Package ‘kitagawa’

June 24, 2020

Type Package

Title Spectral Response of Water Wells to Harmonic Strain and Pressure Signals

Version 3.1.0

Date 2020-06-21

Description Provides tools to calculate the theoretical hydrodynamic response of an aquifer undergoing harmonic straining or pressurization, or analyze measured responses. There are
two classes of models here, designed for use with confined
aquifers: (1) for sealed wells, based on the model of
Kitagawa et al (2011, <doi:10.1029/2010JB007794>),
and (2) for open wells, based on the models of
Cooper et al (1965, <doi:10.1029/JZ070i016p03915>),
Hsieh et al (1987, <doi:10.1029/WR023i010p01824>),
Rojstaczer (1988, <doi:10.1029/JB093iB11p13619>),
Liu et al (1989, <doi:10.1029/JB094iB07p09453>), and
Wang et al (2018, <doi:10.1029/2018WR022793>). Wang's
solution is a special exception which
allows for leakage out of the aquifer
(semi-confined); it is equivalent to Hsieh's model
when there is no leakage (the confined case).
These models treat strain (or aquifer head) as an input to the
physical system, and fluid-pressure (or water height) as the output. The applicable frequency band of these models is characteristic of seismic waves, atmospheric pressure fluctuations, and solid earth tides.

License GPL (>= 2)

URL https://github.com/abarbour/kitagawa

BugReports https://github.com/abarbour/kitagawa/issues

Depends R (>= 2.10.1), stats

Imports Bessel, kelvin (>= 1.2.0), psd (>= 2.0.0)

Suggests dplyr, tibble, RColorBrewer, signal, testthat, knitr, rmarkdown, formatR, covr

VignetteBuilder knitr

Encoding UTF-8

RoxygenNote 7.1.0

NeedsCompilation no

Author Andrew J. Barbour [aut, cre] (<https://orcid.org/0000-0002-6890-2452>),
Jonathan Kennel [ctb] (<https://orcid.org/0000-0003-4474-6886>)

Maintainer Andrew J. Barbour `<andy.barbour@gmail.com>`

Repository CRAN

Date/Publication 2020-06-24 08:40:13 UTC

R topics documented:

`kitagawa-package` *Spectral Response of Water Wells to Harmonic Strain and Pressure Signals*

Description

Provides tools to calculate the theoretical hydrodynamic response of an aquifer undergoing harmonic straining or pressurization. There are two classes of models here: (1) for sealed wells, based on the model of Kitagawa et al (2011), and (2) for open wells, based on the models of Cooper et al (1965), Hsieh et al (1987), Rojstaczer (1988), Liu et al (1989), and Wang et al (2018). These models treat strain (or aquifer head) as an input to the physical system, and fluid-pressure (or water height) as the output. The applicable frequency band of these models is characteristic of seismic waves, atmospheric pressure fluctuations, and solid earth tides. The Wang et al (2018) can explicitly model vertical leakage.

Details

The following functions provide the primary features of the package:

`well_response` and `open_well_response`, which take in arguments for well- and aquifer-parameters, and the frequencies at which to calculate the response functions. They both access the constants-calculation routines as necessary, meaning the user need not worry about those functions (e.g., `alpha_constants`).

Helper functions:

`sensing_volume` can be used to compute the sensing volume of fluid, for the specified well dimensions.

Scientific background

The underlying model is based upon the assumption that fluid flows radially through an homogeneous, isotropic, confined aquifer.

The underlying principle is as follows. When a harmonic wave induces strain in a confined aquifer (one having aquitards above and below it), fluid flows radially into, and out of a well penetrating the aquifer. The flow-induced drawdown, s, is governed by the following partial differential equation, expressed in radial coordinates(r):

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} - \frac{S}{T}\frac{\partial s}{\partial t} = 0$$

where S, T are the aquifer storativity and transmissivity respectively.

The solution to this PDE, with periodic discharge boundary conditions, gives the amplitude and phase response we wish to calculate. The solution for an open well was presented by Cooper et al (1965), and subsequently modified by Liu et al (1989). Wang et al (2018) modified this solution for the leaky aquifer case. Kitagawa et al (2011) adapted the solution of Hsieh et al (1987) for the case of a sealed well. When there is no leakage, Wang et al (2018) is equivalent to Hsieh et al (1987).

These models are applicable to any quasi-static process involving harmonic, volumetric strain of an aquifer (e.g. passing Rayleigh waves, or changes in the Earth's tidal potential). In practice, however, the presence of permeable fractures can violate the assumption of isotropic permeability, which may substantially alter the response by introducing shear-strain coupling. But these complications are beyond the scope of this model.

Author(s)

Andrew J. Barbour <andy.barbour@gmail.com> with contributions from Jonathan Kennel

References

Abramowitz, M. and Stegun, I. A. (Eds.). "Kelvin Functions." §9.9 in Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, 9th printing. New York: Dover, pp. 379-381, 1972.

Cooper, H. H., Bredehoeft, J. D., Papadopulos, I. S., and Bennett, R. R. (1965), The response of well-aquifer systems to seismic waves, *J. Geophys. Res.*, **70** (16)

Hsieh, P. A., J. D. Bredehoeft, and J. M. Farr (1987), Determination of aquifer transmissivity from Earth tide analysis, *Water Resour. Res.*, **23** (10)

Kitagawa, Y., S. Itaba, N. Matsumoto, and N. Koisumi (2011), Frequency characteristics of the response of water pressure in a closed well to volumetric strain in the high-frequency domain, *J. Geophys. Res.*, **116**, B08301

Liu, L.-B., Roeloffs, E., and Zheng, X.-Y. (1989), Seismically Induced Water Level Fluctuations in the Wali Well, Beijing, China, *J. Geophys. Res.*, **94** (B7)

Roeloffs, E. (1996), Poroelastic techniques in the study of earthquake-related hydrologic phenomena, *Advances in Geophysics*, **37**

Wang C.-Y., Doan, M.-L., Xue, L., Barbour, A. (2018), Tidal Response of Groundwater in a Leaky Aquifer—Application to Oklahoma, *Water Resour. Res.*, **54** (10)

See Also

`open_well_response`, `well_response`, `sensing_volume`, `wrsp-methods`

`alpha_constants` *Calculate any constants depending on effective stress coefficient α*

Description

This function accesses the appropriate method to calculate the α-dependent constant associated with the choice of `c.type`. There are currently four such constants, which correspond to **Equations 10, 11, 18, 19** in Kitagawa et al (2011).

This function is not likely to be needed by the user.

Usage

```
alpha_constants(alpha = 0, c.type = c("Phi", "Psi", "A", "Kel"))

## Default S3 method:
alpha_constants(alpha = 0, c.type = c("Phi", "Psi", "A", "Kel"))
```

Arguments

`alpha`	the constant alpha (see `omega_constants`)
`c.type`	the constant to calculate

Details

What is `"alpha"`?: The constant α is a function of frequency ω as well as aquifer and well parameters; it is formally defined as

$$\alpha \equiv R_S \sqrt{\omega S/T}$$

where S is the storativity, T is the aquifer's effective transmissivity, and R_S is the radius of the screened portion of the well.

What is calculated?: The various constants which may be calculated with this function are

`Phi`	Given as Φ in Eqn. 10
`Psi`	Given as Ψ in Eqn. 11
`A`	Given as $A_i, i = 1, 2$ in Eqns. 18, 19
`Kel`	The complex Kelvin functions (see Abramowitz and Stegun, 1972)

Value

Complex matrix having values representing the constant represented by `c.type`, *as well as* any other α-dependent constants which are needed in the computation.

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

See Also

`omega_constants`, `well_response`

Other ConstantsCalculators: `kitagawa-constants`, `omega_constants()`

Examples

```
alpha_constants()   # kelvin::Keir gives warning
alpha_constants(1)  # defaults to constant 'Phi' (note output also has Kel)
alpha_constants(1:10, c.type="A")  # constant 'A' (again, note output)
```

`cross_spectrum` *Calculate the cross-spectrum of two timeseries*

Description

Calculate the cross-spectrum of two timeseries

Usage

```
cross_spectrum(x, ...)

## S3 method for class 'mts'
cross_spectrum(x, ...)

## Default S3 method:
cross_spectrum(
  x,
  y,
  k = 10,
  samp = 1,
  q,
  adaptive = FALSE,
```

```
  verbose = FALSE,
  ...
)
```

Arguments

`x`	numeric; timeseries
`...`	additional arguments to `pspectrum`
`y`	numeric; timeseries. if missing, assumed to be column no. 2 in `x`
`k`	integer; the number of sine tapers, unless this is `NULL`; in the latter case a Welch-based spectrum is calculated rather than a multitaper spectrum. There are distinct advantages and disadvantages to either of these.
`samp`	numeric; the sampling rate (e.g., `deltat`) of the data; must be the same for `x` and `y`
`q`	numeric; the probability quantile [0,1] to calculate coherence significance levels; if missing, a pre-specified sequence is included. This is will be ignored for Welch-based spectra (see `k`).
`adaptive`	logical; should adaptive multitaper estimation be used?
`verbose`	logical; should messages be printed?

Examples

```
require(stats)
require(psd)

n <- 1000
ramp <- seq_len(n)
parab <- ramp^2

set.seed(1255)
X <- ts(rnorm(n) + ramp/2)
Y <- ts(rnorm(n) + ramp/10 + parab/100)

# Calculate the multitaper cross spectrum
csd <- cross_spectrum(X, Y, k=20)
```

`kitagawa-constants` *Access to constants used by default*

Description

The response of an aquifer depends on its mechanical and hydrological properties; if these are not known or specified, these constants are used.

Usage

```
constants(do.str = TRUE)
```

Arguments

`do.str`	logical; should the structure be printed?

Details

The function `constants` shows the structure of (optionally), and returns the assumed constants, which do *not* reside in the namespace.

Values:

For water: Density and bulk modulus

Gravity: Standard gravitational acceleration at 6371km radius (Earth)

Conversions: Degrees to radians

Value

The constants, invisibly.

See Also

`well_response` and `open_well_response`

`kitagawa-package`

Other ConstantsCalculators: `alpha_constants()`, `omega_constants()`

Examples

```
constants()
constants(FALSE) # returns invisibly
```

`kitagawa-utilities` *General utility functions*

Description

General utility functions

Usage

```
.nullchk(X)

.in0to1(X)

is.wrsp(X)

is.owrsp(X)
```

Arguments

`X`	something to be checked (vector, scalar, wrsp object, ...)

Details

`.nullchk` quickly checks for `NULL` and `NA`, and raises an error if `TRUE`; *This function is not likely to be needed by the user.*

`.in0to1` checks if values are numeric and in [0,1] (inclusive).

`is.wrsp` and `is.owrsp` report whether an object has S3 class 'wrsp' or 'owrsp', respectively. Such an object would be returned by, for example, `well_response`.

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

See Also

`kitagawa-package`

Examples

```
## Not run:
.nullchk(1:10) # OK
.nullchk(NULL) # error
.nullchk(c(1:10,NULL)) # error
.nullchk(NA) # error
.nullchk(c(1:10,NA)) # error

.in0to1(1:10) # error
.in0to1(NULL) # error
.in0to1(c(1:10,NULL)) # error
.in0to1(NA) # error
.in0to1(c(1:10,NA)) # error
.in0to1(c(1,NA)) # error

is.wrsp(1) # FALSE

## End(Not run)
```

`logsmoo` *Logarithmic smoothing with loess*

Description

Logarithmic smoothing with loess

Usage

```
logsmoo(x, y, x.is.log = FALSE, ...)
```

Arguments

`x`	numeric; the index series (cannot contain `NA`)
`y`	numeric; the series of values associated with `x`
`x.is.log`	logical; determines whether the series in `x` has been log-transformed already. If `FALSE` then `log10` is used.
`...`	additional parameters (e.g., `span`) passed to `loess.smooth`

Value

The result of `loess.smooth`

References

Barbour, A. J., and D. C. Agnew (2011), Noise levels on Plate Boundary Observatory borehole strainmeters in southern California, Bulletin of the Seismological Society of America, 101(5), 2453-2466, doi: 10.1785/0120110062

See Also

`loess.smooth` and `approxfun`

Examples

```
set.seed(11133)
n <- 101
lx <- seq(-1,1,length.out=n)
y <- rnorm(n) + cumsum(rnorm(n))
plot(lx, y, col='grey')
lines(logsmoo(lx, y, x.is.log=TRUE))
```

`logticks` *Add proper logarithm ticks to a plot axis.*

Description

Add proper logarithm ticks to a plot axis.

Usage

```
logticks(
  ax = 1,
  n.minor = 9,
  t.lims,
  t.ratio = 0.5,
  major.ticks = NULL,
  base = c("ten", "ln", "two"),
```

```
  ...
)

log_ticks(...)

log2_ticks(...)

log10_ticks(...)
```

Arguments

`ax`	numeric; the axis number to add tick-marks to
`n.minor`	numeric; the number of minor ticks to display
`t.lims`	numeric; the upper and lower tick limits (in log space)
`t.ratio`	numeric; the ratio of minor to major tick lengths.
`major.ticks`	numeric; the axis limits.
`base`	numeric; the base of the logarithm (somewhat experimental)
`...`	additional parameters passed to the `axis` call for the major ticks.

Details

This uses `pretty` with `n==5`, and assumes that the data along the axis `ax` has *already* been transformed into its logarithm. *Only integer exponents are labeled.*

The functions `log_ticks`, `log2_ticks`, and `log10_ticks` are wrapper functions.

Set the `axt` parameter (e.g. `xaxt`) to `'n'` in the original plot command to prevent adding default tick marks.

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

References

This was modified from a post on StackOverflow: `http://stackoverflow.com/questions/6955440/displaying-minor-logarithmic-ticks-in-x-axis-in-r`

See Also

Other PlotUtilities: `wrsp-methods`

Examples

```
x <- 10^(0:8)
y <- 1:9
plot(log10(x),y,xaxt="n",xlab="x",xlim=c(0,9))
logticks()
```

`omega_constants` *Calculate any constants that depend on angular frequency ω*

Description

This function accesses the appropriate method to calculate the ω-dependent constant associated with the choice of `c.type`.

This function is not likely to be needed by the user.

Usage

```
omega_constants(omega = 0, c.type = c("alpha", "diffusivity_time"), ...)

## Default S3 method:
omega_constants(omega = 0, c.type = c("alpha", "diffusivity_time"), ...)
```

Arguments

`omega`	frequency, $[rad/sec]$
`c.type`	the constant to calculate
`...`	additional params passed to calculator. In the case of `ctype="alpha"`, set `S.`,`T.`,`Rs.`; and, in the case of `ctype="diffusivity_time"`, set `D.` or `S.`,`T.`.

Details

What is `"omega"`?: The name is in reference to radial frequency ω, which is defined as

$$\omega \equiv 2\pi/\tau$$

where τ is the period of oscillation.

What is the `"alpha"` calculation?:
The parameter α is defined as

$$\alpha \equiv r_w \sqrt{\omega S/T}$$

where r_w is the radius of the well, where S is the storativity, and T is transmissivity. See the parameter ... for details on how to pass these values.

This definition is common to many papers on the topic. For example, it corresponds to **Equation 12** in Kitagawa et al (2011). Because the computation of α depends also on physical properties, additional parameters can be passed through (e.g. the transmissivity).

What is the `"diffusivity_time"` calculation?: This is a similar calculation to `omega_norm`. It uses the effective hydraulic diffusivity D, which is defined in this case as the ratio of transmissivity to storativity:

$$D \equiv \frac{T}{S}$$

Value

Values of the constant represented by `c.type` for the given parameters

Warnings Issued

In the case `c.type='alpha'`, the parameters `S.`, `T.`, and `Rs.` should be passed; otherwise, values are assumed to ensure the calculation does not fail, and the results are essentially meaningless.

Warnings will be issued if any necessary parameters are missing, indicating default values were used.

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

See Also

`alpha_constants`, `well_response`, and `kitagawa-package` for references and more background.

Other ConstantsCalculators: `alpha_constants()`, `kitagawa-constants`

Examples

```
# alpha
omega_constants() # default is alpha, but will give warnings about S., T., Rs.
omega_constants(T.=1,S.=1,Rs.=1)  # 0, no warnings
omega_constants(1:10)  # sequence, with warnings about S., T., Rs.
omega_constants(1:10,T.=1,S.=1,Rs.=1) # sequence, no warnings
# diffusivity time
omega_constants(c.type="diffusivity_time", D.=1)  # 0, no warnings
omega_constants(c.type="diff", D.=1)  # 0, no warnings (arg matching)
omega_constants(c.type="diff")  # 0, warnings about S., T. because no D.
omega_constants(c.type="diff", S.=1)  # 0, warnings about T. because no D. or S.
```

`omega_norm` *Dimensionless frequency from diffusivity and depth*

Description

Dimensionless frequency from diffusivity and depth

Usage

```
omega_norm(omega, Diffusiv, z, invert = FALSE)
```

Arguments

`omega`	numeric; angular frequency
`Diffusiv`	numeric; hydraulic diffusivity
`z`	numeric; depth
`invert`	logical; should omega be taken as normalized frequency?

Details

Dimensionless frequency Q is defined as

$$Q = \frac{z^2\omega}{2D}$$

where z is the well depth, ω is the angular frequency and D is the hydraulic diffusivity.

Value

`omega_norm` returns dimensionless frequency, unless `invert=TRUE` where it will assume `omega` is dimensionless frequency, and return radial frequency.

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

See Also

`open_well_response`, `kitagawa-package`

Other utilities: `sensing_volume()`

`open_well_response` *Spectral response for an open well*

Description

This is the primary function to calculate the response for an open (exposed to air) well.

Usage

```
open_well_response(omega, T., S., ...)

## Default S3 method:
open_well_response(
  omega,
  T.,
  S.,
  Rs. = (8/12) * (1200/3937),
  rho,
  grav,
  z,
  Hw,
  Ta,
  leak,
  freq.units = c("rad_per_sec", "Hz"),
  model = c("rojstaczer", "liu", "cooper", "hsieh", "wang"),
  as.pressure = TRUE,
  ...
)
```

Arguments

`omega`	numeric; frequency, (see `freq.units`)
`T.`	numeric; effective aquifer transmissivity $[m^2/s]$
`S.`	numeric; well storativity, $[unitless]$
`...`	additional arguments
`Rs.`	numeric; the *radius* of the open (screened) section
`rho`	numeric; fluid density (assumed if missing)
`grav`	numeric; the local gravitational acceleration (assumed if missing)
`z`	numeric; From Rojstaczer (1988): the depth from the water table (assumed if missing and if needed)
`Hw`	numeric; height of water column above confined surface (assumed if missing and if needed)
`Ta`	numeric; thickness of aquifer (assumed if missing and if needed)
`leak`	numeric; specific leakage K'/b' $[1/s]$
`freq.units`	character; setup the units of `omega`
`model`	character; use the response model from either Rojstaczer (1988), Liu et al (1989), Cooper et al (1965), Hsieh et al (1987), or Wang et al (2018).
`as.pressure`	logical; should the response be relative to aquifer pressure? (default is aquifer head)

Details

As opposed to `well_response`, this calculates the theoretical, complex well response for an unsealed (open) well.

The response depends strongly on the physical properties given. Default values are assumed where reasonable–for instance, the pore-fluid is assumed to be water–but considerable care should be invested in the choice of parameters, especially in the case of starting parameters in an optimization scheme.

The responses returned here are, effectively, the amplification of water levels in a well, relative to the pressure head in the aquifer; or

$$Z = \frac{z}{h} \equiv \frac{\rho g z}{p}$$

If `as.pressure=TRUE`, then the responses are scaled by `rho*grav` so that they represent water levels relative to aquifer pressure:

$$Z = \frac{z}{p}$$

Not all parameters need to be given, but should be. For example, if either `rho` or `grav` are not specified, they are taken from `constants`. *Parameters which do not end in `.` do not need to be specified (they may be excluded); if they are missing, assumptions may be made and warnings will be thrown.*

Value

An object with class `'owrsp'`

Models

`"rojstaczer"`: Rojstaczer (1988) is based on measurements of water level and strain from volumetric or areal strainmeters.

`"cooper"`, `"hsieh"`, and `"liu"`: Cooper et al (1965), Hsieh et al (1987) and Liu et al (1989) are based on measurements of water level and displacements from seismometers or strainmeters; these models are expressed succinctly in Roeloffs (1996).

The sense of the phase shift for the Liu and Rojstaczer models are reversed from their original presentation, in order to account for differences in sign convention.

`"wang"`: Wang et al (2018) allows for specific leakage – vertical conductivity across a semi-permeable aquitard – but the perfectly confined case (i.e., Hsieh, et al 1987) is recovered when leakage is zero.

Author(s)

A. J. Barbour and J. Kennel

References

See `kitagawa-package` for references and more background.

See Also

`well_response` for the sealed-well equivalents, and `owrsp-methods` for a description of the class `'owrsp'` and its methods.

Other WellResponseFunctions: `well_response()`

Examples

```
OWR <- open_well_response(1:10,1,1)
plot(OWR)
OWR <- open_well_response(1/(1:200),1,1,Ta=100,Hw=10,model="liu",freq.units="Hz")
plot(OWR)
```

`owrsp-methods` *Generic methods for objects with class* `'owrsp'`.

Description

An object with class 'owrsp' is a list containing the response information, and the mechanical, hydraulic, and material properties used to generate the response for an open well.

Usage

```
## S3 method for class 'owrsp'
as.data.frame(x, ...)

data.frame.owrsp(x, ...)

## S3 method for class 'owrsp'
print(x, n = 3, ...)

## S3 method for class 'owrsp'
summary(object, ...)

## S3 method for class 'summary.owrsp'
print(x, ...)

## S3 method for class 'owrsp'
lines(x, series = c("amp", "phs"), ...)

## S3 method for class 'owrsp'
points(x, series = c("amp", "phs"), pch = "+", ...)

## S3 method for class 'owrsp'
plot(
  x,
  xlims = c(-3, 1),
  ylims = list(amp = NULL, phs = 185 * c(-1, 1)),
  logamp = TRUE,
  ...
)
```

Arguments

`x`	'owrsp' object
`...`	optional arguments
`n`	numeric; the number of `head` and `tail` to print
`object`	'owrsp' object
`series`	character; the series to plot (amplitude or phase)
`pch`	point character, as in `par`
`xlims`	limits for x-axis (applies to both amp and phs frames)
`ylims`	optional list of limits for y-axis (i.e., `list(amp=c(..),phs=c(...))`)
`logamp`	logical; should the amplitude be in log10 units

Details

The response information is a matrix with frequency, complex response $[\omega, Z_\alpha(\omega)]$ where the units of ω will be as they were input. The amplitude of Z is in meters per strain, and the phase is in radians.

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

See Also

`open_well_response`

`kitagawa-package`

Examples

```
S. <- 1e-5   # Storativity [nondimensional]
T. <- 1e-4 # Transmissivity [m**2 / s]
frq <- 1/(1:200)
# Defaults to the Rojstaczer formulation
W <- open_well_response(frq, T. = T., S. = S., Rs. = 0.12, freq.units="Hz")
# (warning message about missing 'z')
W <- open_well_response(frq, T. = T., S. = S., Rs. = 0.12, freq.units="Hz", z=1)
str(W)
print(W)
print(summary(W))
plot(rnorm(10), xlim=c(-1,11), ylim=c(-2,2))
lines(W)
lines(W, "phs", col="red")
points(W)
points(W, "phs")
#
Wdf <- as.data.frame(W)
plot(Mod(wellresp) ~ omega, Wdf) # amplitude
plot(Arg(wellresp) ~ omega, Wdf) # phase
plot(W)
# change limits:
plot(W, xlims=c(-4,0), ylims=list(amp=c(-7,-3), phs=185*c(-1,1)))
```

`sensing_volume` *Calculate volume of fluids in the sensing region of the borehole.*

Description

This function calculates the volume of fluid in the screened section, namely **Equation 2** in Kitagawa et al (2011).

Usage

```
sensing_volume(rad_grout, len_grout, rad_screen, len_screen)
```

Arguments

`rad_grout`	radius of the grouting $[m]$
`len_grout`	length of the grouting $[m]$
`rad_screen`	radius of the screened interval $[m]$
`len_screen`	length of the screened interval $[m]$

Details

Although typical scientific boreholes with water-level sensors are drilled very deeply, pore-fluids are only allowed to flow through a relatively short section, known as the "screened" section. The calculation assumes two pairs of radii and lengths: one for the cemented (grout) section, and another for the screened section.

The volume calculated is

$$\pi R_C^2 (L_C - L_S) + \pi R_S^2 L_S$$

where R and L denote radius and length respectively, and subscripts C and S denote the cemented and screened sections respectively.

This calculation assumes the measurement is for a sealed well.

Value

scalar, with units of $[m^3]$

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

See Also

`well_response`

Other utilities: `omega_norm()`

Examples

```
#### dummy example
sensing_volume(1, 1, 1, 1)
#
#### a more physically realistic calculation:
# Physical params applicable for B084 borehole
# (see: http://pbo.unavco.org/station/overview/B084/ for details)
#
Rc <- 0.0508   # m, radius of water-sensing (2in)
Lc <- 146.9    # m, length of grouted region (482ft)
Rs <- 3*Rc     # m, radius of screened region (6in)
Ls <- 9.14     # m, length of screened region (30ft)
#
# calculate the sensing volume for the given well parameters
sensing_volume(Rc, Lc, Rs, Ls) # m**3, ~= 1.8
```

`well_response` *Spectral response for a sealed well*

Description

This is the primary function to calculate the response for a sealed well.

Usage

```
well_response(omega, T., S., Vw., Rs., Ku., B., ...)

## Default S3 method:
well_response(
  omega,
  T.,
  S.,
  Vw.,
  Rs.,
  Ku.,
  B.,
  Avs,
  Aw,
  rho,
  Kf,
  grav,
  freq.units = c("rad_per_sec", "Hz"),
  as.pressure = TRUE,
  ...
)
```

Arguments

`omega`	frequency, (see `freq.units`)
`T.`	effective aquifer transmissivity $[m^2/s]$
`S.`	well storativity, $[unitless]$
`Vw.`	well volume, $[m^3]$
`Rs.`	radius of screened portion, $[m]$
`Ku.`	undrained bulk modulus, $[Pa]$
`B.`	Skempton's coefficient, $[unitless, bounded]$
`...`	additional arguments
`Avs`	amplification factor for volumetric strain $E_{kk,obs}/E_{kk}$, []
`Aw`	amplification factor of well volume change for E_{kk}, []
`rho`	fluid density $[kg/m^3]$
`Kf`	bulk modulus of fluid, $[Pa]$

`grav`	local gravitational acceleration $[m/s^2]$
`freq.units`	set the units of `omega`
`as.pressure`	logical; should the response for water pressure? (default is water height)

Details

The response depends strongly on the physical properties given. Default values are assumed where reasonable–for instance, the pore-fluid is assumed to be water–but considerable care should be invested in the choice of parameters, unless the function is used in an optimization scheme.

Assumed values are:

`Avs`	1	amplification factor for volumetric strain
`Aw`	1	amplification factor for water well

The responses returned here are, effectively, the amplification of water levels in a well, relative to the aquifer strain; or

$$Z = \frac{z}{\epsilon} \equiv \frac{p}{\rho g \epsilon}$$

If `as.pressure=TRUE`, then the responses are scaled by `rho*grav` so that they represent water pressure relative to aquifer strain:

$$Z = \frac{p}{\epsilon}$$

Not all parameters need to be given, but should be. For example, if either `rho` or `grav` are not specified, they are taken from `constants`. *Parameters which do not end in . do not need to be specified (they may be excluded); if they are missing, warnings will be thrown.*

Value

An object with class `'wrsp'`

Author(s)

A. J. Barbour

References

See `kitagawa-package` for references and more background.

See Also

`open_well_response` for the open-well equivalents `wrsp-methods` for a description of the class `'wrsp'` and its methods, `sensing_volume` to easily estimate the volume `Vw.`, and `kitagawa-package` for references and more background.

Other WellResponseFunctions: `open_well_response()`

Examples

```
#### dummy example
well_response(1:10, T.=1, S.=1, Vw.=1, Rs.=1, Ku.=1, B.=1)

#### a more physically realistic calculation:
# Physical params applicable for B084 borehole
# (see: http://pbo.unavco.org/station/overview/B084/ for details)
#
Rc <- 0.0508   # m, radius of water-sensing (2in)
Lc <- 146.9    # m, length of grouted region (482ft)
Rs <- 3*Rc     # m, radius of screened region (6in)
Ls <- 9.14     # m, length of screened region (30ft)
#
# calculate the sensing volume for the given well parameters
Volw <- sensing_volume(Rc, Lc, Rs, Ls) # m**3, ~= 1.8
#
Frqs <- 10**seq.int(from=-4,to=0,by=0.1) # log10-space
head(Rsp <- well_response(omega=Frqs, T.=1e-6, S.=1e-5,
Vw.=Volw, Rs.=Rs, Ku.=40e9, B.=0.2, freq.units="Hz"))

# Access plot.wrsp:
plot(Rsp)
```

`wrsp-methods` *Generic methods for objects with class* '`wrsp`'.

Description

An object with class 'wrsp' is a list containing the response information, and the mechanical, hydraulic, and material properties used to generate the response for a sealed well.

Usage

```
## S3 method for class 'wrsp'
as.data.frame(x, ...)

data.frame.wrsp(x, ...)

## S3 method for class 'wrsp'
print(x, n = 3, ...)

## S3 method for class 'wrsp'
summary(object, ...)

## S3 method for class 'summary.wrsp'
print(x, ...)
```

```
## S3 method for class 'wrsp'
lines(x, series = c("amp", "phs"), ...)

## S3 method for class 'wrsp'
points(x, series = c("amp", "phs"), pch = "+", ...)

## S3 method for class 'wrsp'
plot(
  x,
  xlims = c(-3, 1),
  ylims = list(amp = NULL, phs = 185 * c(-1, 1)),
  logamp = TRUE,
  ...
)

kitplot(x, ...)

## S3 method for class 'wrsp'
kitplot(
  x,
  xlims = c(-3, 1),
  ylims = list(amp = NULL, phs = 185 * c(-1, 1)),
  logamp = TRUE,
  ...
)
```

Arguments

`x`	'wrsp' object
`...`	optional arguments
`n`	numeric; the number of `head` and `tail` to print
`object`	'wrsp' object
`series`	character; the series to plot (amplitude or phase)
`pch`	point character, as in `par`
`xlims`	limits for x-axis (applies to both amp and phs frames)
`ylims`	optional list of limits for y-axis (i.e., `list(amp=c(..),phs=c(...))`)
`logamp`	logical; should the amplitude be in log10 units

Details

The response information is a matrix with frequency, complex response $[\omega, Z_\alpha(\omega)]$ where the units of ω will be as they were input. The amplitude of Z is in meters per strain, and the phase is in radians.

`kitplot` was previously a standalone function, but is now simply a reference to `plot.wrsp`.

Author(s)

A. J. Barbour <andy.barbour@gmail.com>

See Also

`well_response`

`kitagawa-package`

Other PlotUtilities: `logticks()`

Examples

```
W <- well_response(1:10, T.=1, S.=1, Vw.=1, Rs.=1, Ku.=1, B.=1)
str(W)
print(W)
print(summary(W))
#
# Plot the response
plot(rnorm(10), xlim=c(-1,11), ylim=c(-2,2))
lines(W)
lines(W, "phs", col="red")
points(W)
points(W, "phs")
#
Wdf <- as.data.frame(W)
plot(Mod(wellresp) ~ omega, Wdf) # amplitude
plot(Arg(wellresp) ~ omega, Wdf) # phase
#
# or use the builtin method plot.wrsp
plot(W)
# change limits:
plot(W, xlims=c(-1,1), ylims=list(amp=c(5,8), phs=185*c(-1,1)))
```

Index