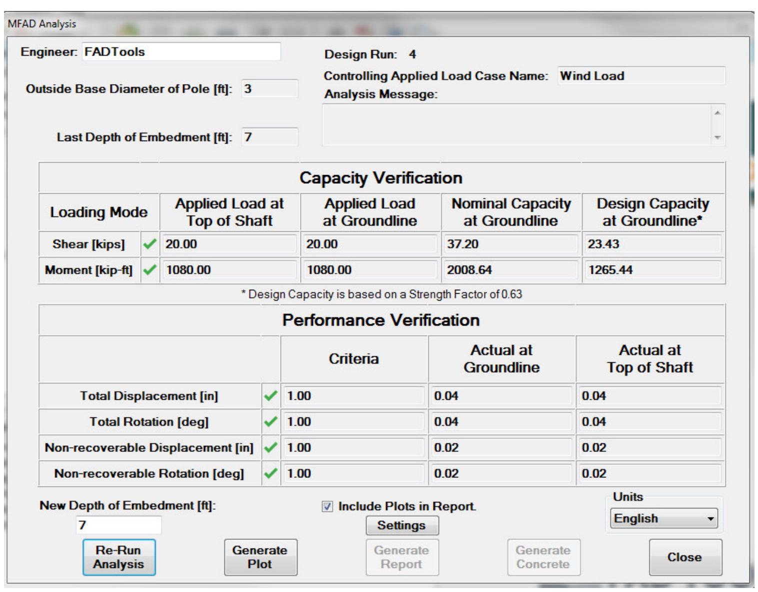


Figure B.55
Run Analysis Screen after Run Analysis (Design Run 4)

Although the user can ignore warnings and run an analysis. Only a design run without warnings and without analysis messages is within the parameters for which FAD was calibrated. It is up to the designer to verify that information has been entered correctly and FAD is the appropriate model for design and/or if supplemental analysis outside of FAD Tools program is required.

When satisfied with the Design Run, the engineer can now generate final plots and reports. Plots need to be generated prior to generating any reports. Click on "Generate Plots" to review the final plots. Close the plots window. By default, Include Plots in Report is selected. New to FAD is the ability for the user to select which plots and data tables are included in the Report. In the Analysis window there is a check box that allows the user to include plots in the report (Figure B.55) and the user can select which plots and data tables to include under the Settings button (Figure B.56).

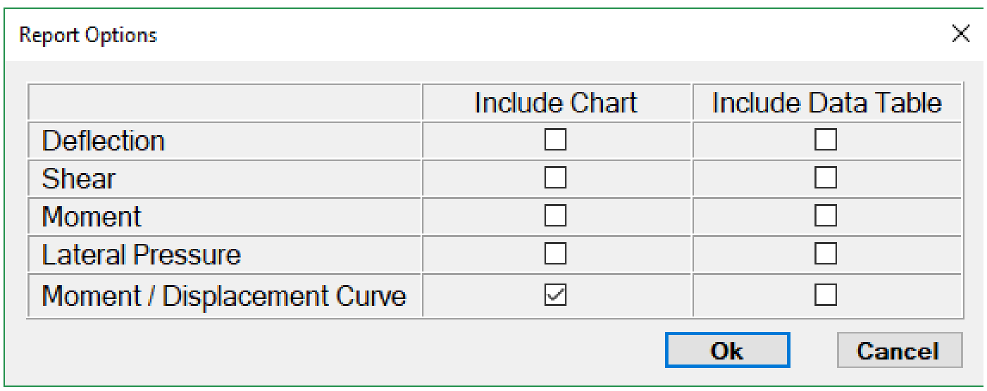


Figure B.56

Options to include plots and data tables in report

After generating plots the user can select Generate Reports. This will open a separate window that contains the Drilled Shaft or Direct Embedded Pole reports. Reports can be saved or printed. The latest FAD version includes an option to default to various file format reports for an entire project. This option is available under the main menu Options (Figure B.57).

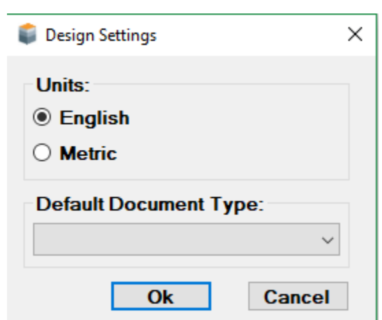


Figure B.57
Options to include plots and data tables in report

If running analysis in drilled shaft mode, the user has the option to run the Concrete Report. This option is only available if concrete data was entered in the Case window and the foundation report has been run. The concrete analysis requires information from the foundation report to complete calculations. After clicking the Concrete button, a separate window that contains the Concrete report will open. Reports can be saved or printed.

B.7. Warnings and Error Messages

B.7.1. Types of Messages

New to the latest FAD version are messages that appear at the bottom of all data entry windows. Pop-up messages have been largely removed from the program to accommodate data entry. There are two types of messages – warning and error messages. Messages indicate issues with user entered values (warnings shown as an exclamation point in a yellow triangle with black text message) or critical issues that may impact program functionality (errors shown with a white x in red circles with red text message). See Figure B.58.

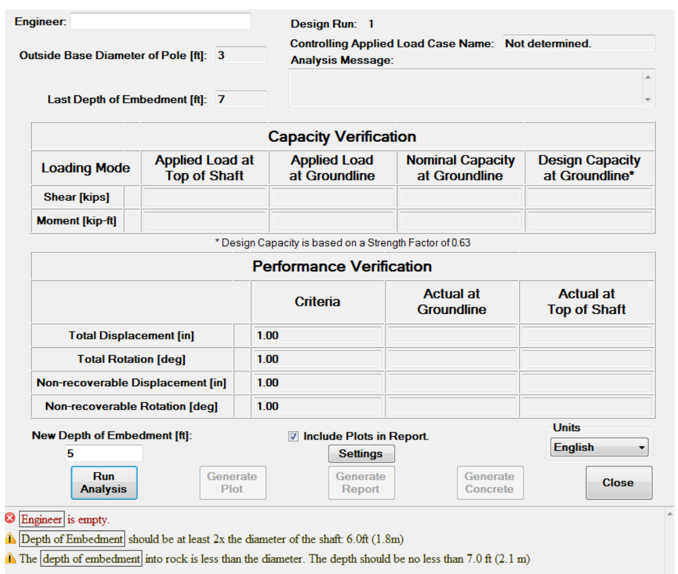


Figure B.58
Example of warning and error messages

For example, pop-up warning messages will occur during saving to prevent overwriting data. See Figure B.59.

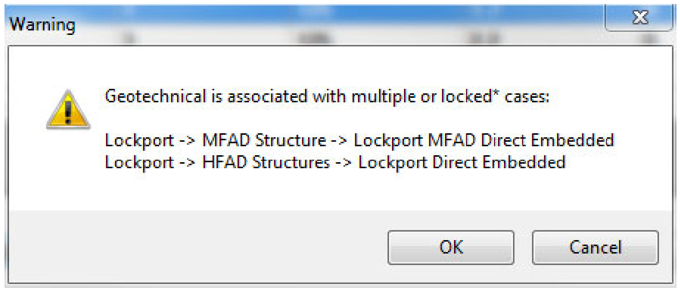


Figure B.59
Example of Pop-Up warning message

New functionality in FAD messages allows all outlined text to be left-clicked or scrolled over to identify the location of the data in question. See Figure B.60.

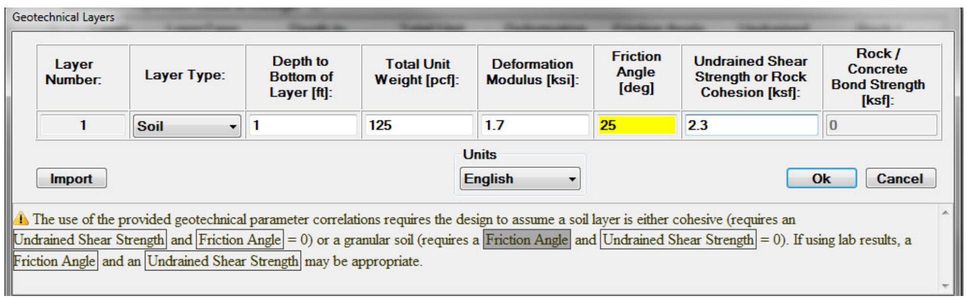


Figure B.60
Example of highlighted text in warning message

B.7.2. Warning Messages

These messages indicated by a yellow yield sign with an exclamation sign (See Figure B.61), identify potential issues with user entered values.

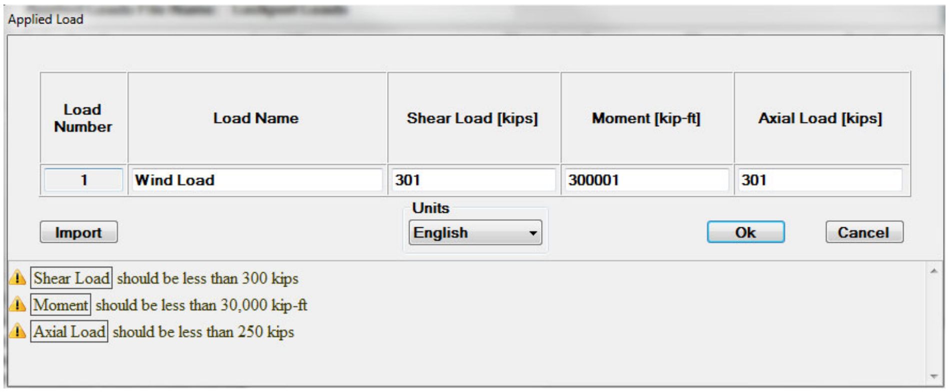


Figure B.61
Example of loads entered that exceeded expect values

The messages indicate that the value entered is outside the expected range. The user can still run an analysis with these entered values but is cautioned that analysis is conducted outside the limits of the program calibration.

In FAD the user only has to enter a deflection or a rotation requirement as the unfilled option will be calculated and included in the report (See section A for discussion on deflection and rotation). See Figure B.62.

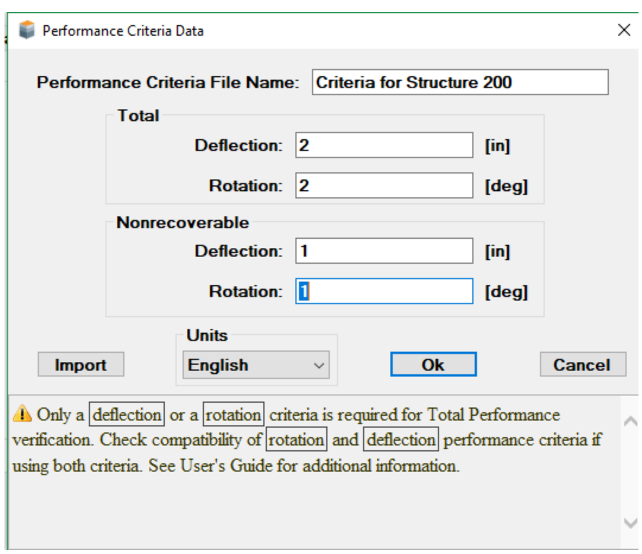


Figure B.62
Example of loads entered that exceeded expect values

Table B-1 contains a list of common warnings in FAD.

Table B-1: Common warnings in FAD

Program	Window	Condition
MFAD, HFAD, TFAD	Foundation	The Stickup should be between 0 to 10 feet.
MFAD, HFAD, TFAD	Foundation	The Diameter should be greater than 0 and less than or equal to 15 feet.
MFAD, HFAD, TFAD	Geotechnical	Total Unit Weight should be between 0(1) - 160 pcf.
MFAD, HFAD, TFAD	Geotechnical	Deformation Modulus should be between 0 to 1800 pcf.
MFAD, HFAD, TFAD	Geotechnical	Friction Angle should be between 0 to 50 deg.
MFAD, HFAD, TFAD	Geotechnical	Rock / Concrete Bond Strength should be between 0 to 25 ksf.
MFAD, HFAD, TFAD	Geotechnical	Undrained Shear Strength or Rock Cohesion should be between 0 to 6 ksf.
MFAD, HFAD, TFAD	Concrete	Verify Concrete Cover Thickness
MFAD	Load	Shear Load should be between 0 to 300 kips.
MFAD	Load	Moment should be between 0 to 30000 kip-ft.
MFAD	Load	Axial Load should be between 0 to 250 kips.
HFAD, TFAD	Load	Max Uplift or Compression Axial Load should be between 0 to 500 kips.
HFAD	Load	Associated Uplift or Compression Moment should be between 0 to 50000 kip-ft.
TFAD	Load	Associated Uplift or Compression Shear should be between 0 to 500 kips.
MFAD, HFAD, TFAD	Performance	Total Deflection should be between 0 to 24 in.
MFAD, HFAD, TFAD	Performance	Total Rotation should be between 0 to 10 deg.
MFAD, HFAD, TFAD	Performance	Nonrecoverable Deflection should be between 0 to 12 in.
MFAD, HFAD, TFAD	Performance	Nonrecoverable Rotation should be between 0 to 5 deg.
MFAD, HFAD, TFAD	Analysis	Depth of embedment should be at least 2 times the diameter of the shaft.

(1) Although allowed, entering a value below the unit weight of water could result in erroneous results

B.7.3. Error Messages

These messages prevent the user from causing the program to stop unexpectedly. Situations such as entry of non-numeric numbers where numeric values are expected (see Figure B.63) or entering an embedment depth exceeding subsurface layer depth in the analysis window (see Figure B.64) will result in an error message. Unlike warnings, the user cannot continue an analysis without fixing the issues or selecting cancel.

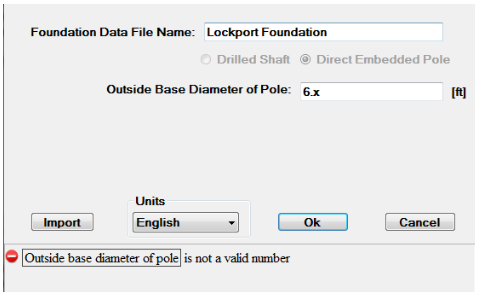


Figure B.63
Example non-numeric number entered

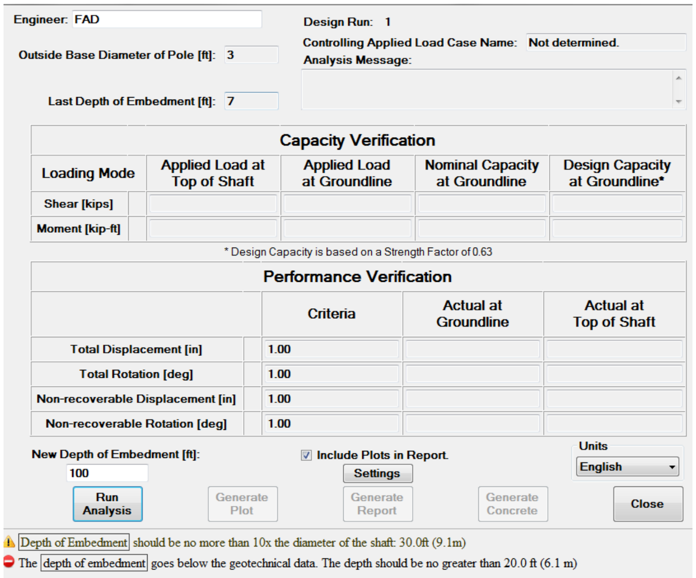


Figure B.64
Example of error message in the analysis window

C. SUBSURFACE CORRELATIONS

C.1. Soil Correlations

In order to use the FAD modules, the user must specify a number of strength and stiffness parameters for the various soil and rock layers. Values of these parameters can be developed from in-situ tests or laboratory tests. However, in lieu of such tests, estimates for these parameters can be obtained from correlations. For soil layers, correlations presented in EPRI (1982) EL-2197 manual (updated in the EPRI 2012, TR-1024138, *Transmission Structure Foundation Design Guide*) and EPRI (1990) EL-6800 can be used to obtain the necessary parameters. Other published parameter correlation sources can be found in the FHWA Geotechnical Engineering Circular No. 5, "Evaluation of Soil and Rock Properties." A well planned and executed geotechnical exploration and testing program is required to use the referenced correlations. Users are recommended to also consider available regional-specific data when developing geotechnical design parameters. Appropriate subsurface properties are necessary to improve the efficiency of drilled shaft foundation design using the FAD software. Ultimately, it is the responsibility of the user to determine appropriate geotechnical design parameters.

C.2. Rock Correlations

The FAD program was calibrated using a specific rock mass rating system as discussed in Section A.6.4. The following correlations to RMR_{76} should be used for developing subsurface rock properties. Correlations to rock/concrete bond strength are provided, however the user is encouraged to use results from testing or regional correlations where possible.

C.2.1.1. Rock Mass Rating System – Shear Strength Parameters

The Rock Mass Rating (RMR_{76}) system developed by Bieniawski (1973, 1976) was used to develop the shear strength and deformation properties during the calibration studies. As shown in Table C-1, the RMR_{76} system considers six parameters in classifying a rock mass:

1. Uniaxial Compressive Strength of the Intact Rock,
2. Rock Quality Designation (RQD),
3. Spacing of Joints,
4. Condition of Joints,
5. Groundwater Conditions, and
6. Adjustment for Rock Orientation.

At a given structure site, the rock mass is divided into appropriate layers based on factors such as rock type (i.e., shale, sandstone, limestone, etc.) and quality. For each layer of rock, a point contribution is assigned for each of the six parameters based on the descriptions provided in Table C-1. The RMR_{76} value of each rock layer is obtained by adding the point contributions for all six parameters.

Table C-1
Parameters and Point Contributions for Using the RMR_{76} System of Rock Classification
(Hoek and Brown, 1980)

Parameter								
Strength of Intact Rock	Point Load Strength Index	>1.16 ksi	0.6-1.16 ksi	0.3-0.6 ksi	0.15-0.3 ksi	-	-	-
	Uniaxial Comp. Strength	>29 ksi	14.5-29 ksi	7.3-14.5 ksi	1.6-7.3ksi	1.5-3.6 ksi	0.4-1.5 ksi	0.15-0.4 ksi
	Points	15	12	7	4	2	1	0

RQD	RQD	90%-100%	75%-90%	50%-75%	25%-50%	<25%
	Points	20	17	13	8	3

Spacing of Joints	Spacing	>9.8 ft	3.3 ft-9.8 ft	1 ft-3.3 ft	2 in – 1 ft	<2 in
	Points	30	25	20	10	5

Condition of Joints	Description of Joint Conditions	Very rough surfaces Not continuous No separation Hard joint wall rock	Slightly rough surfaces Separation <1mm Hard joint wall rock	Slight rough surfaces Separation <1mm Soft joint wall rock	Slickensided surfaces or Gauge <5mm thick or Joints open 1-5 mm Continuous joints	Soft gauge >5mm thick or Joint open >5mm Continuous joints
	Rating	25	20	12	6	0

Ground Water Conditions	Description	Completely Dry	Moist only (Interstitial Water)	Water under moderate pressure	Severe water problems
	Rating	10	7	4	0

Adjustment for Joint Orientations for Foundations	Strike and Dip Orientation of Joint Relative to Loading	Very Favorable	Favorable	Fair	Unfavorable	Very Unfavorable
	Points	0	-2	-7	-15	-25

Once the RMR_{76} values are estimated for each rock layer, each can be assigned a rock mass classification description as shown in Table C-2 (i.e., very poor rock, poor rock, fair rock, good rock, and very good rock).

Table C-2
Rock Mass Classes Based on RMR_{76} Values (Hoek and Brown, 1980)

RMR_{76}	81-100	61-80	41-60	21-40	<20
Class No	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

In general, it is difficult to compute the RMR_{76} values for each rock layer, since data for each of the parameters described in Table C-1 may not be available at each structure site. However, based on the results of borings drilled in conjunction with seven full-scale load tests conducted on drilled shafts, RMR_{76} values varied from 20 to 45 for the sixteen rock layers at the seven test sites. Thus, as presented in Table C-2, all of the rock layers fell within the very poor rock (Class V) to fair rock (Class III) range. This is not unexpected since the test drilled shafts constructed at the seven test sites were embedded in the surficial rock which is the weathered zone. Thus, the user may choose to assume for design purposes, that the rock layers at each foundation site will vary from very poor to fair rock.

C.2.1.2. Rock Mass Shear Strength

Table C-3 presents rock effective shear strength parameters (ϕ’ and c’) for each rock classification number.

Table C-3
Rock Mass Shear Strength Parameters Based on RMR_{76}

Class No	I	II	III	IV	V
RMR_{76}	81-100	61-80	41-60	21-40	<20
Effective Cohesion of the Rock Mass - c’	>6.3ksf	4.2-6.3 ksf	3.1-4.2 ksf	2.1-3.1 ksf	<2.1 ksf
Effective Friction Angle of the Rock Mass – ϕ’	>45 degrees	40-45 deg	35-40 deg	30-35 deg	<30 deg

Figure C.1 and Figure C.2 present the shear strength data shown in Table C-3 in the form of graphs of RMR_{76} versus effective friction angle (ϕ’) and effective cohesion (c’), respectively.

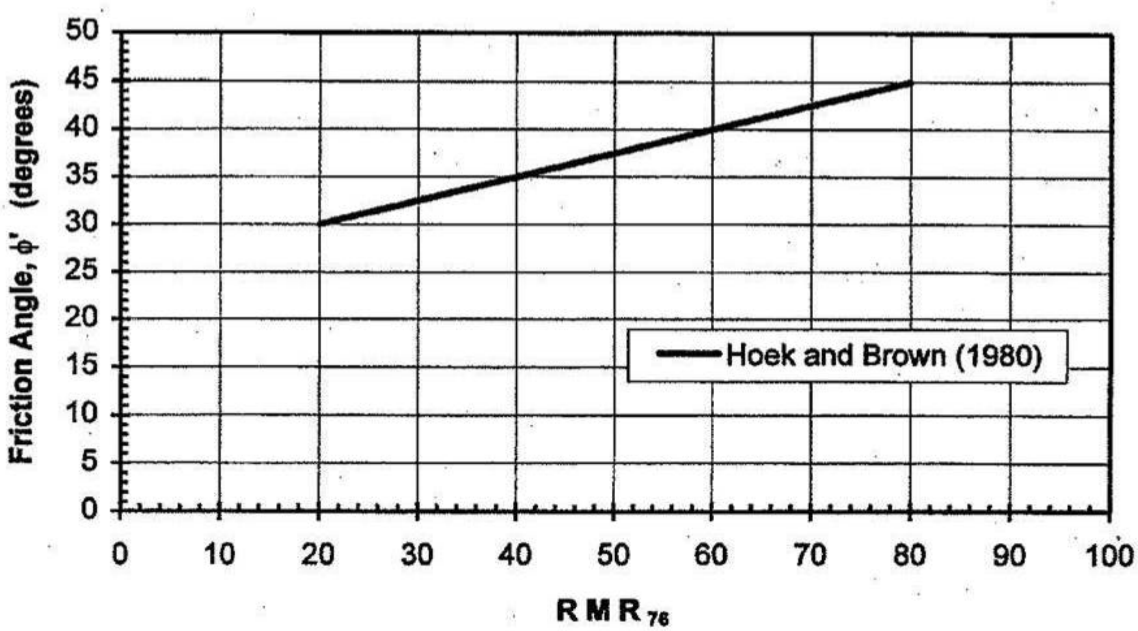


Figure C.1
Effective Friction Angle (ϕ') versus RMR_{76}

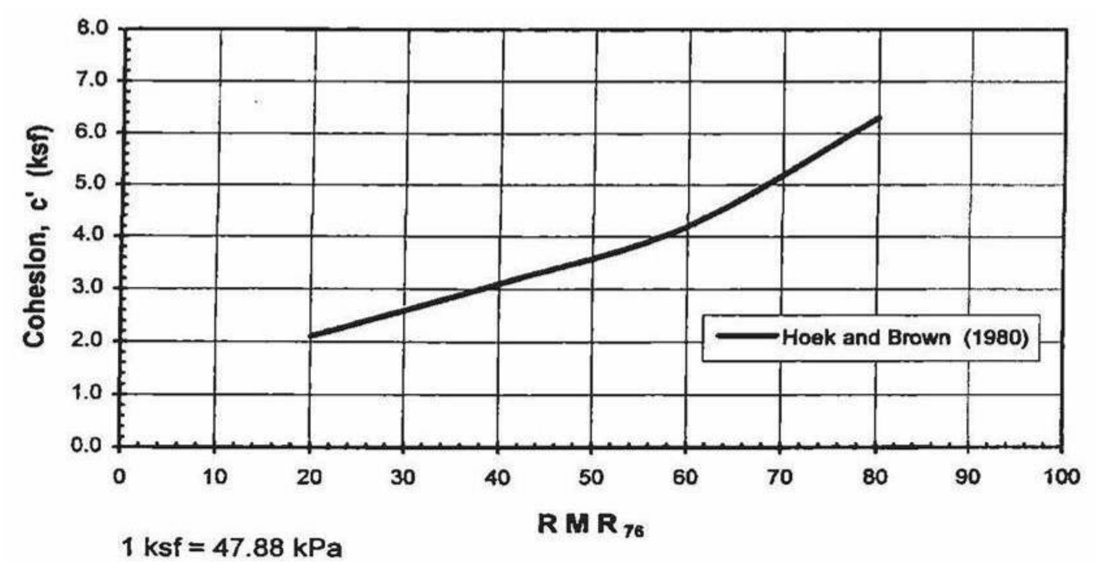


Figure C.2
Effective Cohesion (c') versus RMR_{76}

C.2.1.3. Deformation Modulus

Figure C.3 presents the relationship between the rock mass modulus of deformation (E) and RMR76. As shown in Figure C.3, equations have been fitted to the data as follows:

$$E(\text{ksi}) = 0.564\ \text{RMR}_{76}^{1.958} \quad \text{for } \text{RMR}_{76} < 60$$

$$E(\text{ksi}) = 290\ \text{RMR}_{76} - 14{,}500 \quad \text{for } \text{RMR}_{76} > 60$$

Since RMR_{76} values for near-surface rock mass layers are normally less than 60. The user should have quality rock testing data to justify using the second equation (e.g. RMR_{76} >60).

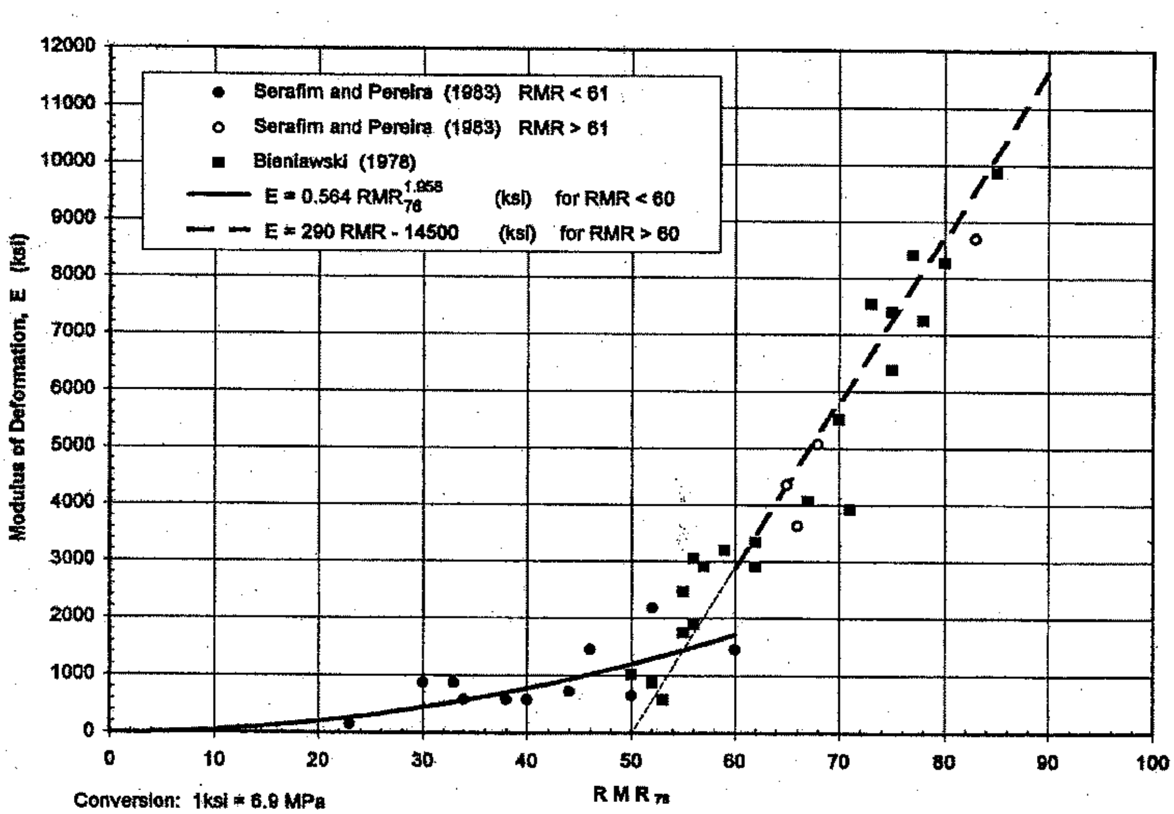


Figure C.3
Modulus of Deformation (E) versus RMR_{76}

C.2.1.4. Rock/Concrete Bond Strength

FAD Tools 5.2.2 modules include the option of accounting for side shear forces in the resistance of axial and overturning loads. Thus, for the portion of a drilled shaft or direct embedded pole constructed in rock, the modules evaluate vertical side shear ultimate capacities at the following interfaces:

- Drilled shaft – concrete/rock interface,
- Direct embedded pole – pole/granular soil backfill interface,
- Direct embedded pole – pole/concrete backfill interface,
- Direct embedded pole – granular soil backfill/rock interface, and
- Direct embedded pole – concrete backfill /rock interface.

C.2.1.5. Correlations for Rock/Concrete Bond Strength

Table C-4 shows average side shear values based on an evaluation of 88 full-scale drilled shaft Osterberg Cell tests (O-cell) in which concrete/rock bond stresses were calculated. In general, the harder rocks such as sandstone, limestone, granite and schist, and other metamorphic rocks exhibit higher concrete/rock bond than the less hard siltstones and shales.

Table C-4
Average Side Shear from O-Cell Tests

Rock Type	Measured Rock/Concrete Bond			
	No. Tests	Avg. (psi)	Avg. (ksf)	COV
Sandstone	14	296	43	0.60
Limestone	17	136	20	0.65
Siltstone	3	91	13	-
Shale	35	101	15	0.63
Granite and Schist	12	153	22	0.43
Other Metamorphic Rock	7	169	24	0.50

The high coefficients of variation (COV) show that there is a high variability in the measured values. This high variability can be attributed to a number of factors such as differential weathering within the test zones, seams of dis-similar rock within the test zones, and the geometry of the shaft and the thickness and location of the rock layer with respect to the O-cell.

Only a few of the O-cell tests were able to reach maximum capacity in side shear. For these tests, the reported values are the maximum achieved but not ultimate capacity.

C.2.1.6. Other Correlations for Rock/Concrete Bond Strength

- Kulhawy, Prokoso and Akbas (2005) concluded, based on evaluation of load tests in rock, the side resistance of a drilled shaft in rock can be estimated as,

  $f/p_a = C\ (q_u/p_a)^n$

  Where f = side resistance, C = Constant, q_u = average uniaxial compressive strength of rock mass, n = 0.5, and p_a = atmospheric pressure. C = 1 for interpreted L_2 failure

- The Post-Tensioning Institute (2004), provide ranges of average ultimate rock/concrete bond strength for small-diameter anchors, as presented in Table C-5.

Table C-5
Typical Average Ultimate Bond Stresses-Rock/Grout from PTI (2004)

	Average Ultimate Rock/Grout Bond Strength (psi)	Average Ultimate Rock/Grout Bond Strength (ksf)
Granite & Basalt	250 – 450	36 – 65
Dolomite Limestone	200 – 300	29 – 43
Soft Limestone	150 – 200	21 – 29
Slates & Hard Shales	120 – 200	17 – 29
Soft Shales	30 – 120	4 – 17
Sandstones	120 – 250	17 – 36
Weathered Sandstones	100 – 120	14 – 17
Chalk	30 – 155	4 – 22
Weathered Marl	25 – 35	3 – 5
Concrete	200 – 400	29 – 58

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