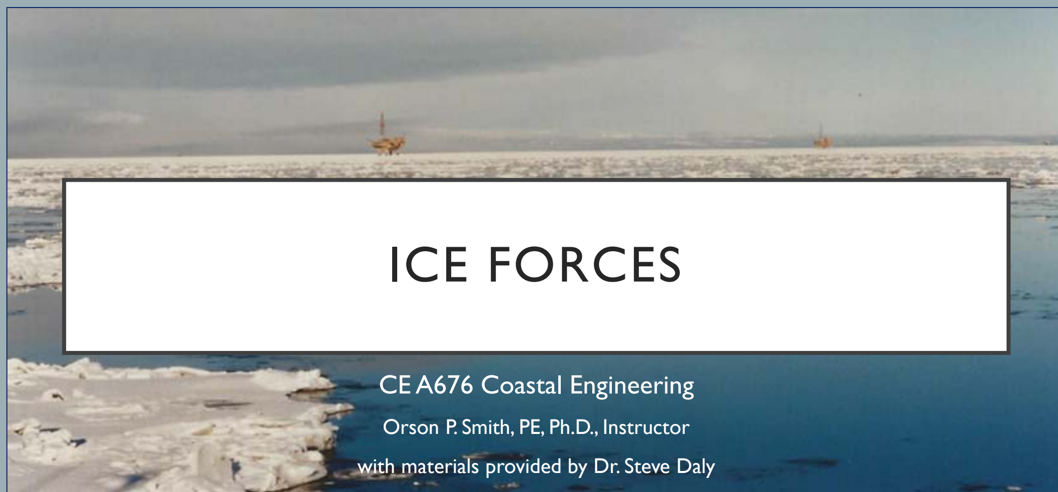

# ICE FORCES

CE A676 Coastal Engineering

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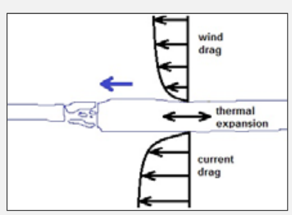
with materials provided by Dr. Steve Daly

UAA College of Engineering
UNIVERSITY of ALASKA ANCHORAGE

## ICE FORCE SITUATIONS

- Ice forces are encountered
  - On river and lake beds and banks
  - On structures in rivers and lakes
  - On coasts and on port and coastal structures in northern regions
  - On ship hulls, drilling platforms, and other Arctic offshore structures




- Ice forces are caused by
  - Wind friction
  - Water currents
  - Thermal expansion
- Ice forces are limited by ice strength

# ICE FORCE DESIGN GUIDANCE

- USACE Ice Engineering Manual, EM 1110-2-1612
  - and other US Army Cold Regions Research and Engineering Laboratory publications
- AASHTO LRFD Bridge Design Specifications
  - and associated AASHTO publications
- ISO19906, Petroleum and natural gas industries - Arctic offshore structures

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# FLUID DRAG FORCES

- $F_D = C_D \rho A u^2$
  - $F_D$ = drag force
  - $C_D$ = drag coefficient
    - $C_D$ = 0.002 for smooth ice sheets
    - $C_D$ = 0.005 for rough ice sheets
  - $\rho$ = fluid density (1.3 kg/m$^3$ for air)
  - A = area on which the fluid friction acts
  - $u$ = fluid velocity
    - Measured 10 m above surface in air
    - Measured 1 m below bottom of ice in water
- Example situation
  - Wind speed 10 m/s over smooth ice
  - Big ice floe: 100 m x 1000 m
  - Air drag = 26 kN
- Combined with 0.4 m/s current, same direction
  - Combined air and water drag = 58 kN

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# ICE FORCE FACTORS

- Forces on a structure limited by ice strength
- Ice failure modes
  - crushing
  - floe splitting
  - bending
  - buckling
- Failure depends on
  - Nature of initial contact
  - Temperature
  - Strain rate
  - Ice type (granular, columnar, etc.)
  - Structure characteristics (shape, smoothness, rigidity…)

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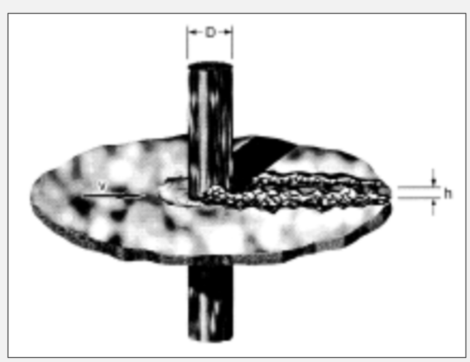
# CRUSHING FAILURE

- $F = p_e D h$
  - $p_e$ = effective pressure
- Depends on compressive strength of ice
  - 0.5 to 20 MPa for freshwater ice
- Function of
  - Strain rate
  - Temperature
  - Ice grain size and structure
  - Ice porosity and brine content

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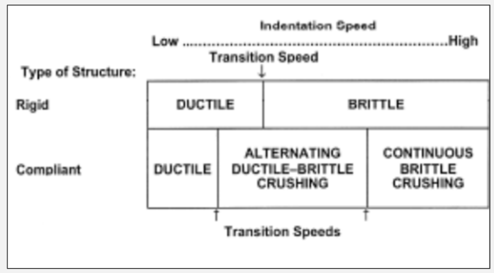
# STRAIN RATE EFFECTS

- High strain rate:
  - Ice behaves as brittle material
  - Ice continuously crushes
  - Varying partial contact area
  - Total force more uniform
- Low strain rate:
  - Ice behaves as ductile material
  - Deforms and fails in creep mode
  - Large variations in total force




- Transition speed ~ 3mm/sec for rigid structures



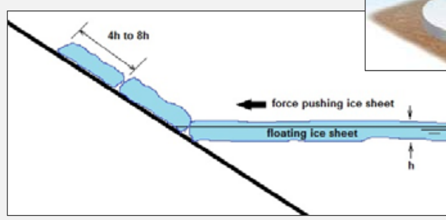
# BRITTLE CRUSHING ICE FAILURE

- $F = A_r p_e D h$
  - $A_r = \left({}^{5h}/_{D+1}\right)^{0.5}$
  - $p_e$ = 1.5 to 2 MPa for brittle crushing of ice
  - $D$ = structure width
  - $h$ = ice thickness


CRREL photos – Yukon River bridge

## BENDING FAILURE

- Ice sheet is pushed up or down on contact with structure
- Ice sheet breaks into blocks
  - 4h to 8h horizontal dimension
- Narrow structures may allow ice to pass around
- Wide structures form rubble pile
- Forces generally less than crushing
- See Ice Engineering Manual for analysis details






## ICE BUCKLING FAILURE

- Flexural (bending) failure against a vertical surface
- Forces less than crushing failure
- May be due to thermal expansion

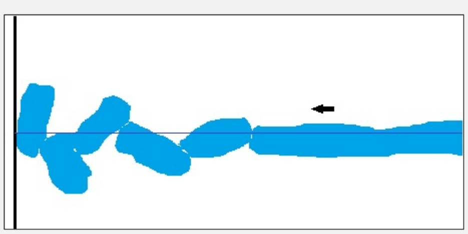
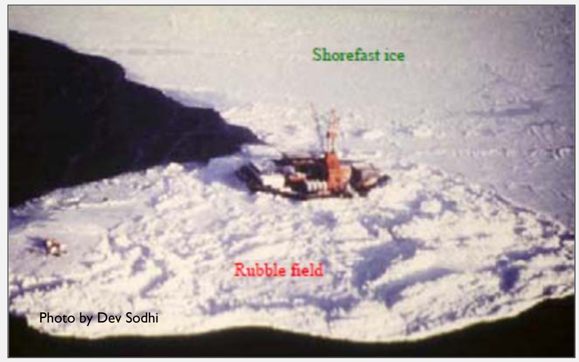



Photo by Dev Sodhi

# LARGE ICE FLOES AND RUBBLE FIELDS

- Large ice floes, on contact may
  - Come to rest
  - Deflect
  - Rebound
  - Crush, stop, deflect, or split
- Moving rubble fields: force limited by
  - internal strength
  - Porosity
  - Thickness of rubble






# ICE ON ROCK SLOPES

- Tests at CRREL revealed
  - Little damage during ride-up events
    - Ride-up generally occurred on 1v:3h+ (shallow) slopes
  - Most damage with pile-up
    - Ice forced beneath ice rubble pile and riprap
    - Most severe damage at or below water level
  - Maximum stone size =
    - 2h for shallow slopes (1v:3h+)
    - 3h for 1v:1.5h
  - More conservatively,
    - $D_{50}$ *should be 2 to 3 x ice thickness (h)*


Conclusion