Modeling Tide's Influence on Seawall's Surface Temperature in Tropical Regions

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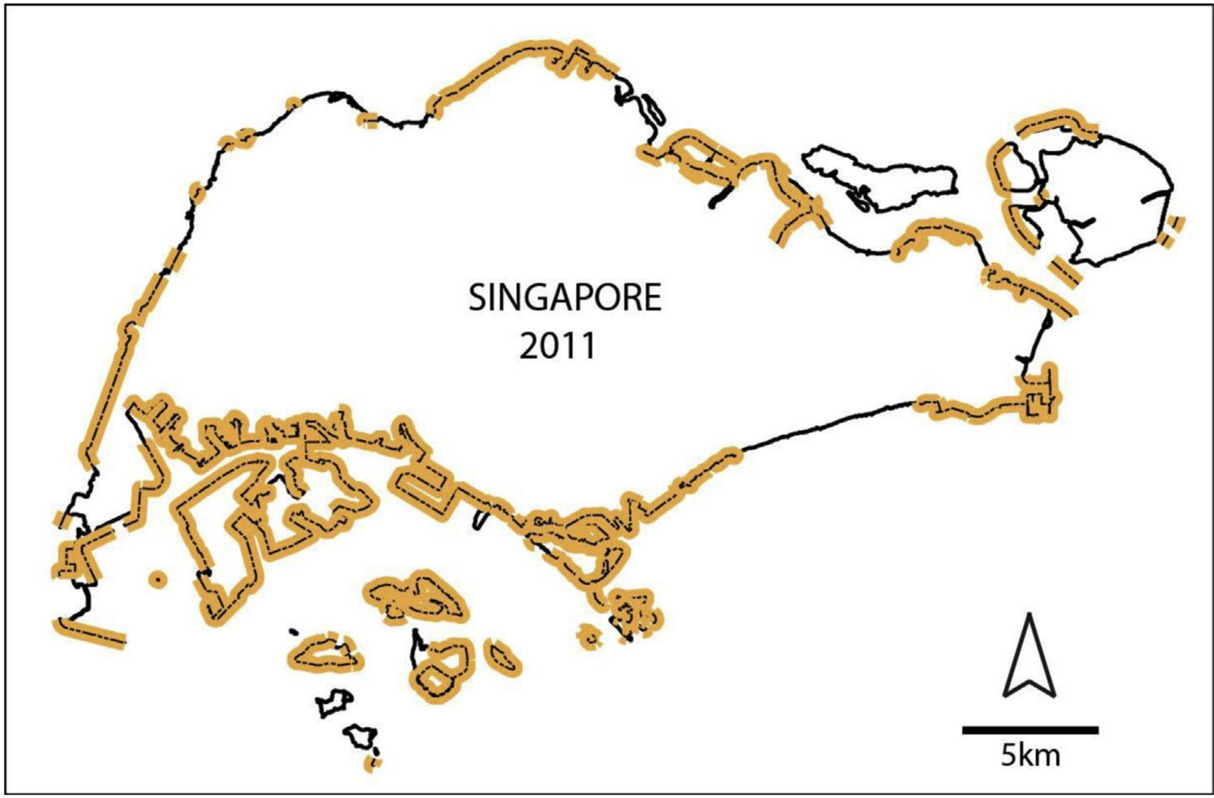
Introduction

Singapore's coastline and seawall

- Coastline - 505 km
- Seawall - 319 km
    - Granite
        - grouted
        - un-grouted
    - Vertical concrete



Data and Image from Lai et. al. (2015). The effects of urbanisation on coastal habitats and the potential for ecological engineering: A Singapore case study

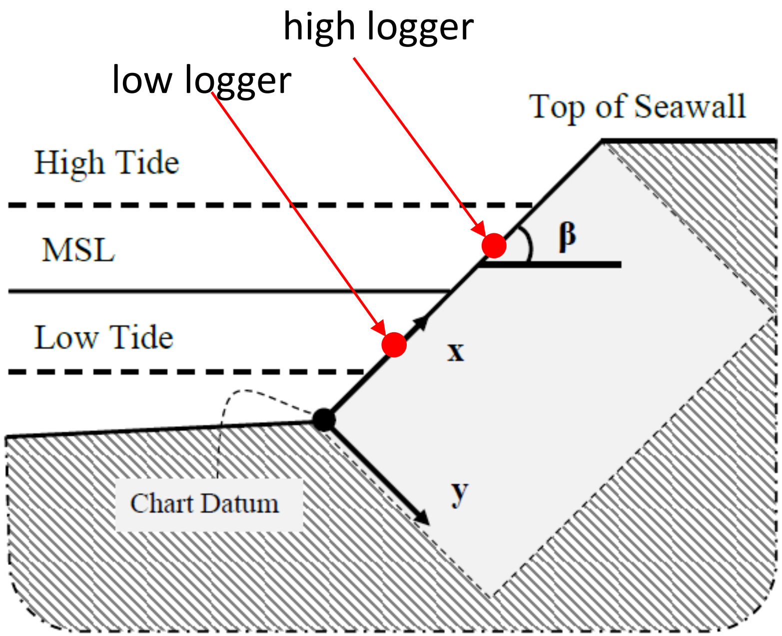
Introduction

- Loss of natural habitat
- Redesign of seawalls
  - mitigating some negative impacts
  - improve their potential as a habitat
  - enhance biodiversity

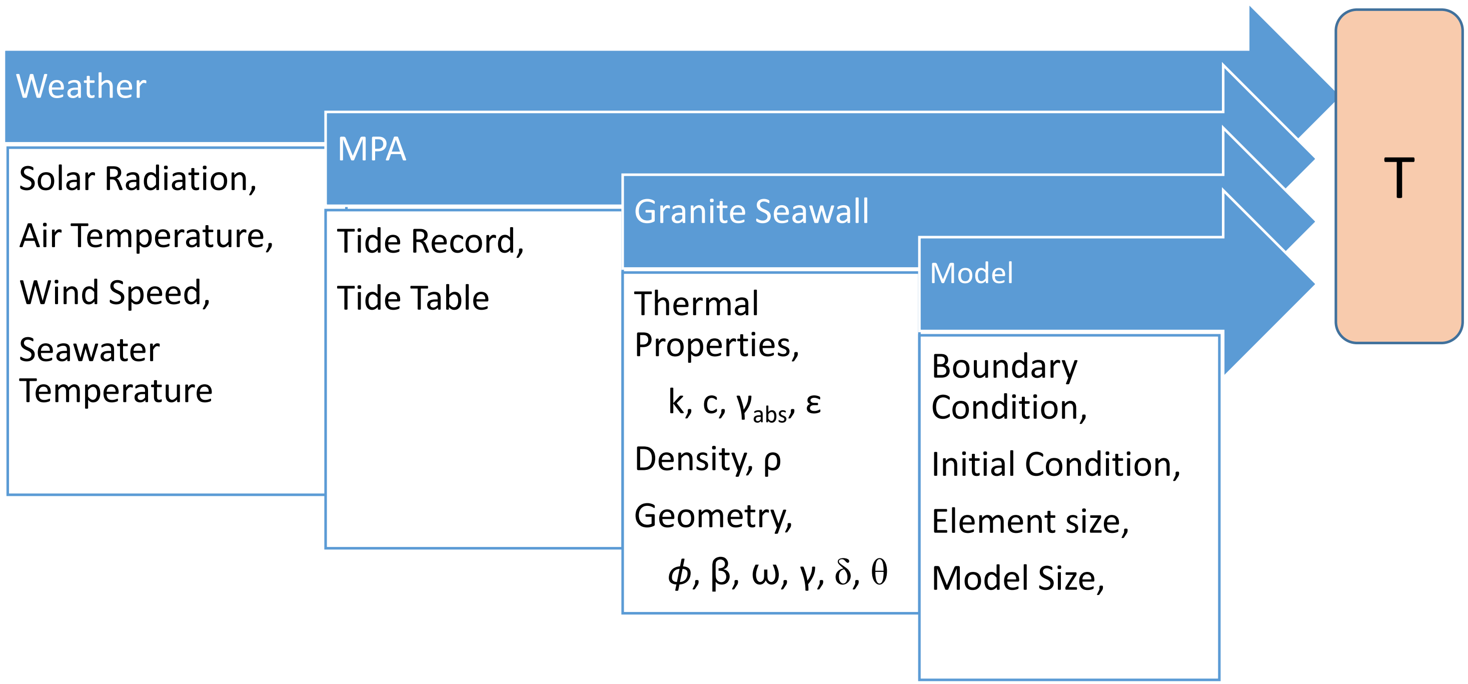
- Why temperature (T)?
  - "Organisms living in the intertidal zone are faced with strong thermal stress given their cyclic exposure to air and immersion in water by tides." (Helmuth et al., 2002).
  - survival rate ↘ to zero, if T > 50 ^{o}C. (Somero, 2002).
  - seawall surface T can reach very high in tropical region, e.g., Singapore

Model extent

- Consider a seawall with 30º slope
  - a simple slope
  - x: parallel with seawall surface
  - y: perpendicular to seawall
  - chart datum: reference elevation
  - model extent: 8m x 5m
  - tidal range: 0.2m – 3.2 m
    - →range of x: 0.4m – 6.4m
  - Element size: 0.05m x 0.05m
- Timestep, dt: 5 min
- Duration of calculation: 1 day



A suite of parameters



Theoretical Background

Image from Yang D. Solar Irradiance Modeling and Forecasting Using Novel Statistical Techniques

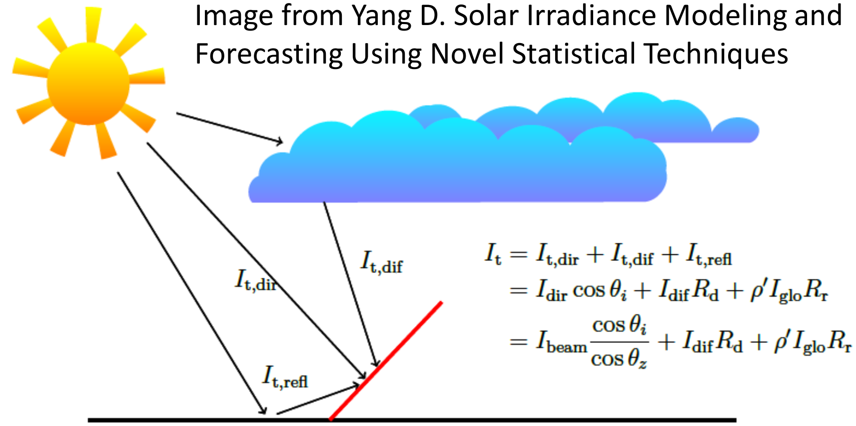


Fig. 1.3 Schematic diagram of various irradiance components received on a collector plane.

- Heat equation

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)$$

- Deep boundary condition
  - no heat flow from deep ground
- Heat flux on surface

$$F_{y=0} = \begin{cases} q_{abs} + q_L + q_{conv,air}, & \text{above water} \\ q_L + q_{conv,sea}, & \text{under water} \end{cases}$$

  - Solar radiation absorption

$$q_{abs}(t) = \gamma_{abs} \cdot [q_{Ray} \cdot I_f + q_{DR} \cdot (\frac{1+\cos\beta}{2})]$$

  - Long wave emission

$$q_L = \sigma \times \epsilon \times (T_{sky}^4 - T_{sw}^4)$$

  - Heat convection by air

$$q_{conv,air} = h_{conv,air}(T_a - T_{sw})$$

  - Convection by seawater

$$q_{conv,sea} = h_{conv,sea}(T_{sea} - T)$$

- Initial temperature
  - 27°C at 0:00 am for Singapore.

Modelling method

- Finite Difference Method
  - central differencing

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)$$

$$\rho c\left(\frac{T_{i,j} - T_{i,j}^{0}}{\Delta t}\right) = \theta\left[k\,\frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j}}{dx^2} + k\,\frac{T_{i,j+1} - 2T_{i,j} + T_{i,j-1}}{dy^2}\right]$$

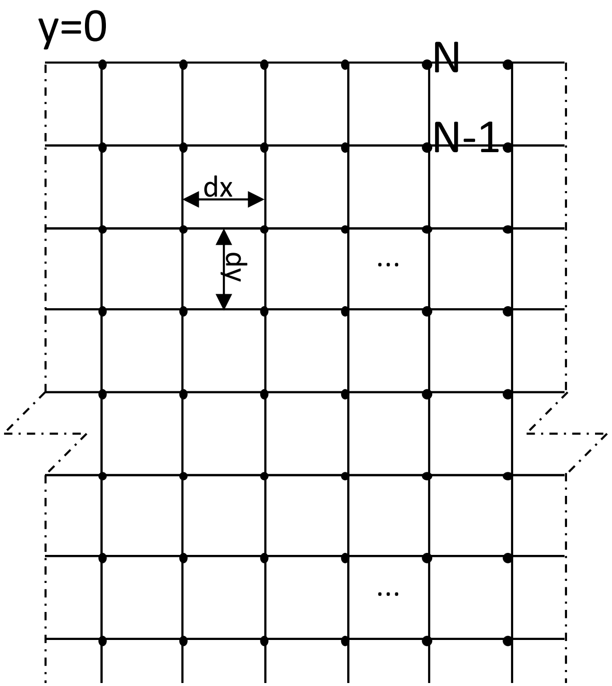
$$+(1-\theta)\left[k\,\frac{T_{i+1,j}^{0} - 2T_{i,j}^{0} + T_{i-1,j}^{0}}{dx^2} + k\,\frac{T_{i,j+1}^{0} - 2T_{i,j}^{0} + T_{i,j-1}^{0}}{dy^2}\right]$$

  - Crank-Nicolson scheme (θ = 0.5)
- Treatment of boundary nodes
  - Ghost point technique (see next slide)

Modelling method

$$\rho c\left(\frac{T_{i,N}-T_{i,N}^{0}}{\Delta t}\right)=\theta\left[k\,\frac{T_{i+1,N}-2T_{i,N}+T_{i-1,N}}{dx^2}+k\,\frac{T_{i,N+1}-2T_{i,N}+T_{i,N-1}}{dy^2}\right]+(1-\theta)\left[k\,\frac{T_{i+1,N}^{0}-2T_{i,N}^{0}+T_{i-1,N}^{0}}{dx^2}+k\,\frac{T_{i,N+1}^{0}-2T_{i,N}^{0}+T_{i,N-1}^{0}}{dy^2}\right]$$

T_N and T_{N-1} are used to find the flux equation on surface and then T_{N+1}. then T_{N+1} is put in the matrix to find T for all nodes. Iteration is required.



Ghost cell with $T_{i,N+1}$

$$F_{sw}\big|_{y=0}=k\,\frac{T_{i,N+1}-T_{i,N-1}}{2dy}$$

therefore

$$T_{i,N+1}=\frac{2dy}{k}\cdot F_{sw}\big|_{y=0}+T_{i,N-1}$$

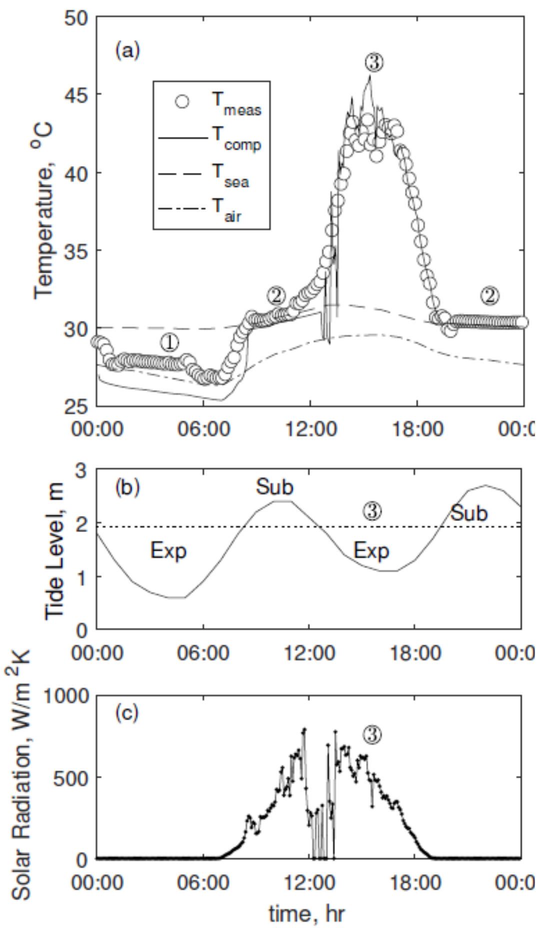
1. Initial guess of $T_{i,N}$ and $T_{i,N-1}$

2a. Find Fsw and $T_{i,N+1}$

$$F_{sw}\big|_{y=0}=\sigma\varepsilon(T_{sky}^{4}-T_{N}^{4})+\gamma_{abs}q_{SR}+h_{air}(T_{air}-T_{N})+h_{sea}(T_{sea}-T_{N})$$

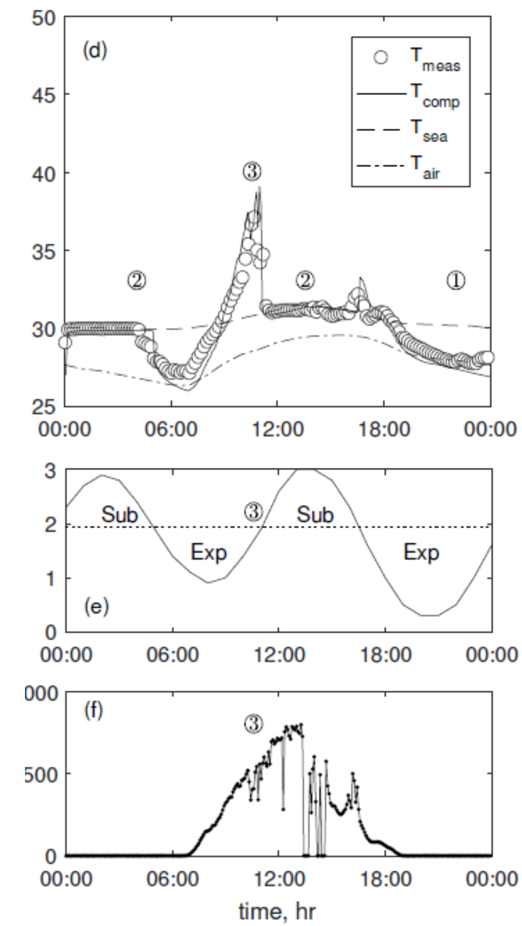
Results: seawall surface temperature

(a) low tide in the afternoon



- Three types of T
  1) exposed night
  2) submerged
  3) exposed daytime

(b) high tide in the afternoon

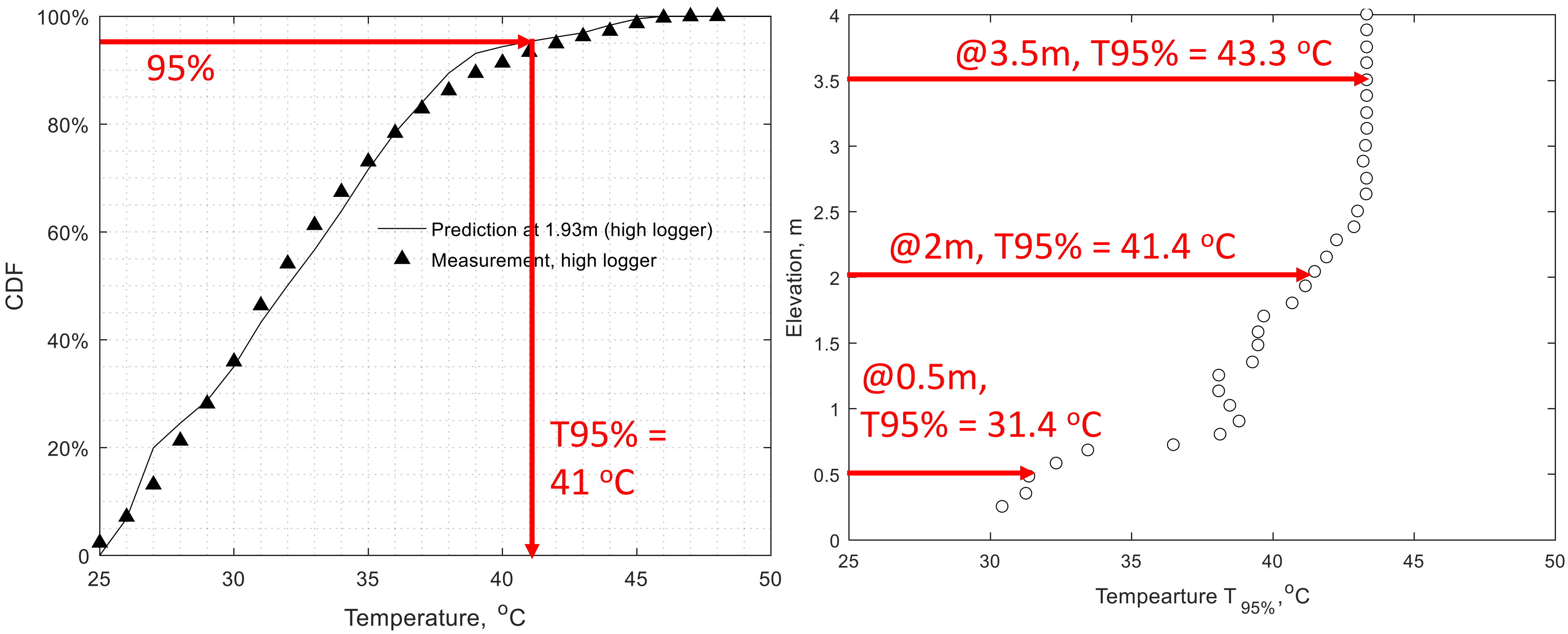


Model data comparison

- Overall performance of model
  - 62% of data are within dashed lines: +- 2^{o}C from perfect
- From the results of each elevation (e.g., at logger level in the figure), plot a cumulative distribution of T

Definition of local high temperature - T95%

- A term: T95% from numerical prediction
  - local high temperature, 95% of temperature do not exceed this threshold during exposed day time.



Model application – seawall slope

- Slope range in figure: 30 – 90 deg
- T95%, local high T
  - 90 deg slope is ~ 9 ^{o}C lower that of 30 deg slope
- Max solar radiation energy
  - Max SR for 90 deg slope is about half that of 30 deg slope seawall

Model application – seasonal effect

- Northeast monsoon
  - Dec, Jan, Feb
- Southwest monsoon
  - Jun, July, Aug, Sep
- Max Temperature difference: 5°C

Conclusion

- A finite difference model for seawall surface temperature
    - Absorption of solar radiation
    - Long wave emission
    - Convection by air and seawater
- Good agreement between prediction and field test
- Tide's cooling effects on the high temperature
- T95% - local high temperature
- Effect of seawall slopes and seasons on T95%

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Q & A

Thank you!