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# Kiva Documentation

*Release 0.6.0*

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Kiva is a free and open source ground heat transfer calculation tool written in C++. Specifically, Kiva is used to calculate heat loss and gain on a timestep basis from building foundations. The goal is to create a tool that can integrate the multi-dimensional heat transfer into standard building energy simulation engines.



# CHAPTER 1

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## Integrations

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Kiva has been integrated into the [EnergyPlus](#) whole building simulation engine. More integrations are in the works.





## 2.1 Getting Started

Kiva is a command line tool. You can execute Kiva from the command line as follows:

```
kiva input.yaml weather.epw output.csv
```

Kiva will simulate the foundation defined in `input.yaml` using the weather conditions specified in `weather.epw` and generate time series results in `output.csv`. Execute the `run-kiva` file in the installation to see a demonstration of how to use Kiva.

Input files are YAML formatted descriptions of building foundations and simulation control settings. This is described in more detail in the following sections.

Weather files are read in the EnergyPlus weather (EPW) file format.

Output files are a simple comma separated variable (CSV) file format, with results corresponding to output requested in the `input.yaml` file.

## 2.2 Input Definition

Kiva input is specified in a hierarchical **YAML** file. This file has six objects at the highest level, Simulation Control, Materials, the Foundation itself, Boundaries, Initialization, Numerical Settings, and Outputs. All inputs are defined in standard International System (SI) units.

### 2.2.1 Simulation Control

This defines the settings of the simulation period and timestep.

**Example:**

**Simulation Control:****Start Date:** 2015-Jan-1**End Date:** 2015-Dec-31**Timestep:** 60 # [min]**Start Date**

Specifies the start date of the simulation. Simulation begins at 12:00am of this day. This is specified as a date string (e.g., YYYY-Mon-DD, YYYY/MM/DD).

<b>Required:</b>	Yes
<b>Type:</b>	Date string

**End Date**

Specifies the end date of the simulation. Simulation ends one timestep previous to 12:00am of the following day. This is specified as a date string (e.g., YYYY-Mon-DD, YYYY/MM/DD).

<b>Required:</b>	Yes
<b>Type:</b>	Date string

**Timestep**

Timestep duration in minutes used in calculations.

<b>Required:</b>	Yes
<b>Type:</b>	Integer
<b>Units:</b>	Minutes

## 2.2.2 Materials

Materials define the intrinsic thermophysical properties of the solid components of the computational domain (eg: surrounding soil, structural concrete, insulation). All materials must fall within a single *Materials:* group.

**Example:****Materials:****Soil:****Conductivity:** 0.864 # [W/m-K]**Density:** 1510.0 # [kg/m3]**Specific Heat:** 1260.0 # [J/kg-K]**Concrete:****Conductivity:** 1.98 # [W/m-K]**Density:** 1900.0 # [kg/m3]**Specific Heat:** 665.0 # [J/kg-K]**XPS:****Conductivity:** 0.029 # [W/m-K]**Density:** 28.0 # [kg/m3]**Specific Heat:** 1450.0 # [J/kg-K]

Each instance of a material begins with a descriptive name (eg: Soil, Concrete or XPS) and contains the following attributes:

### Conductivity

Thermal conductivity of the material.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	W/m-K

### Density

Density of the material.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	kg/m <sup>3</sup>

### Specific Heat

Specific heat of the material.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	J/kg-K

## 2.2.3 Foundation

The description of the foundation design is provided within the two-dimensional context. This profile is applied along the entire perimeter of the foundation.

The foundation insulation and structural components are defined by (up to) six sub-objects. These objects allow the user to flexibly describe any foundation construction.

### Example:

```
Foundation:
  Foundation Depth: 0.0 # [m]
  Polygon:
    - [0, 0] # [m, m]
    - [0, 20] # [m, m]
    - [20, 20] # [m, m]
    - [20, 0] # [m, m]
  Soil: Typical Soil # Material reference
  Slab:
    Layers:
      -
        Material: Concrete # Material reference
        Thickness: 0.2032 # [m]
  Wall:
```

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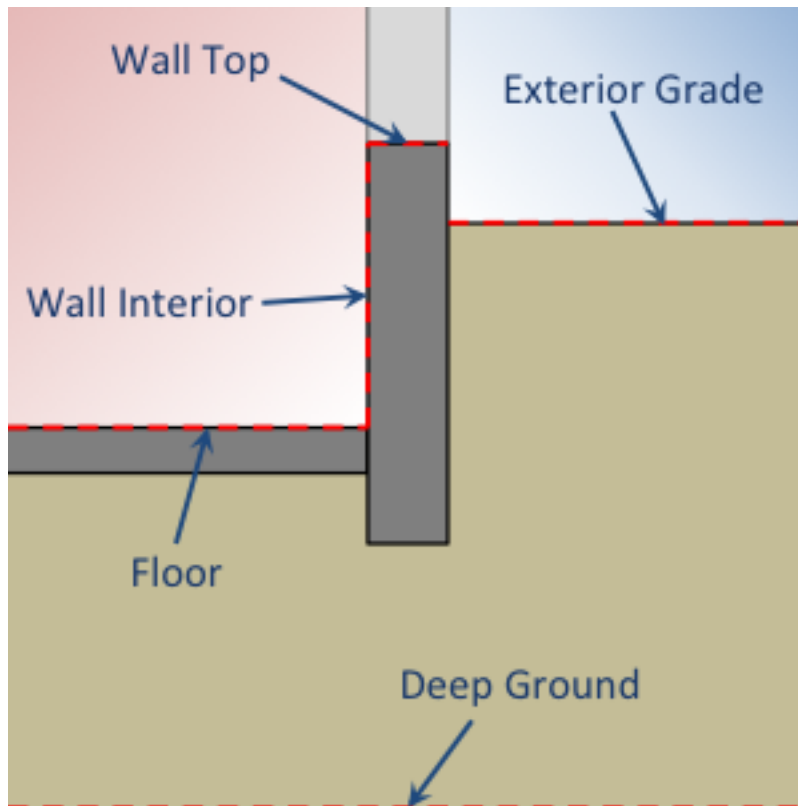


Fig. 1: Two-dimensional context for `Foundation` object definition

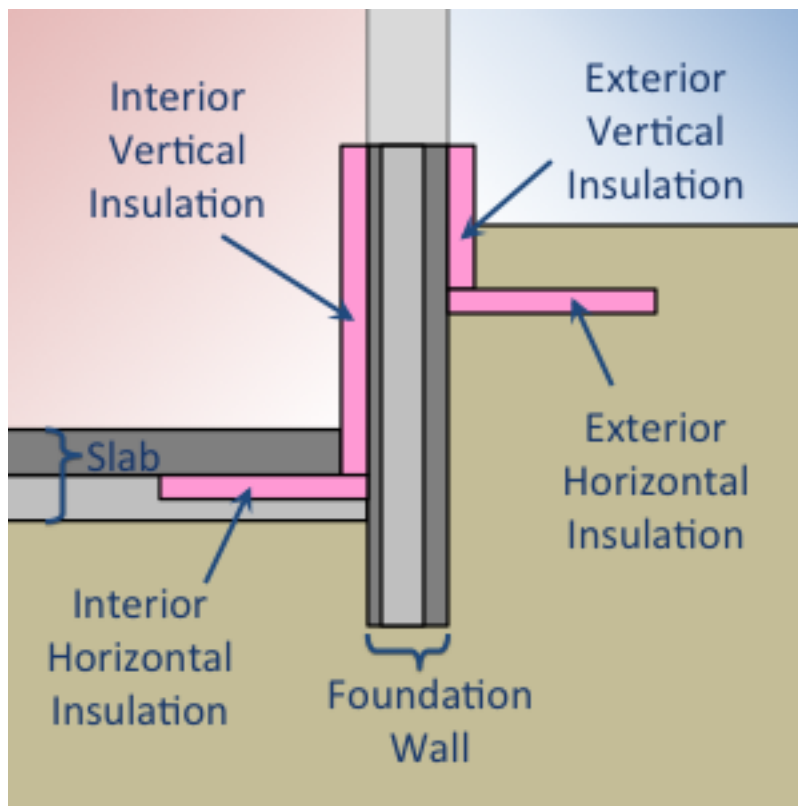


Fig. 2: Insulation and structural design components

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```

Layers:
-
  Material: Concrete # Material reference
  Thickness: 0.3048 # [m]
  Height Above Grade: 0.3048 # [m]
  Depth Below Slab: 0.3 # [m]
Interior Horizontal Insulation:
  Width: 0.4064 # [m]
  Material: XPS # Material reference
  Thickness: 0.0508
Interior Vertical Insulation:
  Depth: 0.2032 # [m]
  Material: XPS # Material reference
  Thickness: 0.0508 # [m]

```

## Foundation Depth

Foundation Depth defines the distance from the wall top to the floor. This value is used to characterize the type of foundation (slab, crawlspace, or basement). For example, a value of zero would represent a slab and a value near 2 meters would represent a basement.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Polygon

The foundation shape is defined by the description of a single polygon. The perimeter of this polygon defines the location of the interior surface of the foundation wall. The positioning of the foundation insulation and structural components are translated into three-dimensional space internally.

The polygon is specified by a list of x-y Cartesian vertices tracing the foundation perimeter in a clockwise fashion. When simulating in three-dimensions, the polygon must be rectilinear (comprised only of right angles).

### Example:

```

Polygon:
- [0, 20]
- [15, 20]
- [15, 30]
- [30, 30]
- [30, 17]
- [22, 17]
- [22, 0]
- [12, 0]
- [12, 10]
- [0, 10]

```

<b>Required:</b>	Yes
<b>Type:</b>	List [N] of lists [2] of numerics
<b>Units:</b>	m

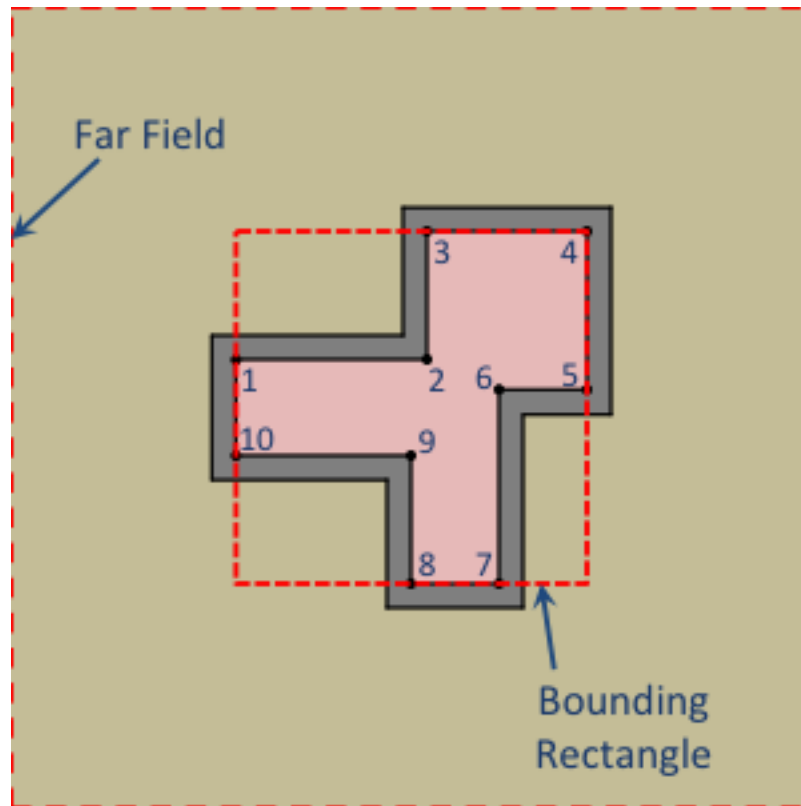


Fig. 3: Plan view illustrating foundation shape vertex definition and far-field boundary.

## Exposed Perimeter

A true/false list corresponding to each segment of the polygon. Segments are defined between polygon vertices  $N$  and  $N + 1$ . A value of *true* implies that the ground adjacent to a segment is exposed to the exterior environment. Conversely, a value of *false* indicates that the ground adjacent to a segment neighbors another interior space.

Only exposed perimeter is considered in heat transfer calculations.

This is only used for two-dimensional simulations.

### Example:

**Exposed Perimeter:**

```
- true
- true
- true
- true
- false
- false
- true
- true
- true
- true
```

<b>Required:</b>	No
<b>Type:</b>	List [N] of booleans
<b>Default:</b>	All true

## Exposed Fraction

Alternative to defining the *Exposed Perimeter*, one may define the fraction of the total perimeter that is exposed. Using this option will revert any *BOUNDARY* type 2Dapprox's to 'AP (as it's not possible to know explicitly which segments represent concave geometry).

This is only used for two-dimensional simulations.

### Example:

**Exposed Fraction:** 0.85

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	N/A (see <i>Exposed Perimeter</i> default)

## Soil

Represents the soil surrounding the building foundation.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference



## Slab

This defines the construction of the floor slab in the foundation. This is not required. If there is no slab defined for a given foundation, then the floor is exposed soil.

### Example:

```
Slab:
  Layers:
  -
    Material: XPS # Material reference
    Thickness: 0.0508 # [m]
  -
    Material: Concrete # Material reference
    Thickness: 0.2032 # [m]
```

<b>Required:</b>	No
<b>Type:</b>	Compound object

## Layers

Layers are specified as a list of material references, and thickness values from the outtermost layer to the innermost layer (at the floor surface). A layer of insulation can be added to model whole-slab insulation.

<b>Required:</b>	Yes
<b>Type:</b>	List of layers (a material and a thickness)

## Material

Material composing the layer.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

## Thickness

Thickness of the layer.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Emissivity

Interior emissivity of the slab used for interior long-wave radiation calculations.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.8

## Wall

This defines the construction of the foundation wall. This is not required. If there is no wall defined for a given foundation, then the wall is exposed soil.

### Example:

```
Wall:
  Depth Below Slab: 0.3 # [m]
  Height Above Grade: 0.3048 # [m]
  Layers:
  -
    Material: XPS # Material reference
    Thickness: 0.0508 # [m]
  -
    Material: Concrete # Material reference
    Thickness: 0.2032 # [m]
  -
    Material: XPS # Material reference
    Thickness: 0.0508 # [m]
```

<b>Required:</b>	No
<b>Type:</b>	Compound object

## Height Above Grade

The height of the wall top relative to the grade ( $z = 0$ ).

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	0.2

## Depth Below Slab

The distance from the bottom of the slab to the bottom of the foundation wall. The total wall extends down to this level.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	0.3

## Layers

Layers are specified as a list of material references, and thickness values from the outtermost layer to the innermost layer (at the interior wall surface).

### Material

Material composing the layer.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

### Thickness

Thickness of the layer.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

### Interior Emissivity

Interior emissivity of the wall used for interior long-wave radiation calculations.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.8

### Exterior Emissivity

Exterior emissivity of the wall used for exterior long-wave radiation calculations.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.8

### Exterior Absorptivity

Exterior absorptivity of the wall used for calculating absorbed solar radiation.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.8

## Interior Horizontal Insulation

This defines the position, dimensions, and material of interior horizontal insulation. Interior horizontal insulation begins at the wall's interior surface and extends inward and downward to a user-specified width and thickness at a user-specified depth at or below the *Foundation Depth*.

### Example:

```
Interior Horizontal Insulation:  
Material: XPS # Material reference  
Thickness: 0.0508 # [m]  
Width: 0.4064 # [m]
```

<b>Required:</b>	No
<b>Type:</b>	Compound object

### Material

Insulation material reference.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

### Thickness

Thickness of the insulation.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

### Depth

Depth of the insulation measured from the bottom of the slab to the top of the insulation.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	0.0

### Width

Width of the insulation extending from the interior wall surface.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Interior Vertical Insulation

This defines the position, dimensions, and material of interior vertical insulation. Interior vertical insulation begins at the wall top and extends downward and inward to a user-specified depth and thickness. The depth can be specified to model partial interior wall insulation.

### Example:

```
Interior Vertical Insulation:
Material: XPS # Material reference
Thickness: 0.0508 # [m]
Depth: 0.6096 # [m]
```

<b>Required:</b>	No
<b>Type:</b>	Compound object

### Material

Insulation material reference.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

### Thickness

Thickness of the insulation.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

### Depth

Depth of the insulation measured from the wall top to the bottom of the insulation.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Exterior Horizontal Insulation

This defines the position, dimensions, and material of exterior horizontal insulation. Exterior horizontal insulation begins at the wall's exterior surface and extends outward and downward to a user-specified width and thickness at a user-specified depth at or below the grade level.

### Example:

**Exterior Horizontal Insulation:****Material:** XPS # *Material reference***Thickness:** 0.0508 # [m]**Width:** 0.6096 # [m]

<b>Required:</b>	No
<b>Type:</b>	Compound object

**Material**

Insulation material reference.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

**Thickness**

Thickness of the insulation.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

**Depth**

Depth of the insulation measured from the exterior grade to the top of the insulation.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	0.0

**Width**

Width of the insulation extending from the interior wall surface.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

**Exterior Vertical Insulation**

This defines the position, dimensions, and material of exterior vertical insulation. Exterior vertical insulation begins at the wall top and extends downward and outward to a user-specified depth and thickness.

**Example:**

**Exterior Vertical Insulation:****Material:** XPS # *Material reference***Thickness:** 0.0508 # [m]**Depth:** 2.0 # [m]

<b>Required:</b>	No
<b>Type:</b>	Compound object

**Material**

Insulation material reference.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

**Thickness**

Thickness of the insulation.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

**Depth**

Depth of the insulation measured from the wall top to the bottom of the insulation.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

**Footing**

This defines dimensions, and material of the foundation footing. The footing is vertically centered and placed immediately below the foundation wall.

The footing is optional, and has minor impacts on foundation heat transfer while the additional detail increases the required computation time. As an approximation, users may choose to extend the depth of a concrete wall to represent the footing.

**Example:****Footing:****Material:** Concrete # *Material reference***Depth:** 0.254 # [m]**Width:** 0.762 # [m]

<b>Required:</b>	No
<b>Type:</b>	Compound object

## Material

Insulation material reference.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

## Depth

Depth (from top to bottom) of the footing (not to be confused with its depth in the ground).

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Width

Width of the footing.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Material Blocks

Beyond the solid materials explicitly defined by the Slab, Wall, and Insulation objects, general Material Blocks may also be used to define any number of variations within the solid domain.

Material Blocks are specified as a list of material references, and geometric inputs. Each block is defined by its position relative to the top interior corner of the foundation wall in the two-dimensional context.

If a Material Blocks overlapping other materials take precedence in the order defined by the list (later blocks have higher precedence).

### Example:

#### Material Blocks:

```
-  
  Material: In-fill Soil # Material reference  
  Z Position: 0.3048 # [m]  
  X Position: 0.254 # [m]  
  Depth: 3.0 # [m]  
  Width: 3.0 # [m]  
-  
  Material: Batt Insulation # Material reference  
  Z Position: 0.0 # [m]
```

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```

X Position: 0.0 # [m]
Depth: 2.44 # [m]
Width: -0.0889 # [m]

```

<b>Required:</b>	No
<b>Type:</b>	List of blocks

## Material

Material reference.

<b>Required:</b>	Yes
<b>Type:</b>	Material reference

## Z Position

Starting position of the block relative to the origin at the top of the foundation wall. Defined as positive in the downward direction. Negative values (above the wall) are not allowed.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## X Position

Starting position of the block relative to the interior of the foundation wall. Defined as positive in the outward direction. Negative values indicate a position interior to the wall.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Depth

Depth (from top to bottom) of the material block (not to be confused with its depth in the ground [see [Z Position](#)]). A positive value extends the block downward (in the positive Z direction) while a negative value extends the block upward.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Width

Width of the material block. A positive value extends the block outward (in the positive X direction) while a negative value extends the block inward.

<b>Required:</b>	Yes
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Soil Absorptivity

Solar absorptivity of the soil or grade surface.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.8

## Soil Emissivity

Long-wave emissivity of the soil or grade surface.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.8

## Surface Roughness

Represents the relief of the surface. This value is used to calculate forced convection and the wind speed near the grade surface. Roughness values in the table below are converted from the more qualitative roughness values used in DOE-2 and EnergyPlus. Estimates for soil, gravel, and grass are also shown.

Example Surface	Roughness [m]
Glass	0.00000
Smooth Plaster	0.00044
Clear Pine	0.00052
Concrete	0.00208
Brick	0.00268
Stucco	0.00468
Soil	0.00500
Gravel	0.01200
Grass	0.03000

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	0.03

## Orientation

Defines the orientation of the building clockwise relative to North (East =  $\pi/2$ , South =  $\pi$ , West =  $3\pi/2$ ). This is used to calculate the solar incidence and wind direction relative to exterior vertical foundation surfaces.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	radians
<b>Default:</b>	0.0

## Perimeter Surface Width

This value is used to define a portion of the slab's perimeter separately from the slab core. This will affect the meshing of the slab, but is intended primarily for separate output reporting for each region.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	0.0

## 2.2.4 Boundaries

Definitions related to the boundary conditions of the ground domain.

### Example:

```
Boundaries:
Far-Field Width: 40.0 # [m]
Deep-Ground Depth: 40.0 # [m]
Deep-Ground Boundary Condition: ZERO-FLUX # AUTO | CONSTANT-TEMP | ZERO-FLUX
Indoor Air Temperature: 295.0 # [K]
```

## Indoor Air Temperature Method

Allows the user to choose between having a constant indoor temperature for the duration of the simulation or to reference temperatures from a file.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	FILE or CONSTANT
<b>Default:</b>	CONSTANT

## Indoor Air Temperature File

If *Indoor Air Temperature Method* is `FILE` the indoor dry-bulb temperature (in Kelvin) will be set using hourly values defined in a comma separated value (CSV) file.

### Example:

**Indoor Air Temperature File:****Name:** ../path/to/file.csv**Index:** [1, 1]

<b>Required:</b>	No
<b>Type:</b>	Compound object

**Name**

Path (relative or absolute) file.

<b>Required:</b>	Yes
<b>Type:</b>	File Path

**Index**

A list of two values corresponding to the row and column where the hourly data begins in the file. A value of [0, 0] starts at the first row and first column. A value of [0, 1] starts at the first row and second column.

<b>Required:</b>	Yes
<b>Type:</b>	List [2] of integers

**Indoor Air Temperature**

If *Indoor Air Temperature Method* is `CONSTANT` the indoor dry-bulb temperature will be set using this value. If *Indoor Air Temperature Method* is `FILE`, then this is not required.

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	K

**Outdoor Air Temperature Method**

Allows the user to choose between having a constant outdoor temperature for the duration of the simulation or to reference temperatures from the weather file.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	WEATHER-FILE or CONSTANT
<b>Default:</b>	WEATHER-FILE

**Outdoor Air Temperature**

If *Outdoor Air Temperature Method* is `CONSTANT` the outdoor dry-bulb temperature will be set using this value. If *Outdoor Air Temperature Method* is `WEATHER-FILE`, then this is not required.

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	K

### Local Boundary Layer Thickness

Local boundary layer thickness used for calculating local wind speeds from weather file wind speeds.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	370

### Local Terrain Exponent

Local terrain exponent used for calculating local wind speeds from weather file wind speeds.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.22

### Far-Field Width

Distance from the interior wall surface to the edge of the domain.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	40

### Deep-Ground Depth

Distance from the grade level to the bottom of the domain.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	40

### Deep-Ground Boundary Condition

Specifies the type of boundary condition to apply at the deep-ground boundary. Options are:

- ZERO-FLUX, which applies a zero heat flux boundary,
- AUTO, which applies a constant temperature equal to the average outdoor dry-bulb temperature from the weather file, and

- `CONSTANT-TEMP`, which applies a user-specified constant temperature (see *Deep-Ground Temperature*).

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	<code>ZERO-FLUX</code> , <code>AUTO</code> , or <code>CONSTANT-TEMP</code>
<b>Default:</b>	<code>ZERO-FLUX</code>

## Deep-Ground Temperature

If *Deep-Ground Boundary Condition* is `CONSTANT-TEMP`, then this value specifies the temperature applied to the deep-ground boundary.

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	K

## Convection Calculation Method

Specifies how convection coefficients are calculated. Options are:

- `AUTO`, which calculates dynamic convection coefficients based on temperature difference, wind speed, and wind direction.
- `CONSTANT`, which applies a user-specified convection coefficients to interior and exterior surfaces (see *Interior Convection Coefficient* and *Exterior Convection Coefficient*). This is used primarily for IEA BESTEST calculations.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	<code>AUTO</code> or <code>CONSTANT</code>
<b>Default:</b>	<code>AUTO</code>

## Interior Convection Coefficient

If *Convection Calculation Method* is `CONSTANT`, then this value specifies the convection coefficient applied to interior surface boundaries (slab floor, interior foundation wall, and interior insulation).

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	$\text{W/m}^2\text{-K}$

## Exterior Convection Coefficient

If *Convection Calculation Method* is `CONSTANT`, then this value specifies the convection coefficient applied to exterior surface boundaries (grade, exterior foundation wall, and exterior insulation).

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	$\text{W/m}^2\text{-K}$

## Wall Top Boundary Condition

Specifies how the boundary condition along the wall top is calculated. Options are:

- ZERO-FLUX, which applies a zero heat flux boundary condition along the wall top. This implies that heat flux above the wall top is one dimensional and does not flow through the wall top boundary.
- LINEAR-DT, which applies a linear change in temperature across the wall top (see ‘**Wall Top Temperature Difference**’\_). This is used only to represent the constraints of the IEA BESTEST analytical solution in case GC10a.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	ZERO-FLUX or LINEAR-DT
<b>Default:</b>	ZERO-FLUX

## Wall Top Interior Temperature

If *Wall Top Boundary Condition* is LINEAR-DT, then this value specifies the interior temperature at the wall top. This is used only to represent the constraints of the IEA BESTEST analytical solution in case GC10a.

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	K

## Wall Top Exterior Temperature

If *Wall Top Boundary Condition* is LINEAR-DT, then this value specifies the exterior temperature at the wall top. This is used only to represent the constraints of the IEA BESTEST analytical solution in case GC10a.

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	K

## 2.2.5 Initialization

Defines how the initial temperatures are generated for the model.

**Example:**

```
Initialization:
  Initialization Method: STEADY-STATE # KUSUDA | CONSTANT | STEADY-STATE
  Accelerated Initialization Timestep: 168 # hours
  Number of Accelerated Initialization Timesteps: 12
  Number of Warmup Days in Initialization: 365 # days
```

## Initialization Method

The initialization method determines how the initial temperatures in the domain are set. Options are:

- CONSTANT, spatially-constant initial temperature,

- KUSUDA, a one-dimensional analytical solution developed by that provides temperature variation as a function of depth driven by an annual harmonic temperature fluctuation. There is no temperature variation in horizontal dimensions,
- STEADY-STATE, a steady-state solution scheme initializes the temperatures with the first timestep's boundary conditions. This provides an initial condition temperature variation in all dimensions.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	CONSTANT, KUSUDA, or STEADY-STATE
<b>Default:</b>	STEADY-STATE

## Initial Temperature

When *Initialization Method* is CONSTANT this specifies the temperature to use.

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	K

## Accelerated Initialization Timestep

An accelerated initialization begins with the user-defined *Initialization Method* and calculates new domain temperatures prior to the beginning of the simulation using long timesteps (on the order of days, weeks, or months). These timesteps are calculated using a fully implicit, unconditionally stable numerical scheme. This allows the simulation to build a history of temperatures without requiring a significant amount of additional calculations. The default, one week, was found to give very accurate initial temperatures.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Units:</b>	hours
<b>Default:</b>	168

## Number of Accelerated Initialization Timesteps

This specifies the number of timesteps (of the size specified by *Accelerated Initialization Timestep*) to calculate prior to the beginning of the simulation.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Default:</b>	12

## Number of Warmup Days in Initialization

Additional days of initialization can be calculated using the *Timestep* and '**Numerical Scheme**'\_ defined by the user. This input specifies the number of days the domain is simulated under these conditions after the accelerated initialization timesteps, but prior to the *Start Date* specified in the *Simulation Control*.



<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Units:</b>	days
<b>Default:</b>	365

## 2.2.6 Numerical Settings

These are additional inputs that can be used to define the numerical approach and discretization. These inputs are largely intended for advanced research or testing purposes.

### Number of Dimensions

Switch between two- and three-dimensional simulations. **Warning:** Three-dimensional simulations can be very computationally intensive. Kiva does not impose any limitations, but be warned: some three-dimensional simulations may require more memory than most computers have available.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Constraints:</b>	2 or 3
<b>Default:</b>	2

### Coordinate System

Allows the user to specify the coordinate system used for calculations. For Three-dimensional simulations, this must be CARTESIAN.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	CARTESIAN or CYLINDRICAL
<b>Default:</b>	CARTESIAN

### Two-Dimensional Approximation

These are methods of approximating three-dimensional foundation heat transfer using a two-dimensional coordinate system. Options are:

- AP: Creates an infinite rectangle (*Coordinate System* = CARTESIAN) or a circle (*Coordinate System* = CYLINDRICAL) with the same *area-to-perimeter* ratio as the three-dimensional *Polygon*.
- RR: Creates the straight section (*Coordinate System* = CARTESIAN) or a rounded cap (*Coordinate System* = CYLINDRICAL) of a rounded rectangle with the same area and perimeter as the three-dimensional *Polygon*.
- BOUNDARY: Creates an infinite rectangle (*Coordinate System* = CARTESIAN) or a circle (*Coordinate System* = CYLINDRICAL) with an adjusted *area-to-perimeter* ratio from the three-dimensional *Polygon*. Adjustments are made to represent concave corners of the *Polygon*.
- CUSTOM: Creates an infinite rectangle (or parallel infinite rectangles) (*Coordinate System* = CARTESIAN) or a circle (or concentric circles) (*Coordinate System* = CYLINDRICAL) based on the specification of *Length 1* and *Length 2*. This is an experimental feature where the three-dimensional *Polygon* is not used directly to define the approximation.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	AP, RR, BOUNDARY, or CUSTOM
<b>Default:</b>	BOUNDARY

## Length 1

Represents the outer width of an infinite rectangle (*Coordinate System* = CARTESIAN) or outer radius of a circle (*Coordinate System* = CYLINDRICAL).

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Length 2

Represents the inner width of parallel infinite rectangles (*Coordinate System* = CARTESIAN) or inner radius of concentric circles (*Coordinate System* = CYLINDRICAL).

<b>Required:</b>	Depends
<b>Type:</b>	Numeric
<b>Units:</b>	m

## Use Symmetry

For three-dimensional simulations Kiva can detect planes of symmetry and automatically reduce the simulation domain by half (for a single plane of symmetry), or three quarters (for two planes of symmetry). If this is the case, then direction dependent boundary conditions such as incident solar and wind driven convection are averaged for the symmetric unit.

<b>Required:</b>	No
<b>Type:</b>	Boolean
<b>Default:</b>	True

## Mesh

The mesh is a compound object that defines the refinement of cells within the calculation domain. Cells are defined within four distinct region types of the domain. The region bounding the foundation wall and insulation elements defines the near-field region. All other regions are defined either laterally (interior and far-field regions) or vertically (deep-field region) relative to the near-field region.

Cells grow geometrically towards the far-field, deep-ground, and symmetry boundaries. Cells grow towards the center of each interior region and within each structural or insulation component. Example meshes are shown in the following figures.

**Example:**

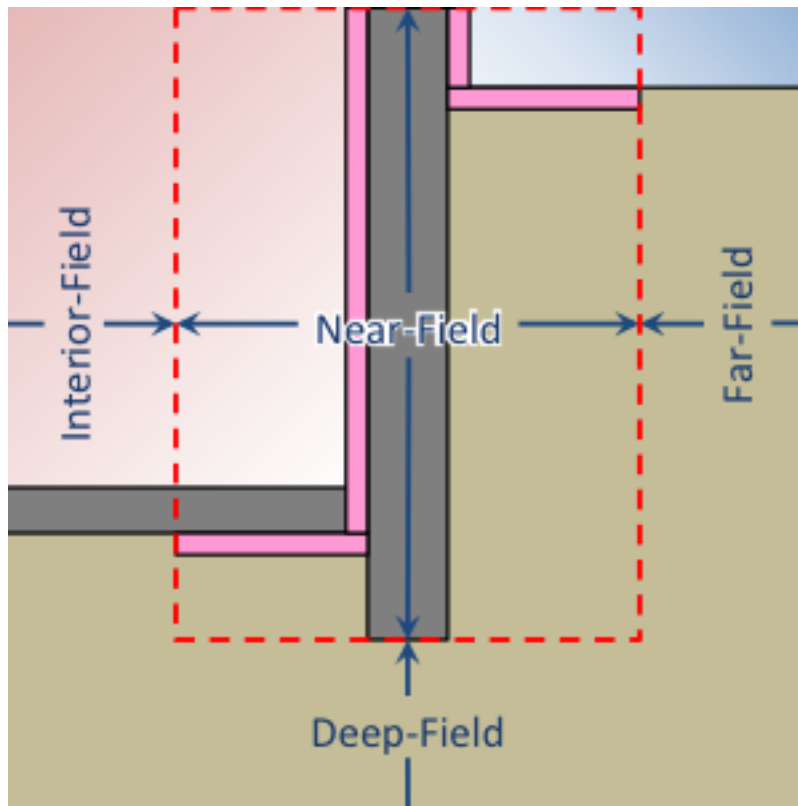


Fig. 4: Illustration of regions (profile view)

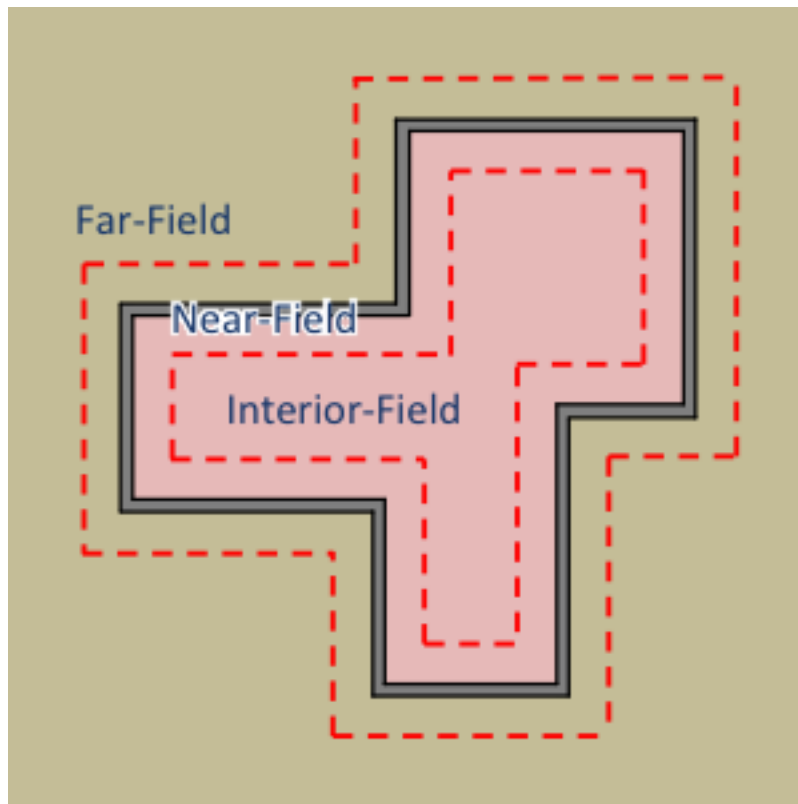


Fig. 5: Illustration of regions (plan view)

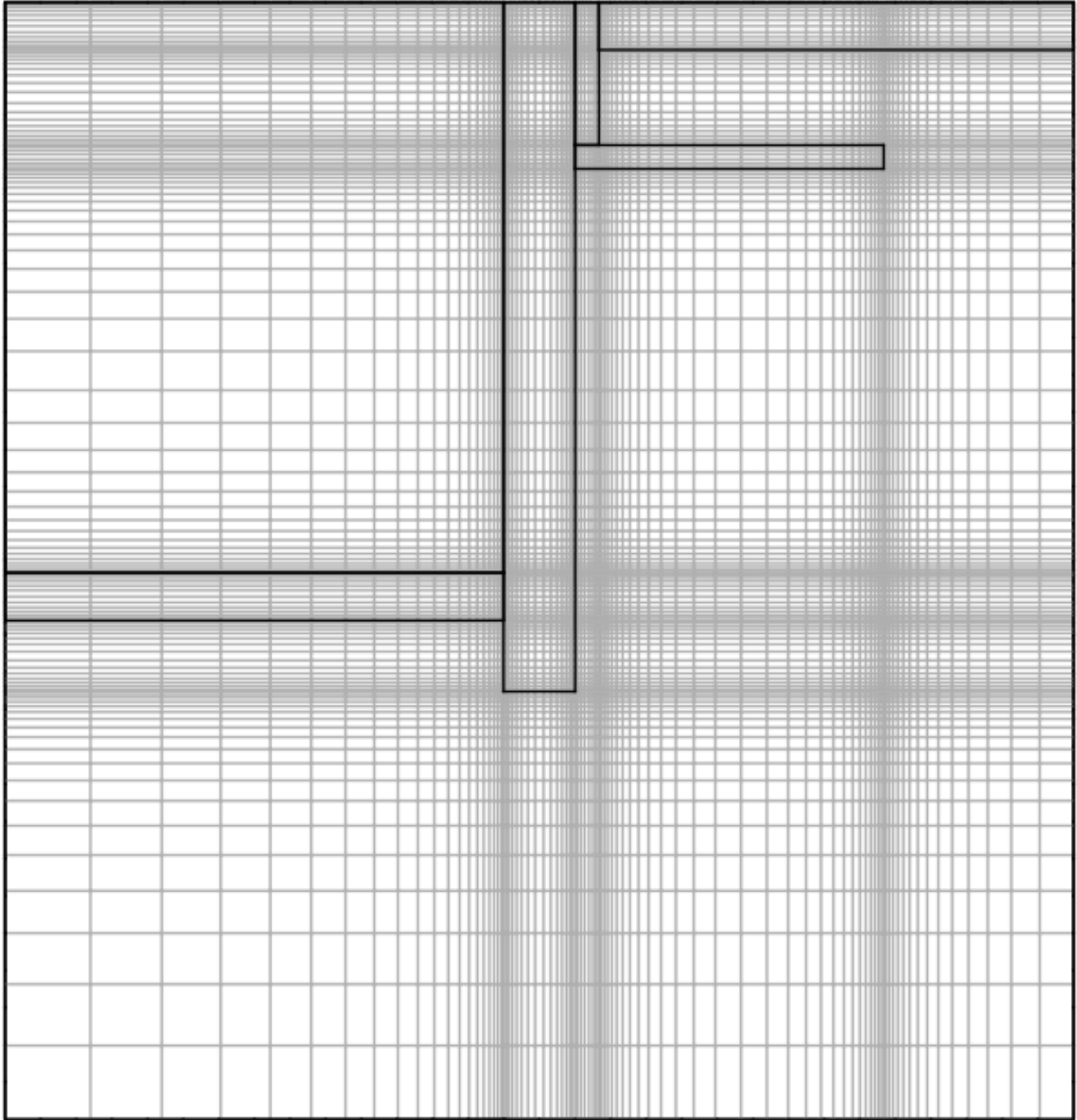


Fig. 6: Profile view of a basement mesh

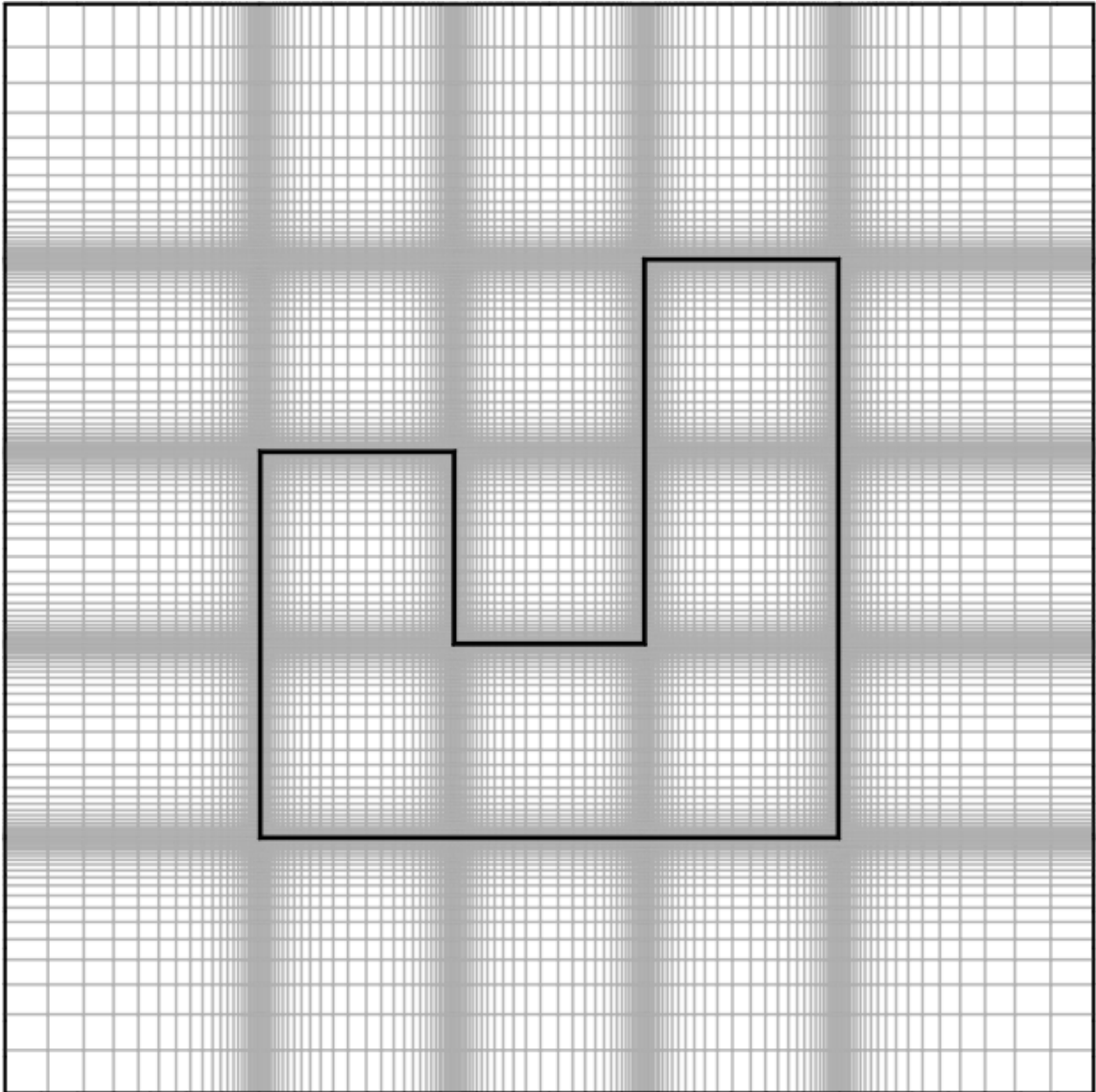


Fig. 7: Plan view of a foundation mesh

**Mesh:**

**Minimum Cell Dimension:** 0.02  
**Maximum Near-Field Growth Coefficient:** 1.5  
**Maximum Deep-Field Growth Coefficient:** 1.5  
**Maximum Interior-Field Growth Coefficient:** 1.5  
**Maximum Far-Field Growth Coefficient:** 1.5

<b>Required:</b>	No
<b>Type:</b>	Compound object

**Minimum Cell Dimension**

The minimum cell dimension defines the smallest possible dimension of a cell within the domain. This defines the allowable number of cells between element or region boundaries. The cells' dimensions are allowed to increase to fit within a component or region boundaries according to the growth and distribution of the cells.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	m
<b>Default:</b>	0.02

**Maximum Near-Field Growth Coefficient**

The maximum size increase between neighboring cells within the near-field region.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	1.5

**Maximum Deep-Field Growth Coefficient**

The maximum size increase between neighboring cells within the deep-field region.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	1.5

**Maximum Interior-Field Growth Coefficient**

The maximum size increase between neighboring cells within the interior-field region.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	1.5

## Maximum Far-Field Growth Coefficient

The maximum size increase between neighboring cells within the far-field region.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	1.5

## Numerical Scheme

This defines the numerical scheme used for calculating domain temperatures for successive timesteps. Options are:

- `IMPLICIT`, a fully implicit scheme with unconditional stability using an iterative solver,
- `EXPLICIT`, an explicit scheme with conditional stability,
- `CRANK-NICOLSON`, a partially implicit scheme with unconditional stability using an iterative solver (may exhibit oscillations),
- `ADI`, a scheme that solves each direction (X, Y, and Z) implicitly for equal sized sub-timesteps. The other two directions are solved explicitly. This allows for an exact solution of the linear system of equations without requiring an iterative solver. This scheme is extremely stable,
- `ADE`, a scheme that sweeps through the domain in multiple directions using known neighboring cell values. This scheme is very stable,
- `STEADY-STATE`, domain temperatures are calculated independently of previous timesteps using a steady-state solution from an iterative solver. This is often slower and less accurate than other methods.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	<code>IMPLICIT</code> , <code>EXPLICIT</code> , <code>CRANK-NICOLSON</code> , <code>ADI</code> , <code>ADE</code> , or <code>STEADY-STATE</code>
<b>Default:</b>	<code>ADI</code>

## f-ADI

When *Numerical Scheme* is `ADI`, this defines the weighting between the implicit, and explicit solutions in the sub-timesteps. In general, it is best to make this number very small.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	dimensionless
<b>Default:</b>	0.00001

## Maximum Iterations

Maximum number of iterations allowed in search for a solution.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Default:</b>	100000



## Tolerance

Tolerance is defined as the relative  $\ell^2$ -norm of the residual when solving the linear system of equations.

<b>Required:</b>	No
<b>Type:</b>	Numeric
<b>Units:</b>	Dimensionless
<b>Default:</b>	1.0e-6

## 2.2.7 Output

Defines what output is provided from Kiva.

**Example:**

```
Output:
Output Report:
  Minimum Reporting Frequency: 60 # [min]
  Reports:
    - 0 # Slab Core Average Heat Flux [W/m2]
    - 1 # Slab Core Average Temperature [K]
    - 2 # Slab Core Average Effective Temperature [C]
    - 3 # Slab Core Total Heat Transfer Rate [W]
    - 4 # Slab Perimeter Average Heat Flux [W/m2]
    - 5 # Slab Perimeter Average Temperature [K]
    - 6 # Slab Perimeter Average Effective Temperature [C]
    - 7 # Slab Perimeter Total Heat Transfer Rate [W]
    - 8 # Slab Average Heat Flux [W/m2]
    - 9 # Slab Average Temperature [K]
    - 10 # Slab Total Heat Transfer Rate [W]
    - 11 # Wall Average Heat Flux [W/m2]
    - 12 # Wall Average Temperature [K]
    - 13 # Wall Average Effective Temperature [C]
    - 14 # Wall Total Heat Transfer Rate [W]
    - 15 # Foundation Average Heat Flux [W/m2]
    - 16 # Foundation Average Temperature [K]
    - 17 # Foundation Total Heat Transfer Rate [W]
  Output Snapshots:
    -
      Directory: Output/Profile
      Size: 800
      Frequency: 1
      Start Date: 2015-Dec-21
      End Date: 2015-Dec-21
      X Range: [0, 30]
      Z Range: [-30, 0.3048]
```

## Output Report

The output report defines what variables are written to the CSV output file and how often they are written.

**Example:**

**Output Report:****Minimum Reporting Frequency:** 60 # [min]**Reports:**

- 0 # Slab Core Average Heat Flux [W/m2]
- 1 # Slab Core Average Temperature [K]
- 2 # Slab Core Average Effective Temperature [C]
- 3 # Slab Core Total Heat Transfer Rate [W]
- 4 # Slab Perimeter Average Heat Flux [W/m2]
- 5 # Slab Perimeter Average Temperature [K]
- 6 # Slab Perimeter Average Effective Temperature [C]
- 7 # Slab Perimeter Total Heat Transfer Rate [W]
- 8 # Slab Average Heat Flux [W/m2]
- 9 # Slab Average Temperature [K]
- 10 # Slab Total Heat Transfer Rate [W]
- 11 # Wall Average Heat Flux [W/m2]
- 12 # Wall Average Temperature [K]
- 13 # Wall Average Effective Temperature [C]
- 14 # Wall Total Heat Transfer Rate [W]
- 15 # Foundation Average Heat Flux [W/m2]
- 16 # Foundation Average Temperature [K]
- 17 # Foundation Total Heat Transfer Rate [W]

<b>Required:</b>	No
<b>Type:</b>	Compound object

**Minimum Reporting Frequency**

Kiva can provide timeseries output at the same interval as the timestep. This input will override to delay output and write it at a lower frequency. This helps to reduce the output size when running at very small timesteps.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Units:</b>	min
<b>Default:</b>	60

**Reports**

This is a list of report ID numbers that Kiva will write to the CSV output file. The IDs and their corresponding output are listed in the table below:

When **‘Perimeter Surface Width’** is not specified, the entire slab is considered to be “Core”.

“Effective Temperature” is used for preprocessed ground temperatures in whole-building simulation engines. These values represent the effective temperature on the ground’s side of the slab core, slab perimeter, or wall layers. When used in a whole-building simulation, the construction in the whole-building model should be the same as the layers defined for the respective surface in Kiva (ignoring any insulation objects).

<b>Required:</b>	No
<b>Type:</b>	List [N] of integers
<b>Default:</b>	No reports

## Output Snapshots

Output snapshots are used to graphically visualize domain temperatures and/or heat fluxes. Each series of snapshots is part of a list within the *Output Snapshots* object. A series consists of potentially many snapshots taken of a slice of the domain at a user-specified frequency between a start and end date.

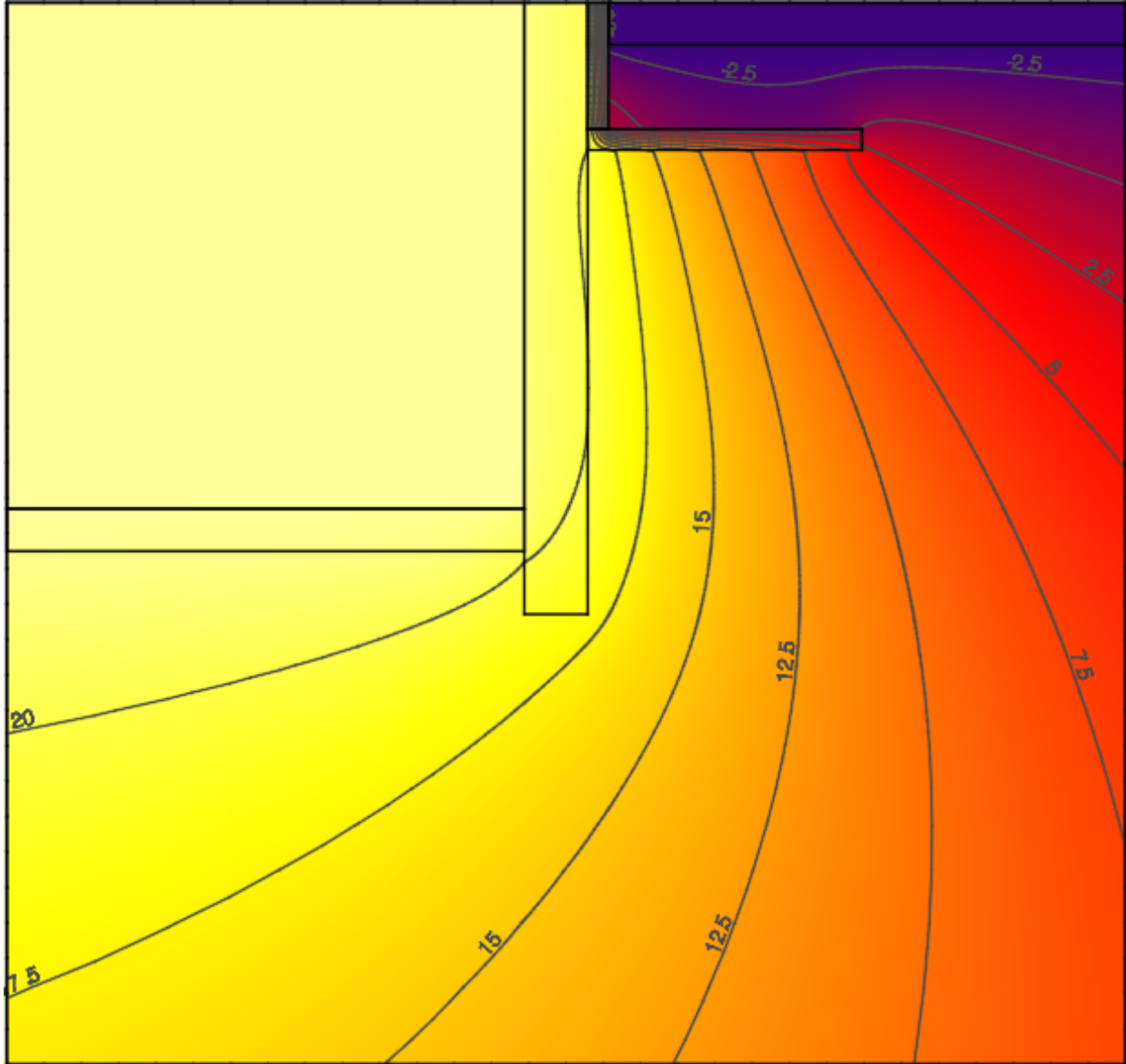


Fig. 8: Example profile snapshot

### Example:

#### Output Snapshots:

```
-  
  Directory: Output/Profile  
  Size: 800  
  Frequency: 1  
  Start Date: 2015-Dec-21
```

(continues on next page)

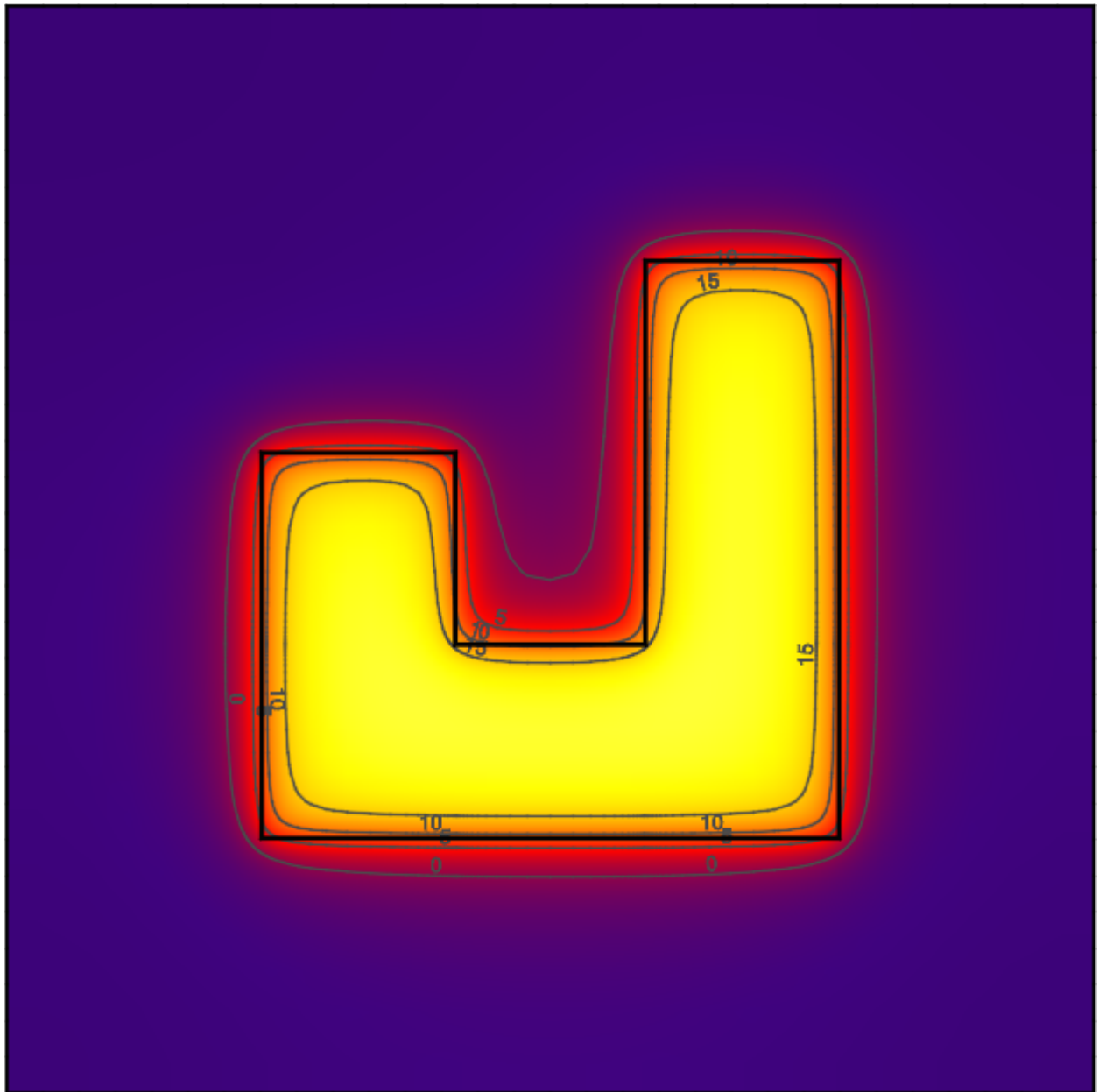


Fig. 9: Example plan snapshot

(continued from previous page)

```

End Date: 2015-Dec-21
X Range: [0, 30]
Z Range: [-30, 0.3048]

```

<b>Required:</b>	No
<b>Type:</b>	List [N] of compound objects

## Directory

Directory where snapshots are created (in same directory as the output CSV file). An ordered file name, XXXX.png, identifies each snapshot within a series. For example, the 134th snapshot in a series with a directory name of Profile will be created as Profile/0134.png.

<b>Required:</b>	Yes
<b>Type:</b>	Directory Path

## Size

The size in pixels of each snapshot file. Outputs are all generated as square images.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Units:</b>	pixels
<b>Default:</b>	800

## Frequency

The frequency, in hours, at which new snapshots are taken. The default is 36 hours so that the snapshots capture both nighttime and daytime output.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Units:</b>	hours
<b>Default:</b>	36

## Start Date

Specifies the start date of the snapshots. Snapshots begin at 12:00am of this day. This is specified as a date string (e.g., YYYY-Mon-DD, YYYY/MM/DD).

<b>Required:</b>	No
<b>Type:</b>	Date string
<b>Default:</b>	Simulation start date

## End Date

Specifies the end date of the snapshots. Snapshots end before 12:00am of the following day. This is specified as a date string (e.g., YYYY-Mon-DD, YYYY/MM/DD).

<b>Required:</b>	No
<b>Type:</b>	Date string
<b>Default:</b>	Simulation end date

## X Range

Defines the range the domain captured in the snapshot in the “X”-direction ( $[X_{min}, X_{max}]$ ). By default the *X Range* will show the entire extents of the “X” direction, and may not show the detail where heat is flowing near the foundation. For three-dimensional solutions, a slice along a plane in the “X”-direction can be specified by giving both  $X_{min}$  and  $X_{max}$  the same value.

The snapshot will round the range to the next cell division.

<b>Required:</b>	No
<b>Type:</b>	List [2] of numerics
<b>Units:</b>	m
<b>Default:</b>	“X” extents of the domain

## Y Range

Defines the range the domain captured in the snapshot in the “Y”-direction ( $[Y_{min}, Y_{max}]$ ). By default the *Y Range* will show the entire extents of the “Y” direction, and may not show the detail where heat is flowing near the foundation. For three-dimensional solutions, a slice along a plane in the “Y”-direction can be specified by giving both  $Y_{min}$  and  $Y_{max}$  the same value. For two-dimensional simulations this should not be included.

The snapshot will round the range to the next cell division.

<b>Required:</b>	No
<b>Type:</b>	List [2] of numerics
<b>Units:</b>	m
<b>Default:</b>	“Y” extents of the domain

## Z Range

Defines the range the domain captured in the snapshot in the “Z”-direction ( $[Z_{min}, Z_{max}]$ ). By default the *Z Range* will show the entire extents of the “Z” direction, and may not show the detail where heat is flowing near the foundation. For three-dimensional solutions, a slice along a plane in the “Z”-direction can be specified by giving both  $Z_{min}$  and  $Z_{max}$  the same value.

The snapshot will round the range to the next cell division.

<b>Required:</b>	No
<b>Type:</b>	List [2] of numerics
<b>Units:</b>	m
<b>Default:</b>	“Z” extents of the domain

## Plot Type

Defines the type of output plotted. Options are `TEMPERATURE` and `HEAT-FLUX`. For `HEAT-FLUX`, the user may also specify a *Flux Direction* for output.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	<code>TEMPERATURE</code> or <code>HEAT-FLUX</code>
<b>Default:</b>	<code>TEMPERATURE</code>

## Flux Direction

When *Plot Type* is `HEAT-FLUX`, the snapshots show the magnitude of heat flux throughout the domain. This input allows the user to specify whether they want to display the overall magnitude, `MAG`, or the magnitude in a given direction, `X`, `Y`, or `Z`.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	<code>MAG</code> , <code>X</code> , <code>Y</code> , or <code>Z</code>
<b>Default:</b>	<code>MAG</code>

## Unit System

Defines the units used in the output snapshots. Options are `IP` (Inch-Pound), and `SI` (International System). Keep in mind that regardless of this value, all other inputs are still defined in the `SI` unit system.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	<code>IP</code> or <code>SI</code>
<b>Default:</b>	<code>SI</code>

## Output Range

Specifies the range of output shown in the snapshots. The units of the range depend on the value of *Plot Type* and *Unit System*.

<b>Required:</b>	No
<b>Type:</b>	List [2] of numerics
<b>Units:</b>	Depends
<b>Default:</b>	<code>[-20, 40]</code>

## Color Scheme

Specifies the color scheme used within the *Output Range*. Options are:

- `CMR`, best color scheme where colors progress in brightness with magnitude (prints in black-and-white),
- `JET`, like a rainbow(!), but doesn't print well,

- NONE, do not show any output. This can be used to illustrate meshing independent of results.

<b>Required:</b>	No
<b>Type:</b>	Enumeration
<b>Values:</b>	CMR, JET, or NONE
<b>Default:</b>	CMR

## Mesh

Enables the display of the mesh (discretized cells).

<b>Required:</b>	No
<b>Type:</b>	Boolean
<b>Default:</b>	False

## Axes

Enables the display of the spatial axes, and the colorbar.

<b>Required:</b>	No
<b>Type:</b>	Boolean
<b>Default:</b>	True

## Timestamp

Enables the display of the timestamp.

<b>Required:</b>	No
<b>Type:</b>	Boolean
<b>Default:</b>	True

## Gradients

Enables the display of gradients.

<b>Required:</b>	No
<b>Type:</b>	Boolean
<b>Default:</b>	False

## Contours

Enables the display of contours.

<b>Required:</b>	No
<b>Type:</b>	Boolean
<b>Default:</b>	True



## Contour Labels

Enables the display of contour labels.

<b>Required:</b>	No
<b>Type:</b>	Boolean
<b>Default:</b>	False

## Number of Contours

Specifies the number of contours to generate between the values specified in *Output Range*.

<b>Required:</b>	No
<b>Type:</b>	Integer
<b>Default:</b>	13

## 2.3 Methodology

Coming sometime (soon?)! In the meantime, refer to Kruis (2015)<sup>1</sup>.

## 2.4 Testing

Kiva has been tested against the *International Energy Agency Building Energy Simulation Test (IEA BESTEST) in-depth diagnostic cases for ground coupled heat transfer related to slab-on-grade construction*<sup>2</sup>. The results match very closely with the analytical truth standard and the verified numerical truth standards:

**Steady-State Results:**

**Harmonic (Unsteady) Results:**

## 2.5 Bibliography

<sup>1</sup> Kruis, N. 2015. *Development and Application of a Numerical Framework for Improving Building Foundation Heat Transfer Calculations*. Ph.D. Dissertation. Department of Civil, Environmental, and Architectural Engineering. University of Colorado, Boulder.

<sup>2</sup> Neymark J., Judkoff R. 2008. *International Energy Agency Building Energy Simulation Test and Diagnostic Method ( IEA BESTEST ) : In-Depth Diagnostic Cases for Ground Coupled Heat Transfer Related to Slab-on-Grade Construction*. Technical Report September, National Renewable Energy Laboratory, Golden, Colorado.

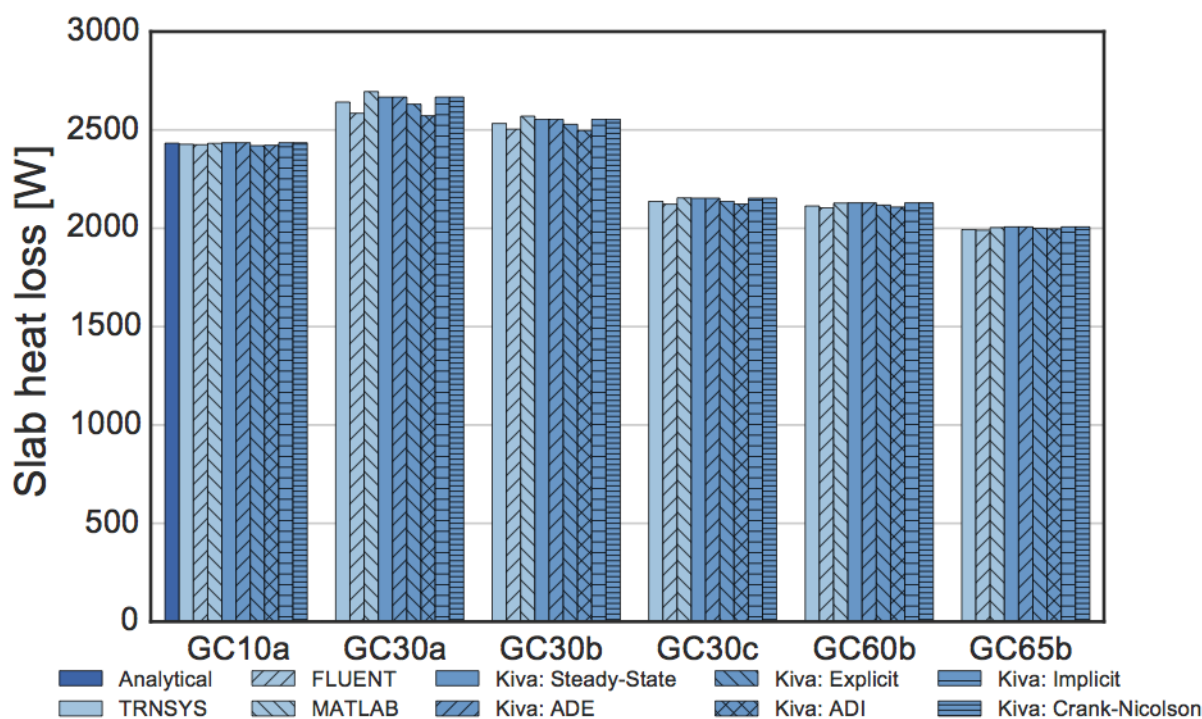


Fig. 10: IEA BESTEST Steady-State Test Case Results

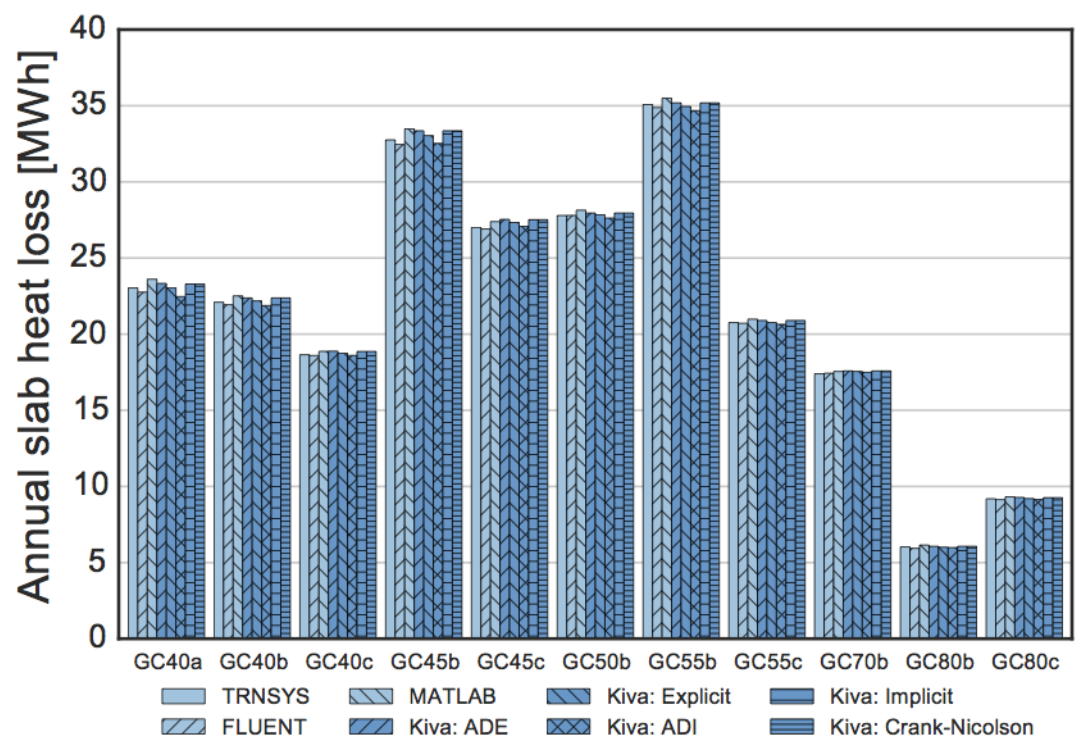


Fig. 11: IEA BESTEST Harmonic Test Case Results