Section 3 Learning Objectives

1) Explain the function of data ranges and default values for input set-up. List the difference between “Errors” and “Warnings” as applied to data ranges.

2) Write, in general terms, the optimization options that can be used by ABLRFD in the design mode for spread footings, pedestal footings, and pile footings.

3) Given an abutment or retaining wall figure with the soil failure wedge superimposed, indicate whether Coulomb or Rankine Theory applies for computing active earth pressure.

4) Given a specified set of loads and a graphic showing an abutment or retaining wall, indicate the following for each load: point(s) of application, direction (horizontal or vertical), and type (point or distributed).

5) List different limit state load combinations used by ABLRFD. Explain the significance of dual load factors that are assigned to some of the loading types.

Section 3 Topics & Additional Objectives

In the last section, we briefly described the program features. This section will discuss how the ABLRFD program uses the program inputs to generate a model of a given structure. Once the model is generated, the program goes through several basic steps when executing. These steps include combining the applied loads which then can be used to provide the most optimum design of the foundation.

3.1. Program Input Discussion

• Become familiar with the ABLRFD program input commands.
• Construct a sample input file and execute the program.

3.2. Program Functions

• Identify the basic steps the program goes through when executing.

3.3. Design Optimization of Foundations

3.4. Applied Loads, Load Factors, and Limit States

• Identify the types of applied loadings that can be used for design or analysis runs and how these loads are combined.

3.5. Section Review and In-Class Exercise
With the release of PENNDOT’s Engineering Assistant Software, the user can now enter or edit the input using a Windows-based application, as opposed to the old way of using a DOS application or ASCII text editor. Also, while still in the Windows environment, the user can run the program and view the program output.

The Engineering Assistant (EngAsst) Software provides a graphical user interface (GUI) for the ABLRFD program as well as many other Department programs. The input data is presented in a user-friendly format with each command on a separate tab page. Each command tab contains text descriptions of each field, relevant images associated with the input being described, and extended help text at both the record/tab level and the field level. If the user needs additional help, the entire Engineering Program User’s Manual can be accessed directly from within EngAsst.

**Dataset Editor**

Before running the ABLRFD program, the user must create an input file. The input file consists of a series of command lines that represent a set of input parameters associated with each command. The Dataset Editor is the portion of the EngAsst program where the user specifies the input. Important user-friendly features of the Dataset Editor are described below for the sample screen shot shown.

**Program Menus** – Pull-down menus and buttons for opening, saving, and executing a program run as well as buttons for additional “Help” topics

**Command Tab Strip** – Shows the various commands of the program

**Command Input Parameters** – Input parameter fields with a description

**“Help” Display Window** – Displays “Help” text and graphics associated with input
Topic 3.1 – Program Input Discussion

Dataset Editor

Command Tab Strip

Program Menus

Command Input Parameters

“Help” Display Window

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus

Dataset Editor

Program Menus
## Topic 3.1 – Program Input Discussion

### Input Commands & Description

The input commands are used to specify the input data for a particular abutment or retaining wall run. Prior to running the ABLRFD program, the user must determine and calculate, if necessary, which program inputs and values should be used. In the following sections, all available commands are discussed. The commands are listed by their three-letter keyword and the command description. Essentially, the input commands can be grouped into seven categories which are used to describe the structures’ properties and loadings.

<table>
<thead>
<tr>
<th>General Information</th>
<th>Structure Type</th>
<th>Foundation Type</th>
<th>Structure Materials</th>
<th>Reinforcement Info</th>
<th>Applied Loadings</th>
<th>Output Printing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFG</td>
<td>AT1</td>
<td>FTG</td>
<td>MAT</td>
<td>MRD</td>
<td>LDC</td>
<td>OIN</td>
</tr>
<tr>
<td>TTL</td>
<td>AT2</td>
<td>SPR</td>
<td>SOI</td>
<td>CVR</td>
<td>LAB</td>
<td>OUR</td>
</tr>
<tr>
<td>CTL</td>
<td>AWB</td>
<td>PIL</td>
<td>RCK</td>
<td>SPD</td>
<td>LRT</td>
<td>OUI</td>
</tr>
<tr>
<td>RWL</td>
<td>CAI</td>
<td>CNS</td>
<td>BAR</td>
<td>SPA</td>
<td>DLL</td>
<td></td>
</tr>
<tr>
<td>PED</td>
<td>LYD</td>
<td>LYA</td>
<td>SRA</td>
<td>SRA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CFG – Configuration Command**

This optional command is used to set the characteristics of the printed output - the number of lines per page and the number of blank lines at the top of each page.

**TTL – Title Command**

This repeatable command specifies the title to be printed at the top of each page. A maximum of ten commands can be printed on the first page but only the first command is printed at the top of each page.
Topic 3.1 – Program Input Discussion

Input Commands & Description

CTL – Control Command
The Control Command specifies the unit of measure (US or Metric), type of run (design or analysis), footing datum for design (fixed top or fixed bottom). For design, the program revises the footing dimensions based on either the top or the bottom of footing being fixed. If the top of the footing is fixed, the footing thickness is increased by lowering the footing bottom but maintaining the same stem height. If the bottom of footing is fixed, the footing thickness is increased by raising the top of footing.
Topic 3.1 – Program Input Discussion

Input Commands & Description

AT1 – Abutment Type I Command
This command describes the geometry of an abutment with a backwall and a straight stem.

AT2 – Abutment Type II Command
This command describes the geometry of an abutment with a backwall and a notched stem.

AWB – Abutment Without Backwall Command
This command describes the geometry of an abutment without a backwall as well as gravity abutments.

RWL – Retaining Wall Command
This command describes the geometry of a retaining wall including the backfill geometry. Gravity walls can also be modeled using this command.

FTG – Footing Command
This command describes the footing dimensions used for design or analysis. The FTG Command must be used for footings of spread footings, pile/caisson foundations, and pedestal foundations.

SPR – Spread Command
The Spread Command is used to describe the parameters used to select and perform the spread footing design optimization. The foundation design optimization is thoroughly discussed later in this section.

PIL – Pile Command
Pile dimensions and pile capacities are described in this command.

CAI – Caisson Command
Similar to the pile command, the caisson dimensions and capacities are described in this command.

PED – Pedestal Command
This command describes the pedestal properties and dimensions used for analysis and design. The program can optimize the pedestal design based on least pedestal density or least footing volume.
Input Commands & Description

LYD – Pile/Caisson Layout Design Command
This command describes the necessary criteria for designing a pile or caisson foundation. Inputs include items such as: minimum and maximum spacings, edge distance, and battering options. Optimized foundation design can be performed based on least pile or caisson density, least footing size by volume, or least installed foundation cost.

LYA – Pile/Caisson Layout Analysis Command
Similar to the LYD command, properties of an existing pile/caisson foundation can be specified using the command.

MAT – Materials Command
The properties of the concrete and steel reinforcement materials used in the abutment or retaining wall are specified using this command. The backfill material properties are also input using this command.

SOI – Soil Data Command
This command describes the properties of the soil beneath the footing. Cohesive soils, sands, and clays can be modeled using this command. Based on the values input, the program internally calculates the allowable bearing capacity and the actual settlement.

RCK – Rock Data Command
This command describes the properties of the rock beneath the footing. The user must determine the ultimate bearing capacity and enter it into the program. Based on the values input, the program calculates the actual settlement.

CNS – Consolidation Command
This command describes data used to calculate consolidation and secondary settlements for spread footings on clay or c-φ soils. Up to two soil layers can be input but soils comprised of only sand cannot be used.

MRD – Miscellaneous Reinforcement Command
This command is used to describe the exposure condition of the reinforcement as well as other parameters related to bar detailing.

CVR – Reinforcement Cover Command
Reinforcement covers are input for the backwall, stem, and footing using this command.
Topic 3.1 – Program Input Discussion

Input Commands & Description

SPD – Reinforcement Design Command
This command is used to specify the maximum bar diameter to be used in the design of the backwall, footing, and stem.

BAR – Bar Size Command
For analysis runs, this command can be used to specify reinforcement bar sizes in the footing and backwall. This command, along with the SPA command, can be used to describe the reinforcement or the ARE command can be used by itself.

SPA – Bar Spacing For Analysis
This command is used to describe the spacing of the reinforcement specified using the BAR command.

ARE – Reinforcement Area Command
In lieu of using the BAR and SPA commands, the user can simply specify the reinforcement area per unit width for the backwall and footing using this command.

SRA – Stem Reinforcement Areas Command
The rear face vertical stem reinforcement area can be entered for an analysis problem using this command.

SRB – Stem Reinforcement Bars Command
The bar sizes and bar spacings can be entered for analysis using this command. Typically, stem reinforcement bars that vary in size or are offset from one another are described using the SRB command.

LDC – Load Control Command
This command is used to describe the factors (ductility, redundancy, and importance) that are used to determine the eta factor, $\eta$. Additionally, the live load surcharge and earth surcharge (in equivalent soil heights) are entered for the temporary and final stages.

LAB – Loads On Abutments Command
This command is used to input the loads per unit width applied to the abutment. These loads include the superstructure dead loads and transient loads as well as backwall live loads. Superstructure live loads are specified using the DLL command.

LRT – Loads On Retaining Walls Command
Parapet loads such as parapet dead load and vehicular collision force can be applied to a retaining wall using this command.
**Topic 3.1 – Program Input Discussion**

**Input Commands & Description**

**DLL – Design Live Load Command**  
Superstructure design live load reactions per unit width are input using this command. These live loads include downward and upward live load, braking force, and centrifugal force but should not include the amplification effects of impact.

**SLL – Special Live Loading Command**  
Similar to the DLL command, the inputs used are for a special live load such as the P-82 permit vehicle.

**EQL – Earthquake Loads Command**  
This command is used to describe the seismic criteria applied to the structure. Additionally, the horizontal earthquake superstructure force is input using this command.

**OIN – Output of Input Command**  
This command is used to control the printing of the input as requested by the user.

**OUR – Output of Results Command**  
This command is used to specify which results are to be printed in the output file.

**OUI – Output of Intermediate Data Command**  
This command is used to specify the intermediate calculations (that are used to determine the results) that should be printed in the output file.
The ABLRFD program can be used for design or analysis of reinforced concrete retaining walls and abutments. Once the user has setup an input file, the program executes the functions in the order listed below.

1) Input Processing
The program processes the user-entered inputs and detects for any errors in the input file. The input values are compared with the upper and lower limits set by the program. If the user’s value is greater than the upper limit or less than the lower limit, a warning or error message is shown. If an error is detected, the program stops processing the input and prints an error message in the program output. Otherwise, the program continues processing the input. The upper and lower limits are indicated in the program manual and as shown in the sample below. An (E) represents an error if the specified input is not within the input range limits. If a (W) is indicated next to the input, the program executes but provides a “Warning” message if the user-specified input is not within the range.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
<th>UNITS</th>
<th>LOWER LIMIT</th>
<th>UPPER LIMIT</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Corbel Width</td>
<td>The corbel width is measured to the seat face of the abutment. A zero value indicates the absence of a corbel.</td>
<td>in</td>
<td>0.0</td>
<td>6.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>0.0 (E)</td>
<td>150.0 (W)</td>
<td>100.0</td>
</tr>
<tr>
<td>7. Corbel Height</td>
<td>The height of the corbel on the front face of the backwall is measured from the top of the backwall to the seat face.</td>
<td>in</td>
<td>0.0</td>
<td>48.0</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>0.0 (E)</td>
<td>1200.0 (W)</td>
<td>600.0</td>
</tr>
<tr>
<td>8. Corbel Slope Height</td>
<td>The corbel slope height indicates whether the transition between the backwall and the corbel is sloped. A zero value indicates an abrupt change in backwall thickness.</td>
<td>in</td>
<td>0.0</td>
<td>6.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>0.0 (E)</td>
<td>150.0 (W)</td>
<td>100.0</td>
</tr>
<tr>
<td>9. Paving Notch Width</td>
<td>The width of the paving notch is measured from the back face of the backwall. A zero value indicates the absence of a paving notch.</td>
<td>in</td>
<td>0.0</td>
<td>24.0</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>0.0 (E)</td>
<td>600.0 (W)</td>
<td>225.0</td>
</tr>
<tr>
<td>10. Paving Notch Height</td>
<td>The height of the paving notch is measured from the top of the structure. A zero value indicates the absence of a paving notch.</td>
<td>in</td>
<td>0.0</td>
<td>36.0</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>0.0 (E)</td>
<td>900.0 (W)</td>
<td>400.0</td>
</tr>
</tbody>
</table>

To help illustrate the concept of range limits, consider the limits shown above for the backwall corbel inputs and the corresponding detail from PennDOT Standards shown below. If the corbel width value entered is greater than 6 inches, the program will print a warning message and continue executing. If the corbel height value entered is less than 0 inches, the program will stop executing and issue an error message.
Additional program errors may be reported if invalid commands are used. For example, if the user is analyzing a structure with a pedestal foundation, the program will detect and report an error if the Pile Command (PIL) has been specified since this command is not applicable for a pedestal foundation.

2) Define Geometry
Once the input has been checked, the program establishes the geometry of the abutment or retaining wall. This geometry is then used to calculate the structures dead load and other applied loads acting on the structure and its components.

3) Apply Loads
Once the geometry is defined, the program calculates and applies the loads for the given structure based on the input. The loads are combined for each applicable limit state and each construction stage. The resulting forces and moments are used to evaluate the stability of the structure.

4) Stability Check
Once the forces and moments are calculated, the program evaluates the structure’s stability for overturning, sliding, bearing capacity, and settlement as applicable.

5) Modify Footing Dimensions
For a design run, the geometry of the footing is revised if the structure is found to be unstable. The possible modifications to the footing geometry include: changes in footings dimensions (width, thickness, toe projection, etc.), changes to the pile pattern (pile spacing, number of piles, pile rows), and changes in the pedestal geometry (width, thickness, back offset, front projection).
Topic 3.2 – Program Functions

The program applies a design optimization algorithm to provide an efficient footing dimension selection while conforming to the user-specified footing dimension limits. Conceptually, this algorithm consists of combinations of width and thickness while looping through the stem positions. A typical iteration is shown below.
Topic 3.2 – Program Functions

The program starts the design algorithm by setting the footing geometry to the minimum toe projection, maximum thickness, and minimum width. The footing width is incrementally increased until a valid design is found. When a valid design is found, the program sets the footing thickness equal to the minimum footing thickness and reduces the footing width by one-half the maximum footing thickness. At this time, the stability of the structure is evaluated and the footing thickness is increased as needed. The following figure illustrates the procedure previously described.

The program can also optimize the design of the foundations based on specific user input values. The optimization for various foundation types is summarized below:

- For a spread footing, the program can optimize based on the least footing cost or least footing volume.
- For pedestal footings, the design can be optimized for the least pedestal density or least footing volume.
- Pile and caisson foundations can also be optimized based on the least pile or caisson density, least footing volume, or least installed foundation cost.

For analysis runs, stability violations are reported in the output.
6) Footing Reinforcement Design
The footing flexural reinforcement is designed considering both strength (moment resistance) and serviceability (crack control) conditions at the footing toe and heel locations. If an acceptable reinforcement solution cannot be obtained, the program modifies the footing dimensions. If the shear resistance of the footing is not adequate, the design is re-evaluated using a thicker footing. The program reverts back to step 2 if either of these two unacceptable conditions occur. The program also performs specification checks including:
- Minimum and maximum bar spacing
- Development length
- Over-reinforced section
- Minimum reinforcement

For analysis runs, the sectional resistance is compared with the applied loads and is reported in the output via the performance ratio.

7) Stem Reinforcement Design
The stem reinforcement is designed similarly to that of the footing but also considers axial load. The program designs the reinforcement at the quarter points along the stem. Additionally, the program tries to find one cutoff point for each bar where every other bar can be cutoff.

For analysis runs, the specified reinforcement and concrete section are analyzed for conformance to the specifications.

Program Tolerances
The ABLRFD program allows tolerances (overstresses) for some of the various structural checks performed by the program. As an example, the tolerances for the bearing pressure beneath a spread footing are calculated as \(((\text{calculated pressure} - \text{allowable pressure}) / \text{allowable pressure})\). The tolerances used by the program are indicated below.

- For spread footings and pedestal footings, a tolerance of 1.5% is used and considered acceptable.

- Tolerances are not used for pile footing checks.

- For the reinforcement used in the stem, backwall, and footing, a 1.5% tolerance is used for the area of steel required, service level stresses, and bar spacing.
Topic 3.3 – Design Optimization of Foundations

The ABLRFD program applies a complex foundation design algorithm that provides efficient footing dimension selection. The algorithm for the optimum design solution varies for each type of footing: spread footing, pile/caisson footing, and pedestal. The following sections describe unique features of the design algorithm and the optimal design solution for each footing type.

Spread Footings
The spread footing algorithm follows the general procedure of iterating through the footing geometry configurations while also checking footing stability and performing reinforcement design. The program evaluates the cost of all successful footing configurations. Based on the user input specified in the Spread Command (SPR), the cost function may be based solely on the footing volume or the cost of the required concrete, excavated material, and backfill material.

If the design is optimized for the least footing volume, the footing is designed considering the footing area per unit length. If two different footing configurations have the same volume, the program selects the one with the largest toe projection.

If the design is to be optimized for least footing cost, the user must specify if the structure is located in a cut or fill area. Unit costs for concrete, excavation (if required), and backfill material must be specified by the user. These costs are based on a per unit length of the structure.

For a structure located in a cut zone, the cost is determined as the sum of:
- Concrete footing cost – footing volume multiplied by the concrete unit cost
- Excavation cost – cut area multiplied by the excavation unit cost
- Backfill cost – fill area multiplied by the backfill unit cost

![Diagram of Cut Area For Structures Situated In A Cut]

Cut Area For Structures Situated In A Cut
Spread Footings
For structures situated in a cut zone, the program calculates the foundation cost based on the slope of the original ground line. The user can specify, in the Spread Command (SPR), if the original ground slope increases towards the toe (T), increases towards the heel (H), or is flat/level (F). The following sketches illustrate the backfill areas for structures in a cut area.

Examples of Backfill Areas in a Cut Zone
**Topic 3.3 – Design Optimization of Foundations**

**Spread Footings**
The program can also accommodate special cases of backfill areas in a cut zone. As shown in sketches below, case (a) illustrates a condition when the original ground is above the backfill elevation. Case (b) illustrates the condition when the original ground slope is steeper than 1 (vertical) to 1.5 (horizontal).

**Special Cases of Backfill Areas in a Cut Zone**
Topic 3.3 – Design Optimization of Foundations

**Spread Footings**
For a structure located in a fill zone, the cost is determined as the sum of:
- Concrete footing cost – footing volume multiplied by the concrete unit cost
- Backfill cost – fill area multiplied by the backfill unit cost

Examples of Backfill Areas in a Fill Zone
**Pedestal Footings**

Similar to the spread footing algorithm, the program iterates through the various footing configurations until the following criteria are satisfied:

- Footing Stability
- Pedestal Stability
- Footing Flexure and Shear

The structurally acceptable solutions, considering the limits imposed by the user, are then compared to determine the optimal solution. The user can specify, using the Pedestal Command (PED), that the program optimize the design based on either the least pedestal density (D) or least footing volume (V). A sketch showing the configurations and design modifications for pedestal footings is shown below.

![Pedestal Footing Diagram](image-url)
Pedestal Footings
An outline depicting the pedestal design procedure is shown below.

START: Enter with footing thickness, width and toe projection.

INITIALIZE: use footing dimensions & minimum front projection to define the pedestal geometry

Is pedestal width within the user specified limits?

yes

Get Maximum Vertical and Horizontal Load for the Service I Limit State

Is V/H ratio acceptable?

yes

Loop over all load combinations - evaluate eccentricity and toe/heel under the footing.

no

Are Eccentricity and Pressures O.K.?

yes

Compute $A_s$ Req'd (strength) and evaluate Shear checks. If shear fails, adjust pedestal thickness

see note

no

Evaluate Pedestal Stability Check

Evaluate Service Limit State Checks (incl. crack control)

Status of Stability?

ok

Evaluate Cost

Compare to governing design encountered so far

Successfull design?

yes

Resize Pedestal

Size acceptable?

yes

no

no

no

no

no

no

SIZE acceptable?

yes

no

EXIT: Next Footing Configuration

1 If thickness exceeds user-specified limits, go to next iteration.
**Topic 3.3 – Design Optimization of Foundations**

**Pile/Caisson Footings**
The design algorithm for pile/caisson footings is sufficiently complex and dictated by the placement of the pile pattern. For each footing configuration, the program searches for the optimum pile placement configuration based on the information input by the user. The user can specify various design dimensions such as: pile edge distance, minimum and maximum pile spacing, pile row placement (evenly spaced or closest to the toe), and pile battering options. Row placement options are illustrated in the sketches below.

A minimum of two piles rows is required for pile and caisson foundations.
Topic 3.3 – Design Optimization of Foundations

Pile/Caisson Footings

The user can optimize the foundation design, using the pile/caisson layout design command (LYD), based on the following options:

- Least pile or caisson density (P)
- Least footing size by volume (F)
- Least installed pile/caisson and footing cost (C)

If the user selects to optimize the footing according to cost, the user must then enter the installed cost of a single pile/caisson and the unit cost of the installed footing concrete.

Important User Note For Pile/Caisson Footing Design

It is important to note that the program does not determine the optimum pile/caisson size or pile/caisson capacity. The program only determines the optimum pile pattern based on the user’s input. Pile/caisson sizes and capacities must be determined and input prior to running the program. Typically, the pile/caisson size and resulting capacities are determined by the Geotechnical Engineer and contained in the Geotechnical Report for the structure.
ABLRFD Sign Convention

The LRFD applied loads are based on user-specified loads and those internally calculated by the program. These loads are used to perform the stability analysis of the structure. In order to perform the analysis of the structure, it is necessary to understand the sign convention used by ABLRFD. The applied moments and forces are summed about the toe of the footing. Positive moments act in the overturning direction while negative moments are in the resisting direction. Similarly, positive horizontal loads are those that act toward the bridge superstructure (i.e., in the abutment overturning direction) while positive vertical loads act in the downward direction. A positive horizontal load causes a positive overturning moment while a positive downward vertical load causes a negative overturning moment. The applied loads per unit width of the structure, both user specified and program calculated, are discussed in detail in the following sections.
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Dead Loads (DC-A, DW-A, EV) – Abutment and Backfill Self Weight
DC-A is the dead load due to the weight of the abutment (including backwall) or retaining wall. The self weight is calculated using the area of the structure above the point of interest and the unit weight of the material. It is also dependant on the construction stage being considered. The construction stages are discussed in more detail at the end of this section. It always includes the self-weight of the abutment or retaining wall and considers the dead loads applied from the superstructure when appropriate. Superstructure dead loads are considered during the final stage of an abutment and discussed on the following pages. Parapet weight, if present on a retaining wall, is only considered during the final stage for retaining walls.

DW-A is the dead load attributed to wearing surfaces, future overlays and utilities acting directly on the abutment. This load is only considered for the final stage of an abutment and internally calculated by applying the future wearing surface over the heel and backwall of the abutment as shown below. DW loads from the superstructure are discussed on the following pages.

EV is the weight of the backfill material acting over the heel, inclined rear face of stem, and paving notch. This load has a vertical component only. If a water table is present in the backfill, the dry unit soil weight is used above the water table and the saturated unit weight is used below the water table.

The following sketch illustrates the dead load components described above for an abutment.
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Dead Loads From Superstructure (DC-S & DW-S)
The superstructure dead load reactions (DC-S and DW-S) applied to the abutment must be calculated and input by the user using the LAB Command. DC-S represents the weight of the superstructure dead load applied to the abutment while DW-S consists of the superstructure wearing surface weight and utility loads. These vertical loads are only considered during the final stage of an abutment and are applied at the centerline bearings. All of the superstructure dead loads should be considered when calculating the dead load reactions applied to the abutment. These reactions should consider the following loads, as applicable:

- Weight due to beam, haunch, slab, and barriers
- Intermediate diaphragms (cross bracing, interior and/or exterior diaphragms)
- End diaphragms (full depth and partial depth)
- Shear blocks, cheekwalls, and curtain walls
- Approach slabs
- Any additional dead load not mentioned above

Most of the dead load reactions from the bridge superstructure can conveniently be taken directly from PENNDOT’s PSLRFD or STLRFD program. The PSLRFD and STLRFD programs now print a dead load girder reaction summary as shown below and live load reaction summary (per lane) to be used for abutment design.

<table>
<thead>
<tr>
<th>REACTIONS (UNFACTORED) FOR ABUTMENT DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL REACTIONS (UNFACTORED) PER GIRDER</td>
</tr>
<tr>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Support No.</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Dead Loads From Superstructure (DC-S & DW-S)
Additional dead loads, which may not have been entered into the superstructure program, must be calculated separately. These loads may include shear blocks, diaphragms (partial, full, midspan, end), curtain and cheek walls, concrete between deck and end diaphragms, and other loads acting directly on the abutment as shown in the sample sketches below.
Dead Loads From Approach Slab (DC-S & DW-S)

Also, if an approach slab is supported directly by the beam bearings or abutment seat, then the additional weight of the approach slab should be added to the beam reaction. The weight of the approach slab should account for the weight of the approach slab itself and any barriers or other structural components supported by the approach slab. Sketches of the different approach slab details which transfer approach slab dead load directly to the bearings are shown below.
Dead Loads From Superstructure (DC-S & DW-S)

The DC reaction per foot entered into ABLRFD can basically be calculated as the summation of each girder’s dead load reaction (excluding wearing surface and utilities), approach slab dead load (as applicable) plus any additional dead load acting on the abutment divided by the abutment length. Refer to the live load section for additional information and sketches on approach slabs.

\[
R_{DC/UnitWidth} = \frac{\sum(R_{DC1} + R_{DC2}) + R_{ADD} + R_{AS}}{L}
\]

where
- \( R_{DC/UnitWidth} \) = Dead load reaction per unit width, kips/ft
- \( R_{DC1} \) = DC1 dead load beam reaction, kips
- \( R_{DC2} \) = DC2 dead load beam reaction, kips
- \( R_{AS} \) = Approach slab reaction, kips
- \( R_{ADD} \) = Total vertical weight of additional components, kips
- \( L \) = Design abutment length, ft

Similarly, the superstructure DW load can be calculated in the same manner.

\[
R_{DW/UnitWidth} = \frac{\sum(R_{FWS} + R_{UTIL})}{L}
\]

where
- \( R_{DW/UnitWidth} \) = Dead load wearing surface and utility reaction, kips/ft
- \( R_{FWS} \) = Future wearing surface dead load beam reaction, kips
- \( R_{UTIL} \) = Utility load beam reaction, kips
- \( L \) = Design abutment length, ft
Earth Pressure (EH & EH-V)
EH is the lateral earth pressure based on the active pressure condition of the backfill soil. The ABLRFD program uses either the Rankine or Coulomb earth pressure theories or the minimum equivalent earth pressure theory to calculate the active earth pressure coefficient, Ka. Determining which lateral earth pressure theory to use is based on the angle of the soil wedge failure and its intersection with the backfilled portion of the stem rear face. If the soil wedge intersects the rear face of the stem at a point that is backfilled, the Coulomb Theory is used. Otherwise, the Rankine Theory is used. For gravity walls, only the Coulomb Theory is used. The sketch shown below illustrates the soil failure wedge and a line indicating when each earth pressure theory is used, Coulomb or Rankine.

Angle of the soil wedge, $\alpha$, measured from the vertical equals $\alpha = \frac{1}{2}(90^\circ + \beta - \phi' - \varepsilon)$

where:

$\varepsilon = \sin^{-1}\left(\frac{\sin(\beta)}{\sin(\phi')}\right)$

$\beta = $ backfill slope angle measured from the horizontal
$\phi' = $ backfill friction angle
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Earth Pressure (EH & EH-V)
Once the angle of the soil wedge is determined, the active earth pressure coefficient and lateral earth pressure force can then be calculated based on the appropriate theory shown below.

Coulomb Theory:

\[
K_a = \frac{\sin^2(\theta + \phi')}{\sin^2(\theta) \sin(\theta - \delta) \left(1 + \frac{\sin(\phi' + \delta) \sin(\phi' - \beta)}{\sin(\theta - \delta) \sin(\theta + \beta)}\right)^2}
\]

where:
\[
\delta = \frac{1}{2} \phi' \text{ Wall Friction Angle}
\]
\[
\theta = \text{Angle of stem rear face to the horizontal}
\]
\[
K_{ah} = K_a \cos(\delta + 90 - \theta)
\]
\[
K_{av} = K_a \sin(\delta + 90 - \theta)
\]

Rankine Theory:

\[
K_a = \cos(\beta) \frac{\cos(\beta) - \sqrt{\cos^2(\beta) - \cos^2(\phi')}}{\cos(\beta) + \sqrt{\cos^2(\beta) - \cos^2(\phi')}}
\]

where:
\[
K_{ah} = K_a \cos(s)
\]
\[
K_{av} = K_a \sin(s)
\]

Regardless of which earth pressure theory is used, the earth pressure used for analysis cannot be less than the minimum equivalent fluid pressure specified by the user in the Materials Command (MAT). Per section 3.11.5.5 of the DM-4, for yielding walls backfilled with AASHTO No. 57 or PENNDOT’s (OGS) open graded subbase, the design earth pressure shall increase with depth at a rate of 0.035 ksf/ft.
Earth Pressure (EH & EH-V)
For the final construction stage of retaining walls, the program can analyze three different backfill slope conditions. They are:

- Level backfill
- Continuously sloping backfill
- Broken backfill

Broken backfill can be visualized as backfill that slopes upward and then levels off. Refer to the program manual for more information on the analysis method when broken backfill is used. For abutments, the backfill is always assumed to be level.

The lateral earth pressure also has a vertical component called EH-V. This vertical component is calculated separately for the overall structure and footing. The calculation of footing forces is discussed in Section 5.
Earth Pressure (EH & EH-V)

Recently, the method used to determine the internal footing shear and moment due to EH-V was revised. The EH-V shear force is now calculated based on an inclined earth pressure due to the height of the soil below the line projected from the heel/stem interface (parallel to the angle of inclination of the lateral earth pressure) to the edge of the heel. As shown in the sketch below, the horizontal earth pressure from Area 2 is resisted by the stem in Area 1. Therefore, the only force considered on the heel is the force, Pa1. These calculations are based on the partial footing force as described in the *Foundation Engineering Handbook* by Winterkorn and Fang.

The effects of a water table in the backfill affect how the partial footing forces are calculated. The following cases illustrate how the partial footing forces are calculated based on the location of the water table. The following equations apply to all cases.

\[
H_3 = F_t - t_e + H_p \left(\frac{K_{av}}{K_{ah}}\right) \\
H_2 = H - H_3
\]

where:
- \(F_t\) = Footing thickness
- \(t_e\) = Depth of embedment into rock (when applicable)
- \(H_p\) = Heel Projection
- \(S_r\) = \(\beta\) (for Rankine) or \(\delta + 90 - \theta\) (for Coulomb)

When the footing is embedded in rock, the height, \(H\), is measured from the top of rock. Otherwise, the height is measured from the bottom of footing.
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Earth Pressure (EH & EH-V)

Case 1: No Back Water or Water Below Footing

\[ EH - V_1 = 0.5K_{av}\gamma_d H^2 - 0.5K_{av}\gamma_d H^2 \]

Case 2: Back Water Above Affected Area

\[ EH - V_2 = K_{av}\gamma_d (H - H_w)H_3 \]
\[ EH - V_3 = 0.5K_{av}(\gamma_s - \gamma_w)H_w^2 - 0.5K_{av}(\gamma_s - \gamma_w)(H_w - H_3)^2 \]
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Earth Pressure (EH & EH-V)

Case 3: Back Water Within Affected Area

The vertical component of the lateral earth pressure coefficient, $K_{av}$, and the horizontal component of the lateral earth pressure coefficient, $K_{ah}$, used to compute the partial footing force are based on the construction stage (temporary or final) and the controlling lateral earth pressure theory used (Rankine, Coulomb, or minimum equivalent fluid pressure).
Earth Surcharges (ES & LS)

Uniform surcharge loads, ES and LS, may be specified by the user for both the temporary and final stage conditions and are expressed as equivalent heights of backfill soil. ES is a uniform earth surcharge applied to the surface of the backfill. Uniform earth surcharge acting over the retained earth surface can be caused by stock piling backfill material behind the wall or other uniformly applied surcharges. LS is a live load surcharge due to vehicular loading acting on the surface of the backfill. These surcharges act on a horizontal plane and also create additional uniform horizontal pressures acting on the structure. Refer to section 3.11.6.2 of the DM-4 to determine the equivalent height of soil to be used to account for live load surcharge. The vertical component of live load surcharge acting on the backfill and the horizontal live load surcharge pressure can be calculated using the following equations. Earth surcharges (ES) are calculated in similar ways.

\[
LS_v = h_{LS} \gamma_D W_{bf} \\
LS_H = h_{LS} \gamma_D K_{ah} H
\]

Where:
- \( h_{LS} \) = Equivalent height of soil as input by user
- \( \gamma_D \) = Dry unit weight of backfill
- \( W_{bf} \) = Width of backfill at the construction stage being considered
- \( K_{ah} \) = Horizontal active earth pressure coefficient
- \( H \) = Height of structure at the construction stage being considered

The following sketch illustrates the horizontal and vertical pressure diagrams for the lateral earth pressure and live load surcharge as well as their resultant locations for the temporary stage of an abutment.
**Water Loads (WA & WA-E)**

WA is a water load consisting of three parts: the buoyant force acting beneath the footing, the downward force due to the weight of the water acting over the footing toe and heel, and the horizontal force due to water pressure acting on the front face of the stem and footing. For buoyancy calculations, different water levels at the front and rear face of stem are considered by the program. However, the buoyant force is not considered for spread footings on rock. The following sketch illustrates the application of the water load, WA.

If the retained soil mass contains groundwater, a water table will develop and exert additional lateral pressure on the structure. The presence of the water table behind the wall has two effects as noted and shown below.

1) Since the unit weight of the retained soil is reduced to its buoyant (or submerged) weight, the lateral earth pressure below the water table is also reduced.

2) The retained water exerts a hydrostatic horizontal water pressure, WA-E, acting at one-third of the height as shown below.

\[
\begin{align*}
EH_1 &= 0.5K_{ah} \gamma_D (H - H_w)^2 \\
EH_2 &= K_{ah} \gamma_D (H - H_w) H_w \\
EH_3 &= 0.5K_{ah} (\gamma_s - \gamma_w)(H_w)^2 \\
WA &= 0.5\gamma_w H_w^2
\end{align*}
\]

Illustration of WA Loads

Illustration of EH, EH-V, WA-E Loads
Transient Force Transfer to Substructure

Transient superstructure forces, such as live load force effects, wind load, and temperature/friction shall be transferred to the substructure with due consideration of the bearing fixity, span configurations, and skew angle.

Per DM-4 section 3.15.1P, longitudinal forces (except friction) shall be carried only by fixed piers. The longitudinal forces transferred from the superstructure shall be directly applied at the bearings and shall be resolved in the directions perpendicular and parallel to the substructure. For the analysis of abutments using ABLRFD, only the forces in the perpendicular (overturning) direction need to be calculated since the analysis is based on a per unit width strip.

Per DM-4 section 3.15.2P, transverse forces applied to the superstructure must be resisted by the bearings. This criteria is intended for bearings supported by piers; however, it may be applied to abutments. Typically, abutments are capable of providing transverse resistance when shear blocks and/or full depth diaphragms are used. Similar to the distribution of longitudinal forces, transverse superstructure forces are applied at the bearings and shall be resolved in the directions perpendicular and parallel to the substructure. However, only the perpendicular components are needed for abutments. Unless a more rational method is used, transverse forces acting on a superstructure shall be transmitted to the bearings based on the following span lengths:

- For simple spans, one-half of the span
- For continuous spans, one-half of the end span

The following sketch shows how the bearing forces are applied to the abutment. These bearing forces include the dead load beam reactions as well the transient forces previously discussed. Additionally, the horizontal and vertical backwall live loads are also shown. Positive sign convention is shown for all the applied loads, except as noted.

Note: Positive directions are shown

Exceptions for LL and WSUP loads

WSUB load is applied at center of wind area on exposed stem
**Topic 3.4 – Applied Loads, Load Factors, and Limit States**

**Wind Loads (WSUB & WSUP) – On Substructure and Superstructure**

The wind loads applied to an abutment consist of wind on the superstructure and substructure as well as wind on live load. The user must calculate these wind loads and input them into the program using the LAB Command. The magnitude of all the horizontal wind forces must also account for the skew of the abutment.

WSUB is the horizontal wind force acting directly on the front face of the abutment. The force is applied to the stem based on the centroid of the exposed area and is calculated assuming a base wind pressure of 0.040 ksf per AASHTO 3.8.1.2.3. A positive WSUB force is directed away from the bridge superstructure as opposed to other positive forces that act toward the bridge superstructure (i.e., in the overturning direction).

WSUP represents the horizontal and vertical wind loads acting on the superstructure that are transferred to the abutment through the bearings.

The vertical force is an upward wind force and is equal to 0.020 ksf times the out-to-out bridge width, per AASHTO 3.8.2. Typically for abutment design, the wind force is not applied at the quarter point of the bridge deck. The upward wind force should be input into the program as a negative value since positive values are for downward forces.

\[
W_{WUP} = -\frac{0.020 \text{ ksf} \times W \times L_{UP}}{L}
\]

where

- \(W_{UP}\) = Upward wind reaction per unit width, kips/ft
- \(W\) = Out-to-out bridge width, ft
- \(L_{UP}\) = Tributary length for upward wind, ft
- \(L\) = Design abutment length, ft
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Wind Loads (WSUP & WSUB) – On Substructure and Superstructure

The horizontal wind load component of WSUP is calculated based on the longitudinal and transverse wind pressures, the exposed superstructure wind height, and the tributary span length exposed to wind. The exposed superstructure wind height should include the beams, deck, parapets, sound barriers, railings, fences, and superelevation effects. The tributary span length can vary depending on the number of spans (simple span or multi-span superstructure), type of bearing connection to abutments and piers (fixed or expansion), and horizontal wind direction (longitudinal or transverse).

The longitudinal and transverse superstructure wind pressures for various wind attack angles can be taken directly from the AASHTO table shown below. The longitudinal and transverse wind pressures shall be applied simultaneously. These wind pressures are based on a base wind velocity of 100 mph. For bridges or parts of bridges more than 30 feet above low ground or water level, the design wind velocity should be increased in accordance with AASHTO 3.8.1.1. Regardless of the wind velocity used, the total wind loading shall not be taken less than 0.30 klf in the plane of the windward chord and 0.15 klf in the plane of the leeward chord on truss and arch components, and not less than 0.30 klf on beam or girders spans.

<table>
<thead>
<tr>
<th>Skew Angle of Wind</th>
<th>Lateral Load</th>
<th>Longitudinal Load</th>
<th>Lateral Load</th>
<th>Longitudinal Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees</td>
<td>KSF</td>
<td>KSF</td>
<td>KSF</td>
<td>KSF</td>
</tr>
<tr>
<td>0</td>
<td>0.075</td>
<td>0</td>
<td>0.050</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0.070</td>
<td>0.012</td>
<td>0.044</td>
<td>0.006</td>
</tr>
<tr>
<td>30</td>
<td>0.065</td>
<td>0.028</td>
<td>0.041</td>
<td>0.012</td>
</tr>
<tr>
<td>45</td>
<td>0.047</td>
<td>0.041</td>
<td>0.033</td>
<td>0.016</td>
</tr>
<tr>
<td>60</td>
<td>0.024</td>
<td>0.050</td>
<td>0.017</td>
<td>0.019</td>
</tr>
</tbody>
</table>

AASHTO Table 3.8.1.2.2-1: Superstructure Wind Pressures
Wind Loads (WSUP & WSUB) – On Substructure and Superstructure

The transverse and longitudinal wind forces on the superstructure, as depicted in the sketch below, can be calculated using the following formulas.

\[
F_{\text{Lat}} = p_{\text{Lat}} \times H_{\text{Wind}} \times L_{\text{Lat}} \quad \text{&} \quad F_{\text{Long}} = p_{\text{Long}} \times H_{\text{Wind}} \times L_{\text{Long}}
\]

where

- \( F_{\text{Lat}} \) = Lateral wind force (perpendicular to superstructure)
- \( F_{\text{Long}} \) = Longitudinal wind force (parallel to superstructure)
- \( p_{\text{Lat}} \) = Lateral wind pressure from AASHTO Table 3.8.1.2.2-1
- \( p_{\text{Long}} \) = Lateral wind pressure from AASHTO Table 3.8.1.2.2-1
- \( H_{\text{Wind}} \) = Exposed superstructure height
- \( L_{\text{Lat}} \) = Tributary length for lateral wind load
- \( L_{\text{Long}} \) = Tributary length for longitudinal wind load

Once the longitudinal and transverse components are determined, the wind force in the overturning direction can be calculated using the following equation.

\[
W_{\text{WSUP}} = \frac{F_{\text{Lat}} \times \cos \theta + F_{\text{Long}} \times \sin \theta}{L}
\]
Wind on Superstructure Class Exercise
Given the following information, determine the controlling horizontal wind on superstructure load to be entered into ABLRFD for the fixed abutment. Assume the structure height is less than 30 feet and the wind velocity is 100 mph.

Simple Span Prestressed Bridge Length = 125 ft
Abutment Length = 45 ft along face
Exposed Wind Height of Superstructure = 10.5 ft
PENNDOT Skew Angle = 60 degrees
Abutment 1 – Fixed Bearings
Abutment 2 – Expansion Bearings

<table>
<thead>
<tr>
<th>Wind Skew</th>
<th>$p_{Lat}$</th>
<th>$p_{Long}$</th>
<th>$F_{Lat}$</th>
<th>$F_{Long}$</th>
<th>$W_{SUP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees</td>
<td>ksf</td>
<td>ksf</td>
<td>kips</td>
<td>kips</td>
<td>Kips/ft</td>
</tr>
<tr>
<td>0</td>
<td>0.050</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.044</td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.041</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>0.033</td>
<td>0.016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.017</td>
<td>0.019</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The abutment overturning force (kips/ft) due to horizontal wind on superstructure load, $W_{SUP} =$
Wind Loads (WL) – On Live Load

WL is the horizontal wind force acting on the live load that is present on the superstructure. The wind pressure on vehicles is represented by an interruptable moving force of 0.100 kips per lineal foot acting normal to the roadway. Wind on live load is calculated similarly to superstructure wind and can be taken as normal to the roadway (bridge) or varying based on the skew angle of the wind.

The following AASHTO table consists of normal and transverse components when wind on live load is not taken normal to the superstructure.

<table>
<thead>
<tr>
<th>Skew Angle of Wind</th>
<th>Normal Component</th>
<th>Parallel Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees</td>
<td>KLF</td>
<td>KLF</td>
</tr>
<tr>
<td>0</td>
<td>0.100</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0.088</td>
<td>0.012</td>
</tr>
<tr>
<td>30</td>
<td>0.082</td>
<td>0.024</td>
</tr>
<tr>
<td>45</td>
<td>0.066</td>
<td>0.032</td>
</tr>
<tr>
<td>60</td>
<td>0.034</td>
<td>0.038</td>
</tr>
</tbody>
</table>

AASHTO Table 3.8.1.3-1: Wind On Live Load

Once the tributary lengths in the longitudinal and lateral directions are determined, the abutment overturning wind on live load force can be calculated using the equation shown below.

\[
W_{WL} = \frac{p_{Normal} \times L_{Lat} \times \cos \theta + p_{Parallel} \times L_{Long} \times \sin \theta}{L}
\]
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Live Loads (PL) – Pedestrian Live Loads
The live load effects applied to an abutment consist of the design vehicle live load (LL), the braking force (BR), the centrifugal force (CE), and the pedestrian live load (PL). These loads act on the superstructure and are transferred to the abutment through the bearings. Additionally, horizontal and vertical live loads can be applied to the backwall for design/analysis of the backwall only. The user may also investigate an additional live load using the Special Live Loading Command (SLL).

PL is the pedestrian live load acting on the superstructure and transferred through the bearings. This load, per AASHTO 3.6.1.6, is a vertical load with an intensity of 0.075 ksf applied to sidewalks wider than 2 feet and should be taken from the superstructure design program.

\[
R_{PED/UnitWidth} = \frac{R_{PED}}{L}
\]

where
- \( R_{PED/UnitWidth} \) = Pedestrian live load reaction per unit width
- \( R_{LL/Lane} \) = Total pedestrian live load reaction
- \( L \) = Design abutment length

The vertical pedestrian load reaction applied to abutments can be calculated using the following formula.

For Sidewalk Widths > 2 ft

The pedestrian live load is considered simultaneously with the vehicular design live load. PENNDOT’s application of the pedestrian loading is different than that indicated by the AASHTO LRFD Bridge Design Specifications where pedestrian load is considered for all limit states in which live load is considered. PENNDOT has created a special limit state for investigating the pedestrian loading, namely the Strength IP Limit State. Under this loading condition, the pedestrian load is simultaneously present with the vehicular design live load. For the Strength IP limit state, these loads are factored by 1.75 and 1.35, respectively. In ABLRFD, pedestrian loading is only considered for this limit state.
**Topic 3.4 – Applied Loads, Load Factors, and Limit States**

**Live Loads (LL) – Vehicular Live Loads**

LL is the design vehicular live loading acting on the superstructure. For Pennsylvania, the design vehicular live loading is designated as PHL-93 and consists of a combination of the design truck or design tandem, and the design lane load. The PHL-93 vehicular loading is shown below.

The PHL-93 design truck is a truck with one axle weighing 8 kips and two axles weighing 32 kips. The spacing between the 8 and 32 kips axles is 14 feet while the spacing between the 32 kip axles varies from 14 to 30 feet. The transverse spacing of the axles is 6 feet, center to center.

The PHL-93 design tandem consists of a pair of 25 kip axles spaced 4 feet apart. Similar to the design truck, the transverse spacing of the axles is 6 feet.

The PHL-93 design lane consists of a uniformly distributed longitudinal load equal to 0.64 kips per foot. This lane load is assumed to be distributed over a 10 foot width in the transverse direction. The lane load may be interrupted as needed when determining the desired force effect (i.e., maximum or minimum reactions).
Live Loads (LL) – Vehicular Live Loads

The application of the vehicular live load varies depending on the extreme force effect being sought (i.e., abutment reactions, pier reactions, and negative superstructure moments). For abutments, the extreme live load force effect per design lane (R as shown below) is the larger of:

- The design truck effect combined with the design lane load effect, OR
- The design tandem effect combined with the design lane load effect.

![Diagram](image-url)
**Topic 3.4 – Applied Loads, Load Factors, and Limit States**

**Live Loads (LL) – Vehicular Live Loads**

Since the beam reactions are taken on a per lane basis, the number of design lanes must be determined. As indicated by AASHTO 3.6.1.1.1, the number of design lanes (n), expressed as an integer, is typically calculated as the clear roadway width (i.e., curb to curb) divided by the traffic lane width of 12 feet. The live load distribution derived for the LRFD code is based on two lanes being simultaneously loaded. Therefore, when a different number of lanes is considered, the live load force effects need to be adjusted by the multiple presence factor, m. Multiple presence factors from AASHTO are shown in the table below.

<table>
<thead>
<tr>
<th>Number of Loaded Lanes, n</th>
<th>Multiple Presence Factors, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.20</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>0.85</td>
</tr>
<tr>
<td>&gt;3</td>
<td>0.65</td>
</tr>
</tbody>
</table>

AASHTO Table 3.6.1.1.2-1: Multiple Presence Factors

Once the maximum number of design lanes is determined, the extreme live load force effect is calculated by considering each combination of the number of loaded lanes multiplied by the corresponding multiple presence factor. PennDOT does not use the multiple presence adjustment factor which accounts for a reduced ADTT.

The following general formula can be used to determine the maximum downward superstructure live load reaction to be input into the ABLRFD program.

\[
R_{LL/UnitWidth} = \frac{\text{Max}[ (R_{LL/Lane} + R_{AASLL/Lane}) \times n \times m ]}{L}
\]

where

- \( R_{LL/UnitWidth} \) = Live load reaction per unit width
- \( R_{LL/Lane} \) = Live load reaction per lane
- \( R_{AASLL/Lane} \) = Approach slab live load reaction per lane
- \( n \) = Number of design lanes (expressed as an integer)
- \( m \) = Multiple presence factor
- \( L \) = Design Abutment Length

The upward live load reaction can be calculated in the same way as the downward live load reaction. The upward live load reaction should be entered into ABLRFD as a negative value. The approach slab live load should be neglected for upward live load.

The approach slab live load for types 1 – 4 is described on the following pages.
Live Loads (LL) – Vehicular Live Loads

The superstructure live load reactions are typically taken directly from one of the Department’s computer programs, such as, PSLRFD ( prestressed beam), STLRFD (steel girder), or CBA (continuous beam analysis). The reactions from any of these programs should be taken on a per lane basis (i.e., without distribution to specific beams) as shown below.

<table>
<thead>
<tr>
<th>Support No.</th>
<th>Maximum Reaction (kips)</th>
<th>Minimum Reaction (kips)</th>
<th>Maximum Rotation (radians)</th>
<th>Minimum Rotation (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>97.23</td>
<td>-11.64</td>
<td>0.001940</td>
<td>-0.001940</td>
</tr>
<tr>
<td>2</td>
<td>179.77</td>
<td>0.00</td>
<td>0.003611</td>
<td>-0.003611</td>
</tr>
<tr>
<td>3</td>
<td>97.23</td>
<td>-11.64</td>
<td>0.005675</td>
<td>-0.005675</td>
</tr>
</tbody>
</table>

Recently, a live load reaction summary for abutment design has been added to the PennDOT programs. This summary table provides the needed reactions which can then be used to calculate the abutment live load reaction and eliminates the need to add the vehicle and lane reactions together.

<table>
<thead>
<tr>
<th>Support No.</th>
<th>Minimum Vehicle Reaction (kips)</th>
<th>Maximum Vehicle Reaction (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62.03</td>
<td>23.42</td>
</tr>
<tr>
<td>2</td>
<td>96.05</td>
<td>68.08</td>
</tr>
<tr>
<td>3</td>
<td>62.03</td>
<td>23.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Support No.</th>
<th>Minimum Lane Reaction (kips)</th>
<th>Maximum Lane Reaction (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10.42</td>
<td>85.45</td>
</tr>
<tr>
<td>2</td>
<td>-10.42</td>
<td>164.13</td>
</tr>
<tr>
<td>3</td>
<td>-10.42</td>
<td>85.45</td>
</tr>
</tbody>
</table>
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Superstructure Live Load Class Exercise
Given the sample *STLRFD* output on the previous page, calculate the controlling live load reaction for the abutment (support 1) to be input into the *ABLRFD* program.

Assume abutment length, \( L = 64.5 \text{ ft} \)

\[
R_{\text{LL/UnitWidth}} = \frac{\text{MAX}(R_{\text{LL/Lane}} \times n \times m)}{L}
\]

Live load reaction/lane, \( R_{\text{LL/Lane}} = \)

1 Lane:

2 Lanes:

3 Lanes:

4 Lanes:

Therefore, \( R_{\text{LL/UnitWidth}} = \)
Vehicular Live Loads On Approach Slab (LL) – Types 1 and 2: Details 4 & 5
Recently, PennDOT has issued the approach slab standards (BD-628M) which contain many new details for the approach slab connection to the bridge. A sample sketch from BD-628M is shown below. When a type 1 or 2 approach slab is used with details 4 or 5, the live load on the approach slab should be applied to the backwall and not included in the beam reaction. Refer to the backwall live load section for more information about the live load forces applied to the backwall when a type 1 or 2 approach slab is used with details 4 or 5.
**Vehicular Live Loads On Approach Slab (LL) – Types 1 and 2: Details 6 Thru 12**  
When a type 1 or 2 approach slab is used with details 6 thru 12, the live load on the approach slab should be added to the live load reaction from the superstructure since there is no backwall. Since the maximum live load beam reaction from live load acting on the superstructure is based on the PHL-93 loading (vehicle plus lane load) being positioned near the abutment support, the live load acting on the approach slab shall consist of the lane load only (0.64 kips/ft). As shown below, the approach slab is considered to be simply supported by the sleeper slab on the highway side and by the end of the beam on the bridge side. The approach slab live load can be calculated as shown below.

\[
R_{\text{ASLL/Lane}} = \frac{(0.64\text{kips/ft}) \times L_{\text{AS}}}{2}
\]

where

\(R_{\text{ASLL/Lane}}\) = Approach slab live load reaction per lane  
\(L_{\text{AS}}\) = Approach slab length

**Approach Slab Live Load For Types 1 & 2 – Details 6 Thru 12**
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Vehicular Live Loads On Approach Slab (LL) – Types 3 and 4: Details 19 Thru 22

When a type 3 or 4 approach slab (details 19 thru 22) is used as shown below, additional dead load and live load acting on the approach slab will be transferred to the beams, bearings, and the abutment. The additional dead load and live load acting on the approach slab must be added to the superstructure dead and live load. The type 3 and 4 approach slab connection to the superstructure is shown below.

**TYPE 3 AND 4 APPROACH SLAB – DETAIL 20**

*Approach slab connected to the superstructure adjacent to P/S concrete spread box beams and concrete end diaphragms with backwall for beam depths 800 (31.5") and greater.*

---

3-51
**Topic 3.4 – Applied Loads, Load Factors, and Limit States**

**Vehicular Live Loads On Approach Slab (LL) – Types 3 and 4: Details 19 Thru 22**

Since the maximum live load beam reaction from live load acting on the superstructure is based on the PHL-93 loading (vehicle plus lane load) being positioned near the abutment support, the live load (for types 3 and 4 only) acting on the approach slab shall consist of the lane load only (0.64 kips/ft). As shown below, the approach slab is considered to be simply supported by the sleeper slab on the highway side and by the end of the beam on the bridge side. The equation shown below can be used to calculate the type 3 and 4 approach slab live load on a per-lane basis.

\[
R_{ASLL/Lane} = \frac{(0.64 \text{kips/ft}) \times L_{AS}}{2}
\]

where 
\[R_{ASLL/Lane}\] = Approach slab live load reaction per lane  
\[L_{AS}\] = Approach slab length

---

**Approach Slab Live Load For Types 3 and 4**

Also for details 19 thru 22, an additional friction force must be considered at expansion bearings per BD-628M. This horizontal friction is caused by the movement of the superstructure and sliding of the approach slab and must be applied to the bearings as friction (FR). It shall be added to the friction force caused by sliding bearings.

\[
R_{FR/UnitWidth} = \frac{\mu \times P_{AS}}{L}
\]

where 
\[R_{FR/UnitWidth}\] = Horizontal friction force per unit width, kips/ft  
\[\mu\] = Coefficient of friction (0.60 per BD-628M)  
\[P_{AS}\] = Entire weight of approach slab & barriers, kips  
\[L\] = Design abutment length, ft
Braking Forces and Centrifugal Forces (BR & CE)

BR is the horizontal braking force from live load transferred from the superstructure to the fixed bearings. The applied braking force is determined by taking 25% of the axle weights of the single design vehicle (truck or tandem) that controls the vertical reaction. This braking force shall be placed in the loaded lanes being considered and which carry traffic in the same direction. The magnitude of the braking force shall be adjusted as indicated in the table below when the length between expansion joints exceeds 500 feet.

<table>
<thead>
<tr>
<th>Length Between Expansion Joints (ft)</th>
<th>Braking Force Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>501 – 1000</td>
<td>2</td>
</tr>
<tr>
<td>1001 – 1500</td>
<td>3</td>
</tr>
<tr>
<td>1501 – 2000</td>
<td>4</td>
</tr>
<tr>
<td>2001 – 2500</td>
<td>5</td>
</tr>
</tbody>
</table>

DM-4 Table A3.6.4P-1: Braking Force Factors

The braking force applied to longitudinally fixed abutments can be calculated using the formula shown below.

\[
R_{\text{BR/UnitWidth}} = \frac{F_{\text{BR/Lane}} \times \beta \times n \times m \times \sin \theta}{L}
\]

where
- \( R_{\text{BR/UnitWidth}} \) = Horizontal braking force per unit width
- \( F_{\text{BR/Lane}} \) = Hor. braking force/lane (25% of controlling vehicle weight)
- \( \beta \) = Braking force factor (see table above)
- \( n \) = Number of design lanes (expressed as an integer)
- \( m \) = Multiple presence factor
- \( \theta \) = PennDOT skew angle
- \( L \) = Design Abutment Length

CE is the horizontal centrifugal force from live load transferred from the superstructure to the abutments. Centrifugal force is based on the axle weights of the design truck or tandem (whichever controls the vertical reaction) and the following C factor.

\[
C = \frac{4v^2}{3gR}
\]

where
- \( v \) = Highway design speed, ft/s
- \( g \) = Gravitational acceleration, 32.2 ft/s²
- \( R \) = Radius of curvature of the traffic lane, ft
Centrifugal Forces (CE)
When the superstructure follows a curved alignment, the centrifugal force applied to fixed abutments can be calculated as using the following equation.

$$R_{CE/UnitWidth} = \frac{C \times P_{Vehicle} \times n \times m \times \cos \theta}{L}$$

where
- $R_{CE/UnitWidth}$ = Horizontal centrifugal force per unit width, kips/ft
- $P_{Vehicle}$ = Vehicle weight, kips
- $n$ = Number of design lanes (expressed as an integer)
- $m$ = Multiple presence factor
- $\theta$ = PennDOT Skew Angle, degrees
- $L$ = Design abutment length, ft

For expansion bearings, the centrifugal force is adjusted based on the angle between the radial line and the guided direction as well as the angle between the centerline of bearings and perpendicular to the guided direction. Typically for expansion bearings, the overturning abutment component of the centrifugal force is small.

Note the following information related to the magnitude of the braking and centrifugal force:
- These forces must be adjusted based on the skew of the abutment.
- These forces shall not include the dynamic load allowance.
- These forces may be specified for the design live load or special live load.

The live loads previously listed must be calculated by the user and input into the program. These live loads are only applicable to abutments in the final stage construction condition. The pedestrian live load (PL) and horizontal and vertical backwall live loads are input using the Loads on Abutments Command (LAB) while the downward and upward live loads (LL), braking force (BR), and centrifugal force (CE) are input using the Design Live Load Command (DLL). Similarly to the design live load, the downward and upward live load, braking force, and centrifugal force for a special live load may be specified using the Special Live Loading Command (SLL).
Temperature Force (TU) – From Superstructure
TU is the horizontal force applied to the abutment bearings caused by thermal expansion or contraction of the superstructure. For neoprene bearing pads designed using the Department’s BPLRFD (LRFD Bearing Pad) program, this force per bearing can be taken directly from the program output. This force is entitled “Horizontal shear force due to thermal movement for substructure design” as shown in the BPLRFD output below. The magnitude of the thermal load should be adjusted due to the skew of the abutment. This load must be calculated by the user and input using the Loads on Abutment Command (LAB). Refer to Design Example #2 for a sample set of bearing pad temperature force calculations.

<table>
<thead>
<tr>
<th>ABUTMENT 1 (NEAR) RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUTTED PAD SIZE</td>
</tr>
<tr>
<td>EXPANSION END:</td>
</tr>
<tr>
<td>Pad length                  = 13.00000</td>
</tr>
<tr>
<td>Pad width                   = 13.00000</td>
</tr>
<tr>
<td>Total elastomer thickness   = 3.12500</td>
</tr>
<tr>
<td>Number of elastomer layers  = 9</td>
</tr>
<tr>
<td>Thick. of inter. elastomer layers = 0.37500</td>
</tr>
<tr>
<td>Thick. of cover elastomer layers = 0.25000</td>
</tr>
<tr>
<td>Thickness of shim plates    = 0.11960</td>
</tr>
<tr>
<td>Total bearing pad thickness = 4.08180</td>
</tr>
</tbody>
</table>

Horizonal shear force due thermal movement for substructure design = 3.60362

The temperature force per beam and horizontal bearing pad temperature force applied to the abutment can also be calculated using the following formulas.

\[
TU_{Beam} = \frac{G \times A \times L_{Exp} \times \alpha \times \Delta t}{h_{rt}}
\]

\[
R_{TU/UnitWidth} = \frac{TU_{Beam} \times N_b \times \sin \theta}{L}
\]

where
- \(TU_{Beam}\) = Temperature force per beam, kips/beam
- \(G\) = Shear Modulus (AASHTO 14.7.5.2), ksi
- \(A\) = Total pad area, in\(^2\)
- \(\alpha\) = Coefficient of thermal expansion, in
- \(L_{Exp}\) = Tributary expansion length, in/in/°F
- \(\Delta t\) = Temperature elastomer change, °F
- \(h_{rt}\) = Total thickness (not pad height), in
- \(R_{TU/UnitWidth}\) = Horizontal temperature force per unit width, kips/ft
- \(N_b\) = Number of beams
- \(\theta\) = PennDOT skew angle, degrees
- \(L\) = Design abutment length, ft
Friction Force (FR) – From Superstructure
Recently, a new input has been added to the program to allow the user to enter the horizontal friction force applied at the bearings (FR). Friction forces are caused by the bearings resistance to slide and are generated from bearings such as pot bearings, spherical and cylindrical bearings, and rocker bearings. Pot bearings are typically used in Pennsylvania when neoprene bearings pads are not adequate for the loads and rotation. For pot bearings, the friction force can be calculated based on the frictional resistance provided by the bearing using the equation shown below. For other bearing types, refer to Chapter 14 of AASHTO and DM-4. The force should be adjusted based on the skew angle between the centerline of bearings and the direction of movement as well as the horizontal restraint provided by the bearings. Friction caused by sliding of the approach slab shall also be accounted for.

\[
R_{FR/UnitWidth} = \frac{\mu \times \sum R_{Beam} \times \sin \theta}{L}
\]

where
- \(R_{FR/UnitWidth}\) = Horizontal friction force per unit width, kips/ft
- \(\mu\) = Coefficient of friction
- \(R_{Beam}\) = Beam reaction, kips
- \(\theta\) = Skew angle as defined above, degrees
- \(L\) = Design abutment length, ft

Earthquake Effects (EQ)
EQ is the total earthquake force applied to the structure and input using the Earthquake Loads Command (EQL). EQ is composed of seismic earth pressure, a user-specified horizontal superstructure earthquake force, and a force applied to the top of a retaining wall. Currently, the seismic earth pressure is set equal to the lateral earth pressure calculated by the program but may be modified by the user. The vertical component of the seismic earth pressure may also be included if specified by the user. The seismic force transferred from the superstructure to the abutment is typically taken from the computer program entitled \textit{SEISAB} (Seismic Analysis of Bridges). Seismic loads applied to retaining walls must be calculated and are discussed in the Retaining Wall Loads section. The EQ load is divided by the specified response modification factor.

Backwall Live Load (BWLL)
When the abutment has a backwall, the user can input the backwall live load. The backwall live loads consist of the vertical backwall live load and horizontal backwall live load and are applied as shown in the sketch below. These loads are only used for the analysis of the backwall itself and are not used for checking stability or in the analysis of the stem and footing.

Based on the backwall and approach slab details, there are several different methods of calculating the backwall live loads. These methods are described on the following pages and depend on the backwall to approach slab connection.
**Topic 3.4 – Applied Loads, Load Factors, and Limit States**

Backwall Live Load (BWLL) - Approach Slab Types 1 and 2 – Details 4 & 5

When approach slab type 1 or 2 is used with details 4 or 5, vertical and horizontal backwall live loads acting at the front and top of the backwall should be entered into the **ABLRFD**. The sketch below illustrates where the backwall live loads are applied in **ABLRFD**. For details 4 and 5, the approach slabs are supported by a sleeper slab on the highway side and supported by a backwall on the bridge side (as shown below).
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Backwall Live Load (BWLL) - Approach Slab Types 1 and 2 – Details 4 & 5
For approach slab details 4 and 5 with a backwall, the live load acting on the approach slab is the PHL-93 live load as shown in the sketches below. The larger reaction of the truck plus lane and tandem plus lane should be used. An impact factor of 33% should also be used for the vehicle. Typically for approach slabs, the design tandem controls the vertical reaction since the span length of the approach slab is approximately 25 ft.

The vertical live load acting on the backwall can be calculated as shown below.

\[
P_{BWLL/UnitWidth} = \frac{R_{LL/Lane} \times n \times m}{L}
\]

where
- \(P_{BWLL/UnitWidth}\) = Vertical backwall live load per unit width, kips/ft
- \(R_{LL/Lane}\) = Live load reaction per lane including impact (33%), kips
- \(n\) = Number of design lanes (expressed as an integer)
- \(m\) = Multiple presence factor
- \(L\) = Design abutment length, ft

The horizontal live load acting on the backwall can be considered to be caused by live load braking forces and calculated as shown below.

\[
H_{BWLL/UnitWidth} = 0.25 \times P_{Vehicle} \times n \times m \times \sin \theta \times L
\]

where
- \(H_{BWLL/UnitWidth}\) = Horizontal backwall live load per unit width, kips/ft
- \(P_{Vehicle}\) = Controlling design vehicle weight (truck or tandem), kips
- \(n\) = Number of design lanes (expressed as an integer)
- \(m\) = Multiple presence factor
- \(\theta\) = PennDOT skew angle, degrees
- \(L\) = Design abutment length

While these loads act in the paving notch area, ABLRFD conservatively applies these loads to the top and front edge of the backwall.
Backwall Live Load (BWLL) - Approach Slab Types 3 and 4 – Details 19 Thru 22
For approach slab types 3 and 4, the approach slab is supported directly by the beams and bearings. Therefore, the dead and live loads acting on the approach slab shall be added to the superstructure loads and not applied to the backwall. For information on the approach slab reactions applied to the abutment, refer to the superstructure dead and live load section.

Backwall Live Load (BWLL) – Without Approach Slab
For a backwall without an approach slab, only one truck axle per lane can be applied. The vertical and horizontal backwall live load can be calculated as follows.

\[ P_{BWLL/UnitWidth} = \frac{P_{Axle} \times n \times m}{L} \]
\[ H_{BWLL/UnitWidth} = 0.33 \times P_{BWLL/UnitWidth} \times \sin \theta \]

where
- \( P_{BWLL/UnitWidth} \) = Vertical backwall live load per unit width, kips/ft
- \( P_{Axle} \) = Axle load with impact = 32 kips \times 1.33
- \( n \) = Number of design lanes (expressed as an integer)
- \( m \) = Multiple presence factor
- \( L \) = Design abutment length, ft
- \( H_{BWLL/UnitWidth} \) = Horizontal backwall live load per unit width, kips/ft
**Topic 3.4 – Applied Loads, Load Factors, and Limit States**

**Loads on Retaining Walls - Vehicular Collision Force (CT)**

CT is the vehicular collision force applied to the top of a parapet located on a retaining wall. The vehicular collision force must be calculated and input using the Load on Retaining Walls Command (LRT).

Per DM-4 section 3.6.5.3, the vehicular collision force transferred to u-wings and retaining walls is a 10 kip force acting over 5 feet. This load should be applied at the top of the concrete barrier. The vehicular collision force can act at any point along the barrier (longitudinally) and may be distributed down at a 1:1 slope from the top of the barrier to the footing. A worst case scenario, as shown in the sketch below, can be used for applying the vehicular collision force. In this scenario, the load is only distributed in one direction as would be the case if a vehicle collided with the barrier at or near an open joint in the wall.
The applied vehicular collision force is calculated based on the length (L) from the open joint shown to the next open joint or end of the wall. The distribution length, $L_{Distr}$, is equal to 5 feet plus $H$ where $H$ equals the height of the stem, $H_{Stem}$, and the height of the barrier, $H_{Barrier}$. However, the distribution length cannot exceed the length (L) as indicated above. The horizontal vehicular collision force, $CT$, can be calculated using the following formulas.

When $L_{Distr} < L$, $CT = \frac{10 \text{ kips}}{L_{Distr}}$

When $L_{Distr} > L$, $CT = \frac{10 \text{ kips}}{L}$
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Loads on Retaining Walls - Vehicular Collision Force (CT)
With the release of version 1.7.0.0, the program now allows the user to enter a negative value for the “Y distance to CT” when the barrier and vehicular collision force are located below the top of the retaining wall as shown below. The absolute value of the negative Y distance cannot be larger than the exposed stem height entered into the program.
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Loads on Retaining Walls – Parapet and Noise Walls Loads
In addition to the vehicular collision force applied to retaining walls, the user can also specify the dead load and wind load due to a parapet and noise wall acting on a retaining wall as shown below. These loads are entered on a per unit width basis and input using the Loads on Retaining Walls Command (LRT).

When a noise wall is supported by a retaining wall, the user must enter the wind force acting on the noise wall. In accordance with DM-4 PP 3.6.4.5(a) and BD-679M, the wind load to be used is 0.037 kips/ft². The wind force acting on a noise wall/barrier, \( W_{LRT} \), can be calculated using the formula below and should be applied at mid-height.

\[
W_{LRT} = 0.037\text{kips/ft}^2 \times H_{NW}
\]

where \( H_{NW} \) = Height of Noise Wall/Barrier, ft
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Loads on Retaining Walls – Parapet and Noise Walls Loads
Recently, a new input has been added to allow the user to specify the horizontal force at the top of a retaining wall due to earthquake effects of an external structure. This horizontal earthquake force is entered on a per unit width basis perpendicular to the wall using the Earthquake Loads Command (EQL).

When an external structure such as a sound barrier wall, concrete barrier, light pole, sign structure or similar structure is supported by a retaining wall, the horizontal earthquake force caused by the seismic acceleration of the external structure, \( EQ_{RWL} \), can be calculated using the equation below.

\[
EQ_{RWL} = DL \times A
\]

where
- \( DL \) = Dead Load of External Structure, kips/ft
- \( A \) = Acceleration Coefficient per DM-4 Figure 3.10.2-1

Figure 3.10.2-1 - Acceleration Coefficients for Pennsylvania Counties
Factored Forces & Resistances
The PENNDOT LRFD fundamental equation shown below is used for the design of all bridge components, both local and global. The left side of the equation represents the force effects applied to the components (i.e., shear, moment, axial load) while the right side of the equation represents the resistance (capacity) of the component.

$$\Sigma \eta_i \gamma Q_i \leq \phi R_n$$

The PENNDOT LRFD fundamental equation is slightly different than the AASHTO equation. For PENNDOT, the factored force effect includes the summation of the products of the eta factor, load factor, and force effect ($\Sigma \eta_i \gamma Q_i$) instead of the eta factor multiplied by the product of the load factor and force effect ($\eta \Sigma \gamma Q_i$).

Eta Factor, $\eta$
The eta factor, $\eta$, is a load modifier that accounts for the ductility, redundancy, and operational importance of the component. If a maximum force effect is sought, the factored load is multiplied by the eta factor. Likewise, if a minimum force effect is sought, the factored load is divided by the eta factor. Per DM-4 1.3.2.1, the eta factor, $\eta$, shall be taken as 1.0.

If the maximum load factor is used:  
$$\eta_i = \eta_D \eta_R \eta_i$$
If the minimum load factor is used:  
$$\eta_i = \frac{1}{\eta_D \eta_R \eta_i}$$

Load Factor, $\gamma$
The load factor, $\gamma$, is a statistically based load factor whose value is typically greater than 1.0. The load factor for a particular load must account for uncertainties in the magnitude of the load, position of the load, and possible combinations of loads.

Force Effect, $Q$
The force effect, $Q$, is the calculated, unfactored force effect applied to the component. Force effects may include moment, shear, torsion, and axial load.

Resistance Factor, $\phi$
The resistance factor, $\phi$, is a statistically based resistance factor applied to the nominal resistance of a component. The resistance factors must account for uncertainties in material properties, workmanship, quality control, and also in the equations used to predict the strength (capacity) of a member.

Nominal Resistance, $R_n$
The nominal resistance, $R_n$, is the available resistance (capacity) of a member to carry load or combined loads. The product of the resistance factor and nominal resistance, $\phi R_n$, is also referred to as the factored resistance, $R_f$. 

3-65
Construction Stages
The extreme force effects determined by the program are based on the construction stage being considered, temporary or final. The temporary construction stage simulates an abutment or retaining wall still under construction. For this stage, an abutment is considered to be backfilled to the seat level prior to the placement of the backwall and beams. Backfilling the abutment to the seat level facilitates beam erection by allowing construction equipment to get closer to the abutment. Typically in construction, backwalls are not constructed until after the beams and deck slab are placed. At this stage, it is important to investigate the stability of the structure. The structure is vulnerable to stability problems since the stabilizing downward beam reactions are not present while the lateral earth pressure is present and tries to overturn the structure. For the temporary stage of retaining walls, the wall is assumed to be fully constructed with a level backfill surface. The final stage construction assumes that an abutment or retaining wall is completely constructed with all applicable loads being considered. Typical sketches for the construction stages are shown below for an abutment and retaining wall.
Limit State Load Combinations

Once the unfactored forces are calculated, the loads are factored and combined using the limit state load combinations. As previously discussed, the ABLRFD program uses limit states based on the AASHTO LRFD limit state load combinations as modified by PENNDOT. The program considers the four general types of limit states:

- Strength Limit State (Strength I, IP, II, III, V)
- Service Limit State (Service I)
- Extreme Event Limit State (Extreme Event I & II)
- Consolidation & Secondary Settlement Limit State (CSS)

The following table contains the load factors for each limit state load combination used by the program at the final stage. A similar table follows for the temporary stage.

### Load Factor/Load Combination Table: Final Stage

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>Service I</th>
<th>Strength I</th>
<th>Strength IP</th>
<th>Strength II</th>
<th>Strength III</th>
<th>Strength V</th>
<th>Extreme I</th>
<th>Extreme II</th>
<th>CSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-A</td>
<td>1.00/1.00</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>DC-S</td>
<td>1.00/1.00</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.25/0.90</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>DW-A</td>
<td>1.00/1.00</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>--</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>DW-S</td>
<td>1.00/1.00</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>1.50/0.65</td>
<td>--</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>EV</td>
<td>1.00/1.00</td>
<td>1.35/1.00</td>
<td>1.35/1.00</td>
<td>1.35/1.00</td>
<td>1.35/1.00</td>
<td>1.35/1.00</td>
<td>1.35/1.00</td>
<td>1.35/1.00</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>EH</td>
<td>1.00/1.00</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>--</td>
<td>1.50/1.50</td>
</tr>
<tr>
<td>EH-V</td>
<td>1.00/1.00</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>--</td>
<td>1.50/1.50</td>
</tr>
<tr>
<td>ES</td>
<td>1.00/1.00</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.50/1.50</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>LS</td>
<td>1.00/1.00</td>
<td>1.75/1.75</td>
<td>1.35/1.35</td>
<td>1.35/1.35</td>
<td>--</td>
<td>1.35/1.35</td>
<td>1.00/1.00</td>
<td>0.50/0.50</td>
<td>--</td>
</tr>
<tr>
<td>LLDD</td>
<td>1.00/--</td>
<td>1.75/--</td>
<td>1.35/--</td>
<td>1.35/--</td>
<td>--</td>
<td>1.35/--</td>
<td>--/--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>LLDU</td>
<td>--/1.00</td>
<td>--/1.75</td>
<td>--/1.35</td>
<td>--/1.35</td>
<td>--</td>
<td>--/1.35</td>
<td>--/--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>LLBW</td>
<td>1.00/--</td>
<td>1.75/--</td>
<td>1.35/--</td>
<td>1.35/--</td>
<td>--</td>
<td>1.35/--</td>
<td>--/--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>LLBH</td>
<td>1.00/--</td>
<td>1.75/--</td>
<td>1.35/--</td>
<td>1.35/--</td>
<td>--</td>
<td>1.35/--</td>
<td>--/--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>PL</td>
<td>--</td>
<td>--</td>
<td>1.75/--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>WSUP</td>
<td>0.30/0.30</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.40/1.40</td>
<td>0.40/0.40</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>WSUB</td>
<td>0.30/0.30</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.40/1.40</td>
<td>0.40/0.40</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>WL</td>
<td>1.00/1.00</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.00/1.00</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>WA</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>BR</td>
<td>1.00/1.00</td>
<td>1.75/1.75</td>
<td>1.35/1.35</td>
<td>1.35/1.35</td>
<td>--</td>
<td>1.35/1.35</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CE</td>
<td>1.00/1.00</td>
<td>1.75/1.75</td>
<td>1.35/1.35</td>
<td>1.35/1.35</td>
<td>--</td>
<td>1.35/1.35</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>TU</td>
<td>1.00/1.00</td>
<td>0.50/0.50</td>
<td>0.50/0.50</td>
<td>0.50/0.50</td>
<td>0.50/0.50</td>
<td>0.50/0.50</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>FR</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>1.00/1.00</td>
<td>--</td>
</tr>
<tr>
<td>EQ</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.00/--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CT</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.00/--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Minimum & Maximum Load Cases

As shown in the load factor/load combination tables above, dual load factors are shown for each type of load. These dual load factors are used for the minimum and maximum load cases. The first load factor shown is used for the maximum load case and the second is for the minimum load case.

The objective of the maximum load case is to maximize the downward vertical load while the minimum load case is used to minimize the downward vertical load. For both load cases, the horizontal load is maximized. For loads or load types that have components in the horizontal and vertical direction, they are multiplied by the maximum load factor since the horizontal force is always maximized and both components must be multiplied by the same factor.
Topic 3.4 – Applied Loads, Load Factors, and Limit States

Minimum & Maximum Load Cases
Typically, engineers like to think that maximizing the load on a component creates the most extreme force effect. While this is generally true, it is not always the case. For example, using the minimum load case factors can actually cause the extreme force effect. Such is the case for checking the sliding stability of a structure as shown below. The figure shown below illustrates the sliding stability performance ratios calculated for a structure supported on rock. Using the equation given, minimizing the vertical force (VLF) using the minimum load factors produces lower (more critical) performance ratios than using the maximum load factors. For this example, the minimum load cases cause the more extreme force effect compared with their respective maximum load cases.

### Sliding Resistance Performance Ratios

\[
\left( \phi \text{ VLF} \tan \phi_s \right) / \text{HLF}
\]

<table>
<thead>
<tr>
<th>Performance Ratios</th>
<th>Max-Temp</th>
<th>Min-Temp</th>
<th>Max-Final</th>
<th>Min-Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength I Limit State</td>
<td>1.677</td>
<td>1.276</td>
<td>1.354</td>
<td>1.024</td>
</tr>
</tbody>
</table>

Applicable Limit States
The program determines which limit state load combinations are applicable based on the construction stage (temporary or final), load case (minimum or maximum), structural component (stem, footing, backwall), type of structure (retaining wall or abutment), and user-specified inputs and input commands. If the user does not specify an input value for pedestrian live load or collision load, the program does not evaluate the Strength IP or Extreme Event II limit states, respectively. If the user does not specify the Special Live Load (SLL) or Earthquake Loading (EQL) Commands, the program does not apply the Strength II or Extreme Event I limit states, respectively.
**Review of Learning Objectives & Topics**

1) Reviewed the program inputs and learned the functions of data ranges and default values. Learned how to setup an input file and execute the program.

2) Discussed the program’s optimum design features for spread, pile/caisson, and pedestal foundations.

3) Learned how the program determines whether to use the Coulomb or Rankine Theory for computing active earth pressure.

4) Learned how the program applies the loads (both user-specified and program calculated) to a structure.

5) Listed the different limit state load combinations used by ABLRFD. Explained the significance of dual load factors.

6) Identified the seven basic steps the program goes through when executing.

**In-Class Exercise**

Indicate if the program will successfully execute and/or provide a warning message for the downward live load inputs shown below.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
<th>UNITS</th>
<th>LOWER LIMIT</th>
<th>UPPER LIMIT</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Downward LL</td>
<td>Design live loading reaction applied in a downward direction and does not include effects due to impact.</td>
<td>kip/ft</td>
<td>0.0</td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kN/m</td>
<td>0.0</td>
<td>75.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

1) Downward Live Load = -2.5 kips/ft  Execute? _________  Warning? __________

2) Downward Live Load = 7.39 kips/ft  Execute? _________  Warning? __________

3) Downward Live Load = 4.82 kips/ft  Execute? _________  Warning? __________

List the possible footing design optimizations (1 thru 5) that can be used by the ABLRFD program with the footing types shown. Answers may be used more than once or not at all.

1) Least Footing Cost  2) Least Pedestal Density
3) Least Footing Volume  4) Least Pile/Caisson Density
5) Least Pile/Caisson Diameter

Spread Footing  Pile/Caisson Footing  Pedestal Footing

______________  ______________  ______________