

# Package ‘slopes’

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**Title** Calculate Slopes of Roads, Rivers and Trajectories

**Version** 1.0.1

**Description** Calculates the slope (longitudinal gradient or steepness) of linear geographic features such as roads (for more details, see Ariza-López et al. (2019) <[doi:10.1038/s41597-019-0147-x](https://doi.org/10.1038/s41597-019-0147-x)>) and rivers (for more details, see Cohen et al. (2018) <[doi:10.1016/j.jhydrol.2018.06.066](https://doi.org/10.1016/j.jhydrol.2018.06.066)>). It can use local Digital Elevation Model (DEM) data or download DEM data via the 'ceramic' package. The package also provides functions to add elevation data to linestrings and visualize elevation profiles.

**License** GPL-3

**URL** <https://github.com/ropensci/slopes/>,  
<https://docs.ropensci.org/slopes/>

**BugReports** <https://github.com/ropensci/slopes/issues>

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cyclestreets\_route     *A journey from CycleStreets.net*

---

## Description

Road segments representing suggested route to cycle in Leeds, UK.

## Usage

```
cyclestreets_route
```

## Format

An object of class `sf` with 18 rows and 14 columns on route characteristics. See <https://rpackage.cyclestreets.net/reference/jou> for details.

**Details**

Simple feature collection with 30 features and 32 fields

See `data-raw/cyclestreets_route.R` in the package's github repo for details.

**Source**

CycleStreets.net

**Examples**

```
library(sf)
class(cyclestreets_route)
plot(cyclestreets_route$geometry)
cyclestreets_route
```

---

dem_lisbon_raster	<i>Elevation in central Lisbon, Portugal</i>
-------------------	--

---

**Description**

A dataset containing elevation in and around Lisbon with a geographic resolution of 10m. The dataset is 200 pixels wide by 133 pixels high, covering 2.7 square kilometres of central Lisbon.

**Usage**

```
dem_lisbon_raster
```

**Format**

A raster dataset containing elevation above sea level in a 1km bounding box in Lisbon, Portugal.

**Details**

The dataset was acquired by Instituto Superior Técnico (University of Lisbon) in 2012, covers all the Northern Metropolitan Area of Lisbon, and has a 10m cell resolution, when projected at the official Portuguese EPSG: 3763 - TM06/ETRS89. The dataset was released as an open access dataset with permission from the University of Lisbon to support this project.

**Source**

<https://github.com/rspatial/terra/issues/29>

**Examples**

```

library(sf)
library(raster)
dim(dem_lisbon_raster)
res(dem_lisbon_raster)
names(dem_lisbon_raster)
plot(dem_lisbon_raster)
if (rlang::is_installed("sf")) {
  plot(lisbon_road_network["Avg_Slope"], add = TRUE)
}

```

---

elevation_add	<i>Take a linestring and add a third (z) dimension to its coordinates</i>
---------------	---

---

**Description**

Take a linestring and add a third (z) dimension to its coordinates

**Usage**

```

elevation_add(
  routes,
  dem = NULL,
  method = "bilinear",
  terra = has_terra() && methods::is(dem, "SpatRaster")
)

```

**Arguments**

routes	Routes, the gradients of which are to be calculated. The object must be of class sf or sfc with LINESTRING geometries.
dem	Raster overlapping with routes and values representing elevations
method	The method of estimating elevation at points, passed to the extract function for extracting values from raster datasets. Default: "bilinear".
terra	Should the terra package be used? TRUE by default if the package is installed <i>and</i> if dem is of class SpatRast

**Value**

An sf object that is identical to the input routes, except that the coordinate values in the output has a third z dimension representing the elevation of each vertex that defines a linear feature such as a road.

**Examples**

```

library(sf)
routes = lisbon_road_network[204, ]
dem = dem_lisbon_raster
(r3d = elevation_add(routes, dem))
library(sf)
st_z_range(routes)
st_z_range(r3d)
plot(st_coordinates(r3d)[, 3])
plot_slope(r3d)

# Get elevation data (requires internet connection and API key):
r3d_get = elevation_add(cyclestreets_route)
plot_slope(r3d_get)

```

---

elevation\_extract      *Extract elevations from coordinates*

---

**Description**

This function takes a series of points located in geographical space and a digital elevation model as inputs and returns a vector of elevation estimates associated with each point. The function takes locations represented as a matrix of XY (or longitude latitude) coordinates and a digital elevation model (DEM) with class raster or terra. It returns a vector of values representing estimates of elevation associated with each of the points.

**Usage**

```

elevation_extract(
  m,
  dem,
  method = "bilinear",
  terra = has_terra() && methods::is(dem, "SpatRaster")
)

```

**Arguments**

m	Matrix containing coordinates and elevations or an sf object representing a linear feature.
dem	Raster overlapping with routes and values representing elevations
method	The method of estimating elevation at points, passed to the extract function for extracting values from raster datasets. Default: "bilinear".
terra	Should the terra package be used? TRUE by default if the package is installed <i>and</i> if dem is of class SpatRast

## Details

By default, the elevations are estimated using **bilinear interpolation** (`method = "bilinear"`) which calculates point height based on proximity to the centroids of surrounding cells. The value of the `method` argument is passed to the `method` argument in `raster::extract()` or `terra::extract()` depending on the class of the input raster dataset.

See Kidner et al. (1999) for descriptions of alternative elevation interpolation and extrapolation algorithms.

## Value

A vector of elevation values.

## References

Kidner, David, Mark Dorey, and Derek Smith. "What's the point? Interpolation and extrapolation with a regular grid DEM." Fourth International Conference on GeoComputation, Fredericksburg, VA, USA. 1999.

## Examples

```
dem = dem_lisbon_raster
elevation_extract(lisbon_road_network[1, ], dem)
m = sf::st_coordinates(lisbon_road_network[1, ])
elevation_extract(m, dem)
elevation_extract(m, dem, method = "simple")

# Test with terra (requires internet connection):
et = terra::rast(dem_lisbon_raster)
elevation_extract(m, et)
```

---

elevation\_get

*Get elevation data from hosted maptile services*

---

## Description

`elevation_get()` uses the `cc_elevation()` function from the `ceramic` package to get DEM data in raster format anywhere worldwide. It requires an API that can be added by following guidance in the package's [README](#) and in the [slopes vignette](#).

## Usage

```
elevation_get(routes, ..., output_format = "raster")
```

## Arguments

routes	Routes, the gradients of which are to be calculated. The object must be of class sf or sfc with LINESTRING geometries.
...	Options passed to cc_elevation()
output_format	What format to return the data in? Accepts "raster" (the default) and "terra".

## Details

Note: if you use the cc\_elevation() function directly to get DEM data, you can cache the data, as described in the package's [README](#).

## Value

A raster object with cell values representing elevations in the bounding box of the input routes object.

## Examples

```
# Time-consuming examples that require an internet connection and API key:

if (rlang::is_installed("ceramic") && rlang::is_installed("sf") && rlang::is_installed("raster")) {
  library(sf)
  library(raster)
  routes = cyclestreets_route
  e = elevation_get(routes)
  class(e)
  crs(e)
  e
  plot(e)
  plot(st_geometry(routes), add = TRUE)
}
```

---

lisbon\_road\_network     *Road segments in Lisbon*

---

## Description

A dataset representing road segments in Lisbon, with X, Y and Z (elevation) dimensions for each coordinate.

## Usage

```
lisbon_road_network
```

**Format**

An object of class sf, key variables of which include

**OBJECTID** ID of the object

**Z\_Min** The minimum elevation on the linear feature from ArcMAP

**Z\_Max** The max elevation on the linear feature from ArcMAP

**Z\_Mean** The mean elevation on the linear feature from ArcMAP

**Slope\_Min** The minimum slope on the linear feature from ArcMAP

**Slope\_Max** The max slope on the linear feature from ArcMAP

**Slope\_Mean** The mean slope on the linear feature from ArcMAP

**geom** The geometry defining the LINESTRING component of the segment

**Details**

The dataset covers 32 km of roads in central Lisbon, overlapping with the area covered by the dem\_lisbon\_raster dataset.

**Source**

Produced by ESRI's 3D Analyst extension

**Examples**

```
library(sf)
names(lisbon_road_network)
sum(st_length(lisbon_road_network))
plot(lisbon_road_network["Avg_Slope"])
```

---

lisbon\_road\_segment    *A road segment in Lisbon, Portugal*

---

**Description**

A single road segment and a 3d version. Different versions of this dataset are provided.

**Usage**

```
lisbon_road_segment
```

**Format**

An object of class sf

**Details**

The lisbon\_road\_segment has 23 columns and 1 row.

The lisbon\_road\_segment\_xyz\_mapbox was created with: `lisbon_road_segment_xyz_mapbox = elevation_add(lisbon_road_segment)`.

**Source**

Produced by ESRI's 3D Analyst extension

**Examples**

```
lisbon_road_segment
lisbon_road_segment_3d
lisbon_road_segment_xyz_mapbox
```

---

lisbon_route	<i>A route composed of a single linestring in Lisbon, Portugal</i>
--------------	--

---

**Description**

A route representing a trip from the Santa Catarina area in the East of central Lisbon the map to the Castelo de São Jorge in the West of central Lisbon.

**Usage**

```
lisbon_route
```

**Format**

An object of class sf

**Details**

Different versions of this dataset are provided.

The lisbon\_route object has 1 row and 4 columns: geometry, ID, length and whether or not a path was found.

The lisbon\_route\_xyz\_mapbox was created with: `lisbon_route_xyz_mapbox = elevation_add(lisbon_route)`.

**Source**

See the lisbon\_route.R script in data-raw

**Examples**

```
lisbon_route
lisbon_route_3d
lisbon_route_xyz_mapbox
```

---

`magnolia_xy`*Road segments in Magnolia, Seattle*

---

**Description**

A dataset representing road segments in the Magnolia area of Seattle with X, Y and Z (elevation) dimensions for each coordinate.

**Usage**`magnolia_xy`**Format**

An object of class `sf`

**Source**

Accessed in early 2021 from the `seattle-streets` layer from the [data-seattlecitygis](#) website.

**Examples**

```
names(magnolia_xy)
plot(magnolia_xy["SLOPE_PCT"])
```

---

`plot_dz`*Plot a digital elevation profile based on xyz data*

---

**Description**

Plot a digital elevation profile based on xyz data

**Usage**

```
plot_dz(
  d,
  z,
  fill = TRUE,
  horiz = FALSE,
  pal = colorspace::diverging_hcl,
  ...,
  legend_position = "top",
  col = "black",
  cex = 0.9,
  bg = grDevices::rgb(1, 1, 1, 0.8),
  title = "Slope colors (percentage gradient)",
```

```

    brks = c(3, 6, 10, 20, 40, 100),
    seq_brks = NULL,
    ncol = 4
  )

```

### Arguments

d	Cumulative distance
z	Elevations at points across a linestring
fill	Should the profile be filled? TRUE by default
horiz	Should the legend be horizontal (FALSE by default)
pal	Color palette to use, <code>colorspace::diverging_hcl</code> by default.
...	Additional parameters to pass to legend
legend_position	The legend position. One of "bottomright", "bottom", "bottomleft", "left", "topleft", "top" (the default), "topright", "right" and "center".
col	Line colour, black by default
cex	Legend size, 0.9 by default
bg	Legend background colour, <code>grDevices::rgb(1, 1, 1, 0.8)</code> by default.
title	Title of the legend, "Slope colors (percentage gradient)" by default.
brks	Breaks in colour palette to show. <code>c(3, 6, 10, 20, 40, 100)</code> by default.
seq_brks	Sequence of breaks to show in legend. By default this is calculated from brks.
ncol	Number of columns in legend, 4 by default.

### Details

This function is called by `plot_slope()` but can be used directly.

### Value

A plot is created on the current graphics device.

### Examples

```

library(sf)
route_xyz = lisbon_road_segment_3d
m = st_coordinates(route_xyz)
d = cumsum(sequential_dist(m, lonlat = FALSE))
d = c(0, d)
z = m[, 3]
plot_dz(d, z, brks = c(3, 6, 10, 20, 40, 100))

```

plot\_slope

*Plot slope data for a 3d linestring with base R graphics***Description**

Plot slope data for a 3d linestring with base R graphics

**Usage**

```
plot_slope(
  route_xyz,
  lonlat = sf::st_is_longlat(route_xyz),
  fill = TRUE,
  horiz = FALSE,
  pal = colorspace::diverging_hcl,
  legend_position = "top",
  col = "black",
  cex = 0.9,
  bg = grDevices::rgb(1, 1, 1, 0.8),
  title = "Slope colors (percentage gradient)",
  brks = c(3, 6, 10, 20, 40, 100),
  seq_brks = seq(from = 3, to = length(brks) * 2 - 2),
  ncol = 4,
  ...
)
```

**Arguments**

route_xyz	An sf linestring with x, y and z coordinates, representing a route or other linear object.
lonlat	Are the routes provided in longitude/latitude coordinates? By default, value is from the CRS of the routes ( <code>sf::st_is_longlat(routes)</code> ).
fill	Should the profile be filled? TRUE by default
horiz	Should the legend be horizontal (FALSE by default)
pal	Color palette to use, <code>colorspace::diverging_hcl</code> by default.
legend_position	The legend position. One of "bottomright", "bottom", "bottomleft", "left", "topleft", "top" (the default), "topright", "right" and "center".
col	Line colour, black by default
cex	Legend size, 0.9 by default
bg	Legend background colour, <code>grDevices::rgb(1, 1, 1, 0.8)</code> by default.
title	Title of the legend, "Slope colors (percentage gradient)" by default.
brks	Breaks in colour palette to show. <code>c(3, 6, 10, 20, 40, 100)</code> by default.

seq_brks	Sequence of breaks to show in legend. Includes negative numbers and omits zero by default
ncol	Number of columns in legend, 4 by default.
...	Additional parameters to pass to legend

**Value**

A plot object is invisibly returned, and a plot is created on the current graphics device.

**Examples**

```
plot_slope(lisbon_route_3d)
route_xyz = lisbon_road_segment_3d
plot_slope(route_xyz)
plot_slope(route_xyz, brks = c(1, 2, 4, 8, 16, 30))
plot_slope(route_xyz, s = 5:8)
```

---

sequential_dist	<i>Calculate the sequential distances between sequential coordinate pairs</i>
-----------------	---

---

**Description**

Set lonlat to FALSE if you have projected data, e.g. with coordinates representing distance in meters, not degrees. Lonlat coordinates are assumed (lonlat = TRUE is the default).

**Usage**

```
sequential_dist(m, lonlat = TRUE)
```

**Arguments**

m	Matrix containing coordinates and elevations. The matrix should have three columns: x, y, and z, in that order. Typically these correspond to location in the West-East, South-North, and vertical elevation axes respectively. In data with geographic coordinates, Z values are assumed to be in metres. In data with projected coordinates, Z values are assumed to have the same units as the X and Y coordinates.
lonlat	Are the coordinates in lon/lat (geographic) coordinates? TRUE by default.

**Value**

A vector of distance values in meters if lonlat = TRUE or the map units of the input data if lonlat = FALSE between consecutive vertices.

**Examples**

```
x = c(0, 2, 3, 4, 5, 9)
y = c(0, 0, 0, 0, 0, 1)
m = cbind(x, y)
d = sequential_dist(m, lonlat = FALSE)
d
nrow(m)
length(d)
```

---

slope_matrix	<i>Calculate the gradient of line segments from a 3D matrix of coordinates</i>
--------------	--

---

**Description**

Calculate the gradient of line segments from a 3D matrix of coordinates

**Usage**

```
slope_matrix(m, elevations = m[, 3], lonlat = TRUE)

slope_matrix_mean(m, elevations = m[, 3], lonlat = TRUE, directed = FALSE)

slope_matrix_weighted(m, elevations = m[, 3], lonlat = TRUE, directed = FALSE)
```

**Arguments**

m	Matrix containing coordinates and elevations. The matrix should have three columns: x, y, and z, in that order. Typically these correspond to location in the West-East, South-North, and vertical elevation axes respectively. In data with geographic coordinates, Z values are assumed to be in metres. In data with projected coordinates, Z values are assumed to have the same units as the X and Y coordinates.
elevations	Elevations in same units as x (assumed to be metres). Default value: m[, 3], meaning the 'z' coordinate in a matrix of coordinates.
lonlat	Are the coordinates in lon/lat (geographic) coordinates? TRUE by default.
directed	Should the value be directed? FALSE by default. If TRUE the result will be negative when it represents a downslope (when the end point is lower than the start point).

**Value**

A vector of slope gradients associated with each linear element (each line between consecutive vertices) associated with linear features. Returned values for `slope_matrix_mean()` and `slope_matrix_weighted()` are summary statistics for all linear elements in the linestring. The output value is a proportion representing the change in elevation for a given change in horizontal movement along the linestring. 0.02, for example, represents a low gradient of 2% while 0.08 represents a steep gradient of 8%.

**Examples**

```

x = c(0, 2, 3, 4, 5, 9)
y = c(0, 0, 0, 0, 0, 9)
z = c(1, 2, 2, 4, 3, 0) / 10
m = cbind(x, y, z)
slope_matrix_weighted(m, lonlat = FALSE)
slope_matrix_weighted(m, lonlat = FALSE, directed = TRUE)
# 0 value returned if no change in elevation:
slope_matrix_weighted(m,lonlat = FALSE, directed = TRUE,
  elevations = c(1, 2, 2, 4, 3, 1))
slope_matrix_mean(m, lonlat = FALSE)
slope_matrix_mean(m, lonlat = FALSE, directed = TRUE)
plot(x, z, ylim = c(-0.5, 0.5), type = "l")
(gx = slope_vector(x, z))
(gxy = slope_matrix(m, lonlat = FALSE))
abline(h = 0, lty = 2)
points(x[-length(x)], gx, col = "red")
points(x[-length(x)], gxy, col = "blue")
title("Distance (in x coordinates) elevation profile",
  sub = "Points show calculated gradients of subsequent lines")

```

slope\_raster

*Calculate the gradient of line segments from a raster dataset***Description**

This function takes an `sf` representing routes over geographical space and a raster dataset representing the terrain as inputs. It returns the average gradient of each route feature.

**Usage**

```

slope_raster(
  routes,
  dem,
  lonlat = sf::st_is_longlat(routes),
  method = "bilinear",
  fun = slope_matrix_weighted,
  terra = has_terra() && methods::is(dem, "SpatRaster"),
  directed = FALSE
)

```

**Arguments**

routes	Routes, the gradients of which are to be calculated. The object must be of class <code>sf</code> or <code>sfc</code> with <code>LINestring</code> geometries.
dem	Raster overlapping with routes and values representing elevations
lonlat	Are the routes provided in longitude/latitude coordinates? By default, value is from the CRS of the routes ( <code>sf::st_is_longlat(routes)</code> ).

method	The method of estimating elevation at points, passed to the extract function for extracting values from raster datasets. Default: "bilinear".
fun	The slope function to calculate per route, slope_matrix_weighted by default.
terra	Should the terra package be used? TRUE by default if the package is installed <i>and</i> if dem is of class SpatRast
directed	Should the value be directed? FALSE by default. If TRUE the result will be negative when it represents a downslope (when the end point is lower than the start point).

### Details

If calculating slopes associated with OSM data, the results may be better if the network is first split-up, e.g. using the function `stplanr::rnet_breakup_vertices()` from the `stplanr` package. **Note:** The routes object must have a geometry type of LINESTRING. The `sf::st_cast()` function can convert from MULTILINESTRING (and other) geometries to LINESTRINGs as follows: `r_linestring = sf::st_cast(routes, "LINESTRING")`.

### Value

A vector of slopes equal in length to the number simple features (rows representing linestrings) in the input object.

### Examples

```
library(sf)
routes = lisbon_road_network[1:3, ]
dem = dem_lisbon_raster
(s = slope_raster(routes, dem))
cor(routes$Avg_Slope, s)
slope_raster(routes, dem, directed = TRUE)
# Demonstrate that reverse routes have the opposite directed slope
slope_raster(st_reverse(routes), dem, directed = TRUE)
```

---

slope_vector	<i>Calculate the gradient of line segments from distance and elevation vectors</i>
--------------	--

---

### Description

`slope_vector()` calculates the slopes associated with consecutive elements in one dimensional distance and associated elevations (see examples).

`slope_distance()` calculates the slopes associated with consecutive distances and elevations.

`slope_distance_mean()` calculates the mean average slopes associated with consecutive distances and elevations.

`slope_distance_weighted()` calculates the slopes associated with consecutive distances and elevations, with the mean value associated with each set of distance/elevation vectors weighted in proportion to the distance between each elevation measurement, so longer sections have proportionally more influence on the resulting gradient estimate (see examples).

**Usage**

```
slope_vector(x, elevations)

slope_distance(d, elevations)

slope_distance_mean(d, elevations, directed = FALSE)

slope_distance_weighted(d, elevations, directed = FALSE)
```

**Arguments**

x	Vector of locations
elevations	Elevations in same units as x (assumed to be metres)
d	Vector of distances between points
directed	Should the value be directed? FALSE by default. If TRUE the result will be negative when it represents a downslope (when the end point is lower than the start point).

**Value**

A vector of slope gradients associated with each linear element (each line between consecutive vertices) associated with linear features. Returned values for `slope_distance_mean()` and `slope_distance_mean_weighted()` are summary statistics for all linear elements in the linestring. The output value is a proportion representing the change in elevation for a given change in horizontal movement along the linestring. 0.02, for example, represents a low gradient of 2% while 0.08 represents a steep gradient of 8%.

**Examples**

```
x = c(0, 2, 3, 4, 5, 9)
elevations = c(1, 2, 2, 4, 3, 0) / 10 # downward slope overall
slope_vector(x, elevations)
library(sf)
m = st_coordinates(lisbon_road_segment)
d = sequential_dist(m, lonlat = FALSE)
elevations = elevation_extract(m, dem_lisbon_raster)
slope_distance(d, elevations)
slope_distance_mean(d, elevations)
slope_distance_mean(d, elevations, directed = TRUE)
slope_distance_mean(rev(d), rev(elevations), directed = TRUE)
slope_distance_weighted(d, elevations)
slope_distance_weighted(d, elevations, directed = TRUE)
```

slope\_xyz

*Extract slopes from xyz data frame or sf objects***Description**

The function takes a sf object with 'XYZ' coordinates and returns a vector of numeric values representing the average slope of each linestring in the sf data frame input.

**Usage**

```
slope_xyz(
  route_xyz,
  fun = slope_matrix_weighted,
  lonlat = TRUE,
  directed = FALSE
)
```

**Arguments**

route_xyz	An sf or sfc object with XYZ coordinate dimensions
fun	The slope function to calculate per route, slope_matrix_weighted by default.
lonlat	Are the coordinates in lon/lat order? TRUE by default
directed	Should the value be directed? FALSE by default. If TRUE the result will be negative when it represents a downslope (when the end point is lower than the start point).

**Details**

The default function to calculate the mean slope is slope\_matrix\_weighted(). You can also use slope\_matrix\_mean() from the package or any other function that takes the same inputs as these functions not in the package.

**Value**

A vector of slopes equal in length to the number simple features (rows representing linestrings) in the input object.

**Examples**

```
route_xyz = lisbon_road_segment_3d
slope_xyz(route_xyz, lonlat = FALSE)
slope_xyz(route_xyz$geom, lonlat = FALSE)
slope_xyz(route_xyz, lonlat = FALSE, directed = TRUE)
slope_xyz(route_xyz, lonlat = FALSE, fun = slope_matrix_mean)
```

---

z_value	<i>Calculate summary values for 'Z' elevation attributes</i>
---------	--

---

**Description**

The `slope_z*`(`x`) functions calculate summary values for the Z axis in sfc objects with XYZ geometries.

**Usage**

`z_value(x)`

`z_start(x)`

`z_end(x)`

`z_mean(x)`

`z_max(x)`

`z_min(x)`

`z_elevation_change_start_end(x)`

`z_direction(x)`

`z_cumulative_difference(x)`

**Arguments**

`x` An sfc object with 'XYZ' coordinates

**Value**

A vector of numeric values representing elevations associated with simple feature geometries that have elevations (XYZ coordinates).

A numeric vector of length 1 representing the first Z coordinate.

A numeric vector of length 1 representing the last Z coordinate.

A numeric vector of length 1 representing the mean of Z coordinates.

A numeric vector of length 1 representing the maximum of Z coordinates.

A numeric vector of length 1 representing the minimum of Z coordinates.

A numeric vector of length 1 representing the difference between the last and first Z coordinates.

A numeric vector of length 1 representing the sign of the difference between the last and first Z coordinates.

A numeric vector of length 1 representing the sum of absolute differences between consecutive Z coordinates.

**Examples**

```
if (rlang::is_installed("sf")) {  
  x = slopes::lisbon_route_3d  
  x  
  z_value(x)[1:5]  
  xy = slopes::lisbon_route  
  try(z_value(xy)) # error message  
  z_start(x)  
  z_end(x)  
  z_direction(x)  
  z_elevation_change_start_end(x)  
  z_direction(x)  
  z_cumulative_difference(x)  
}
```

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