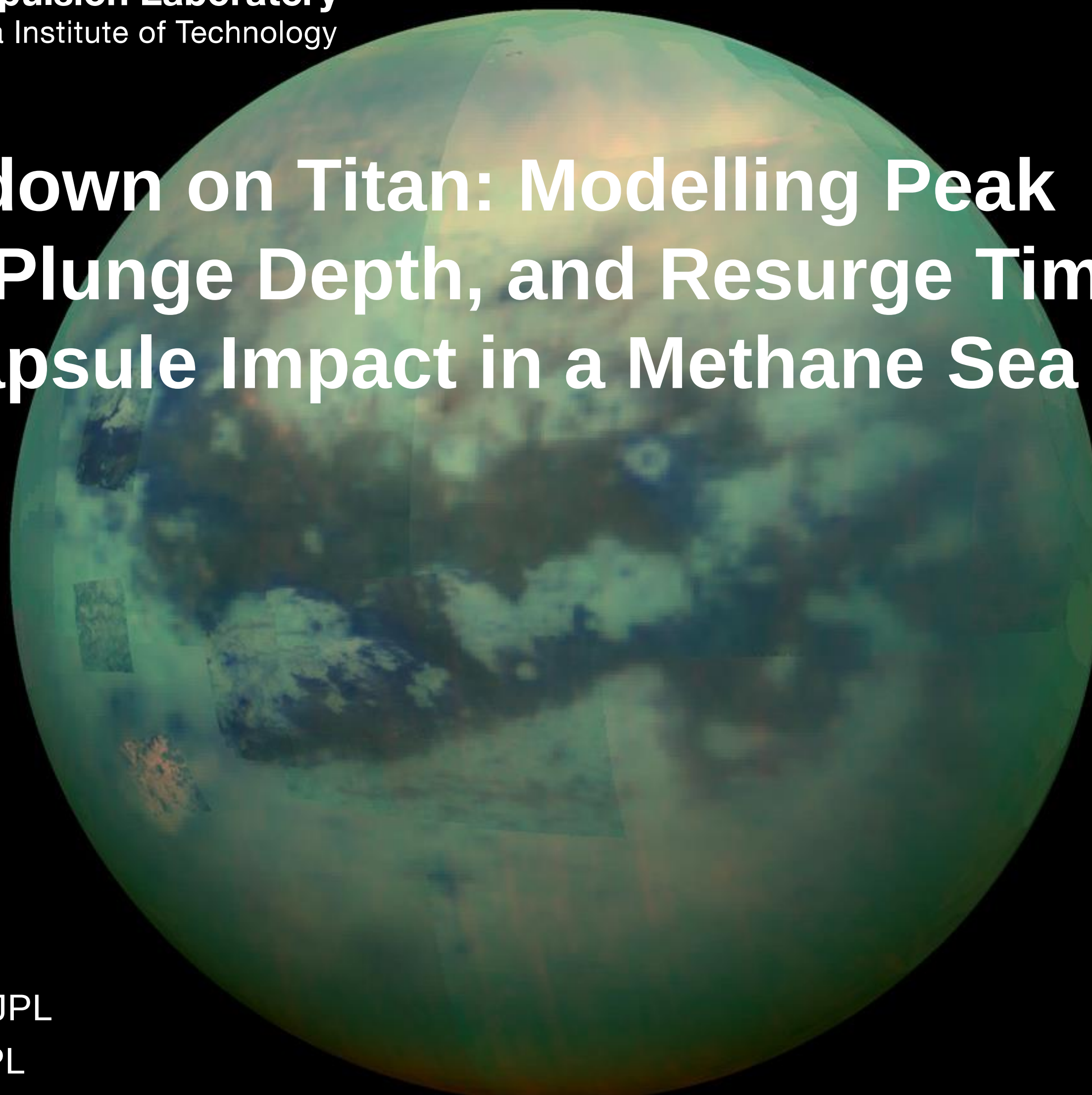
Jet Propulsion Laboratory
California Institute of Technology

Splashdown on Titan: Modelling Peak Loads, Plunge Depth, and Resurge Time for a Capsule Impact in a Methane Sea



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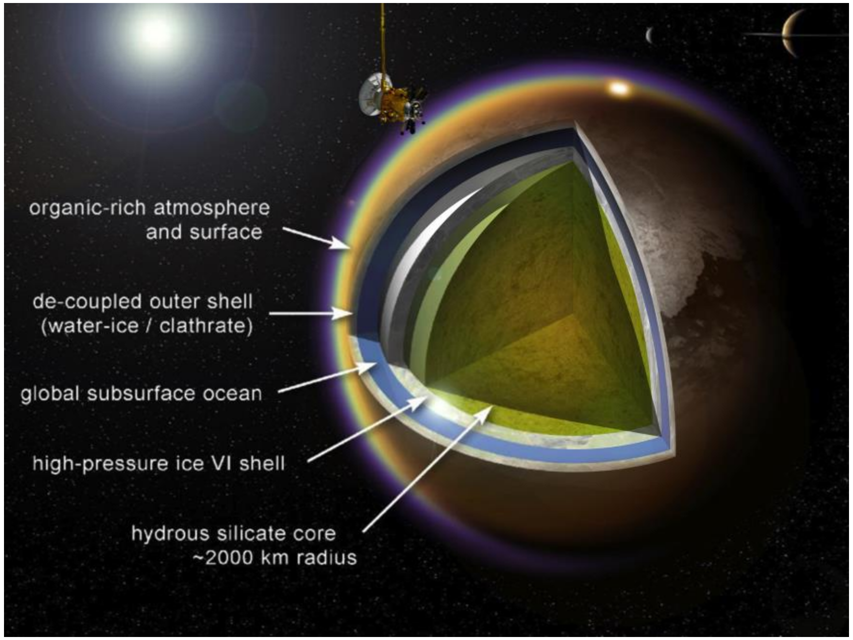
Predecisional information for planning and discussion only

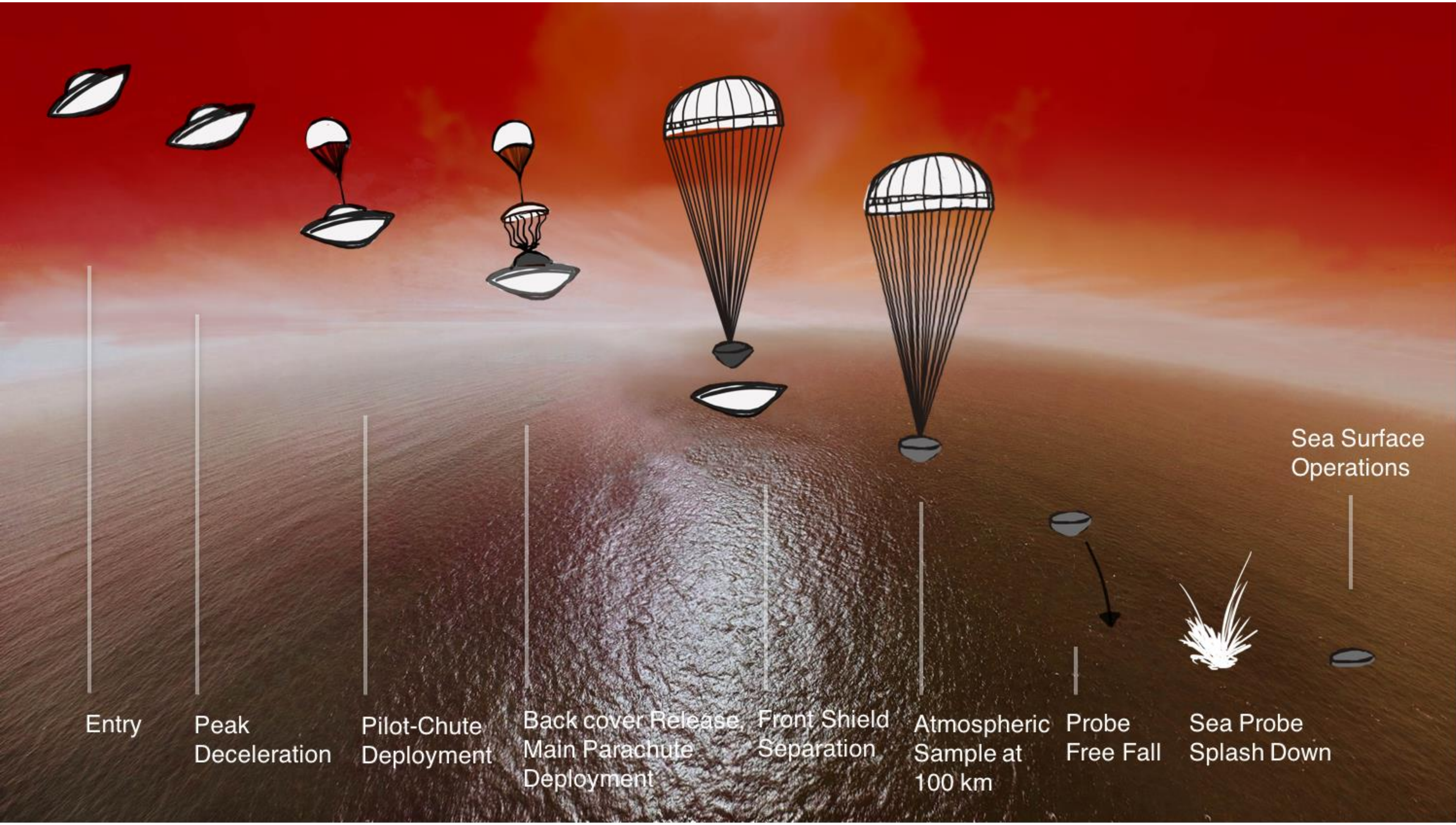
Motivation



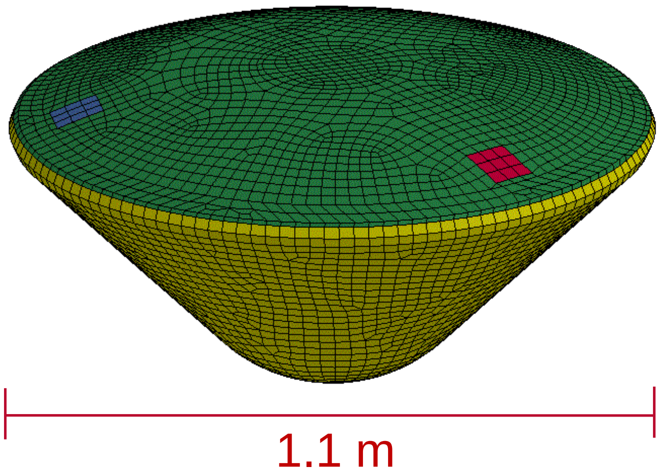
- Titan is only body besides Earth to support standing bodies of liquid
- Hydrocarbon seas of astrobiological and oceanographic interest
- A probe structure and instruments would need to survive splashdown event
  - Need to predict impact loads
- Knowledge of plunge depth vital for probe design (liquid resistance) and operations timing
  - Ensure doesn't hit bottom
  - Informs ability to take sample at depth
- Analytical solutions limited to simple axisymmetric shapes and ideal vertical entry

Probe EDL Concept of Operations

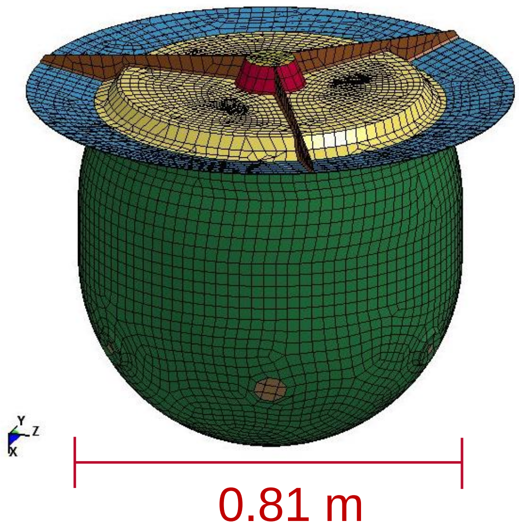
Freefall segment would reduce landing dispersions due to winds



Candidate Probe Designs



- **45° Spherecone Probe**
  - Provides subsonic aero stability in freefall
  - Provides tapered shape for low-G impact
  - Provides high drag for low velocity impact and low-G load on splashdown



- **Cylinder with Spherical Nose Probe**
  - Drag plate reduces velocity and provides stability in freefall
  - Flexible packaging

Analytical Methodology

Impact G-Loads

- Impact velocity is terminal descent velocity
  - $V_0 = \sqrt{\frac{2Mg}{\rho_{atm} S C_D}}$
- Method 1: Closed form solution for spherical noses [Hirano and Miura]
  - Froude number, $F = V_0 (g R_N)^{-1/2}$
  - Mass ratio, $\mu = \frac{3M}{4\pi\rho R_N^3}$
  - Max deceleration, $A_{max} = 0.491 F^2 \mu^{-2/3} g$
- Method 2: Solve numerically over time [McGehee, et al],[Lorenz, et al]:
  - For general axisymmetric shape, radius R is a function of height: R = f(h)
  - $A = \frac{V^2 \pi k \rho R^2 dR}{\left(M + \frac{2}{3} k \pi \rho R^3\right) dh}$
  - For spherical nose, $V = \frac{M g V_0}{Mg + \left(\frac{3}{4}\right) \frac{2\pi}{3} \rho g R^3 \left[\sin^3 \cos^{-1}\left(1 - \frac{h}{R}\right)\right]}$
  - $A = \frac{\Delta V}{\Delta t}$

Analytical Methodology

Plunge Depth

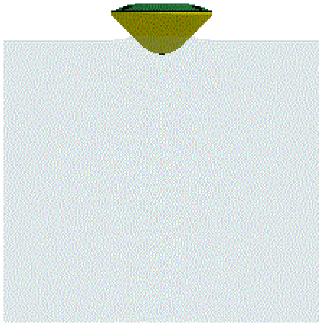
- Method 1: 1-D differential equation solved numerically
  - Buoyancy (*B*), drag (*D*), and weight (*W*) forces act on probe
  - $Ma = B - sign(V)D - W$
- Method 2: Conservation of momentum and energy
  - Use conservation of momentum to calculate residual velocity after impact
  - $Work_{Buoyancy} = KE$
  - Ignore drag, potential energy

LS-DYNA

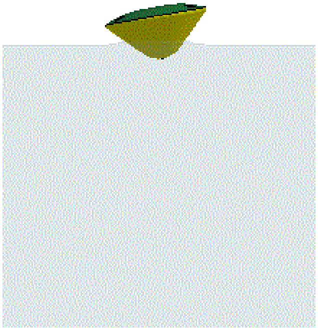
- Explicit, transient dynamic finite element code
- Fluid modeled with Arbitrary Langrangian-Eulerian approach
  - Takes into account movement of fluid mass and compressibility
  - Not full Navier-Stokes
- Probe is rigid body
- Maximum expected sea density used for impact loads: 500 kg/m^3
- Minimum expected sea density used of plunge depth: 630 kg/m^3

Test Suite for 45° Spherecone Candidate Probe

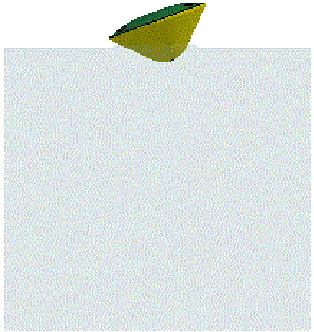
Case 1: 0° Vertical High Load
Vv = 8.8 m/s
Vh = 0.0 m/s
Angle = 0°
Liquid Density = 630 kg/m^3



Case 2: 10° Vertical High Load
Vv = 8.8 m/s
Vh = 0.0 m/s
Angle = 10°
Liquid Density = 630 kg/m^3



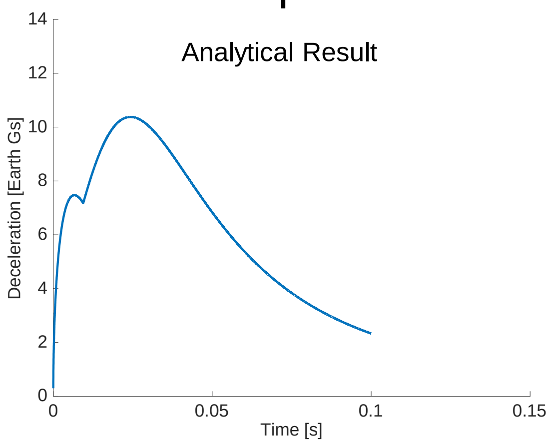
Case 3: 20° Vertical High Load
Vv = 8.8 m/s
Vh = 0.0 m/s
Angle = 20°
Liquid Density = 630 kg/m^3



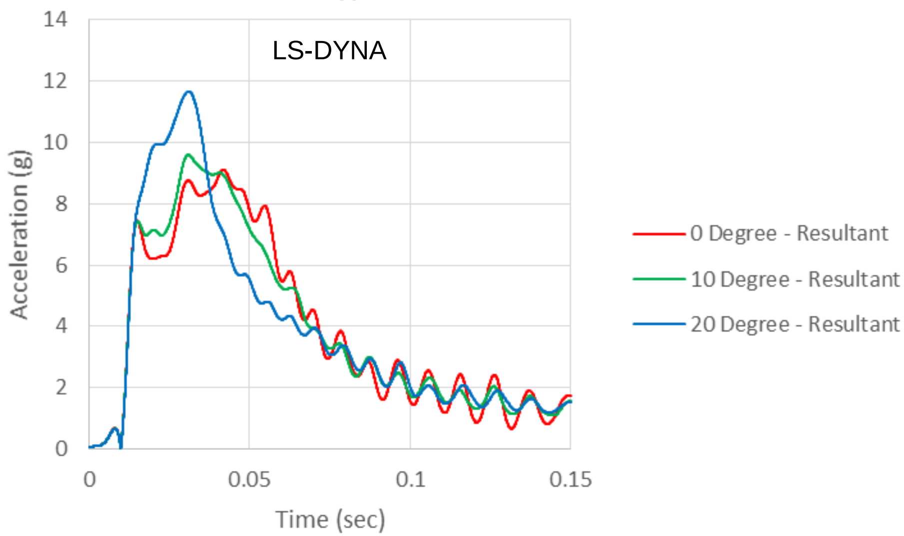
Results: G-Loads

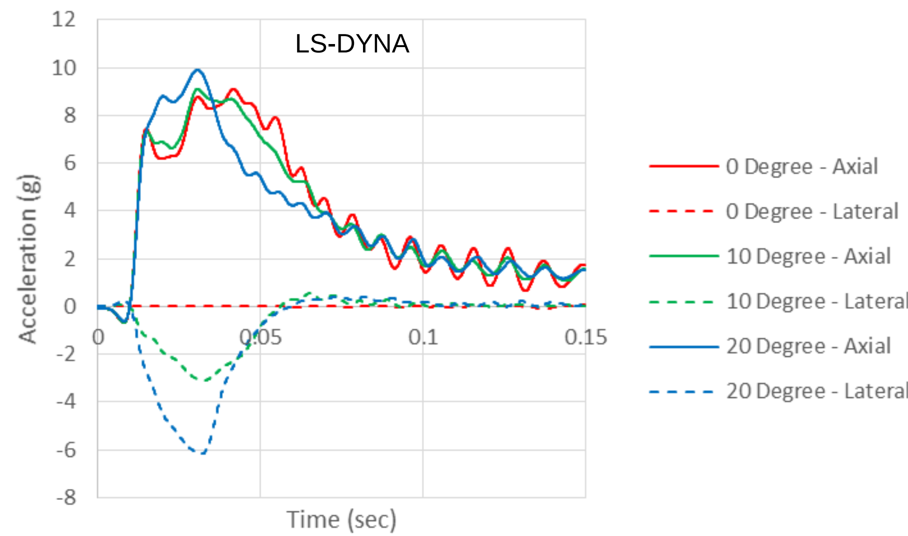
45° spherecone LS-DYNA compared to analytical

- Note two peaks seen in both LS-DYNA and numerical integration
  - 1st peak corresponds to max $^{dR}/_{dh}$ of spherical nose
  - 2nd peak occurs on cone



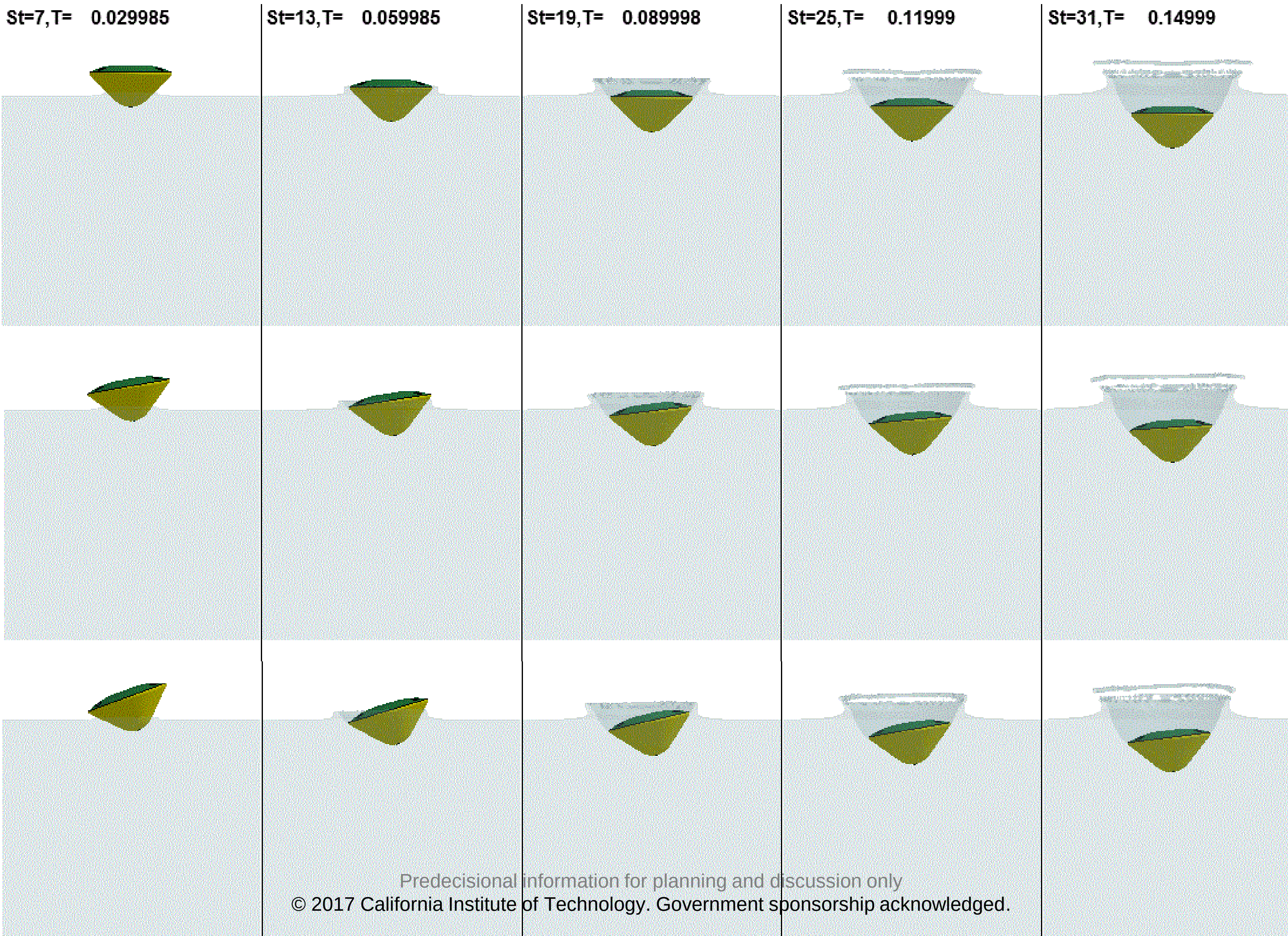
Method	Peak Acceleration [Earth G's]
Closed Form Spherical	9.4
Numerical Integration	10.4
LS-DYNA	9.0



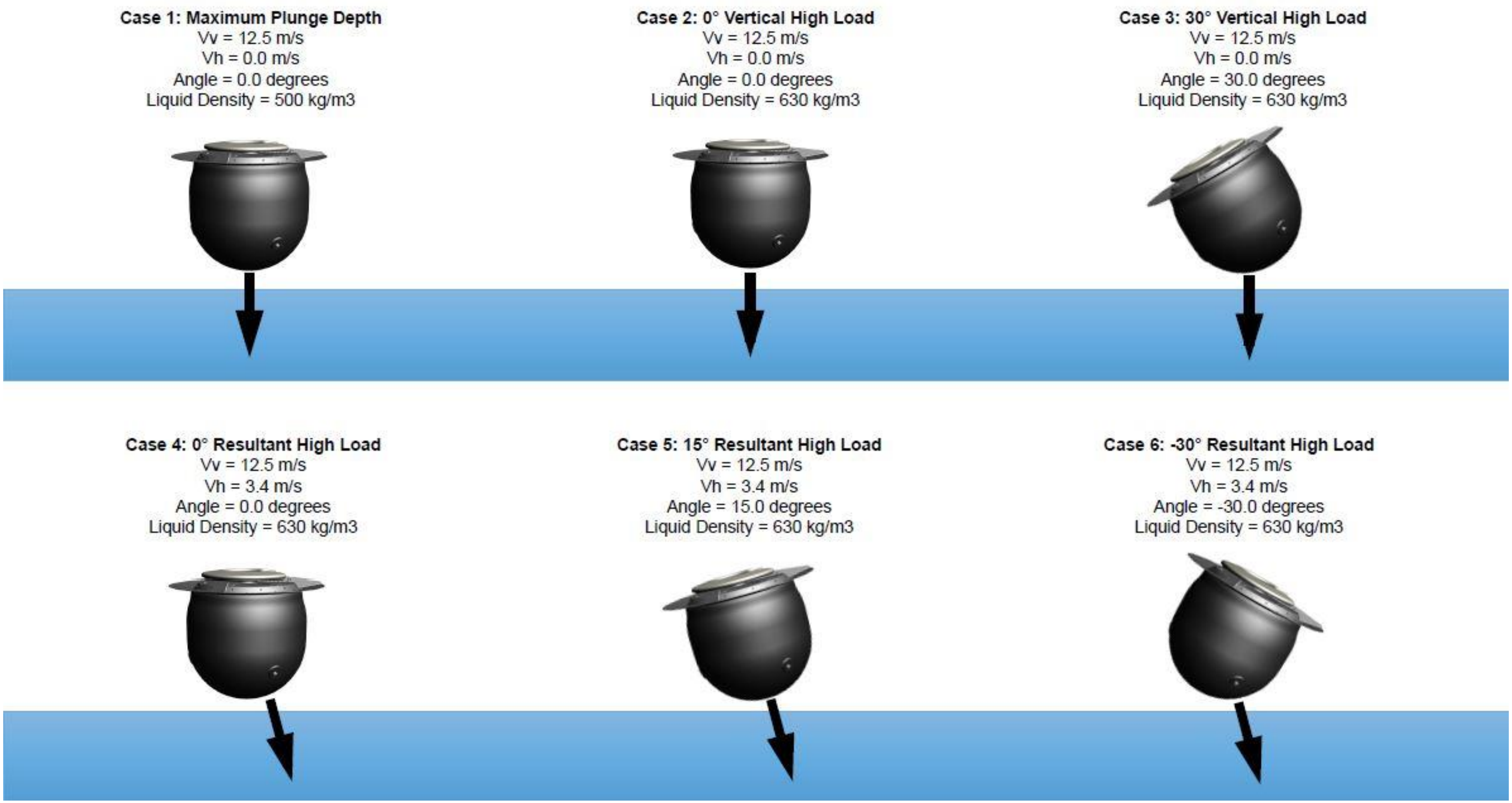


Results: G-Loads Motion Sequence

45 degree spherecone LS-DYNA, all cases



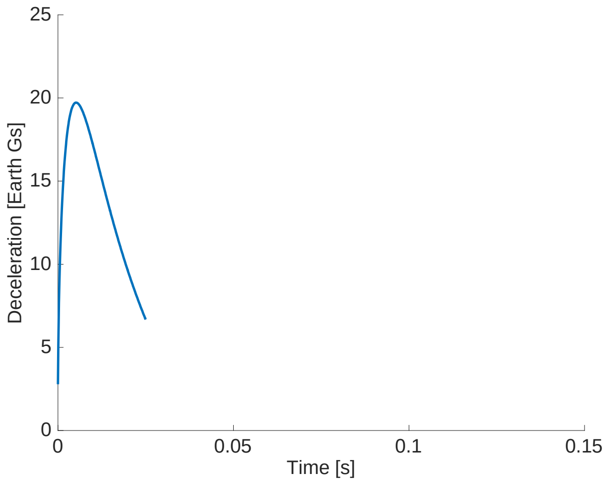
Test Suite for Candidate Drag Plate Probe



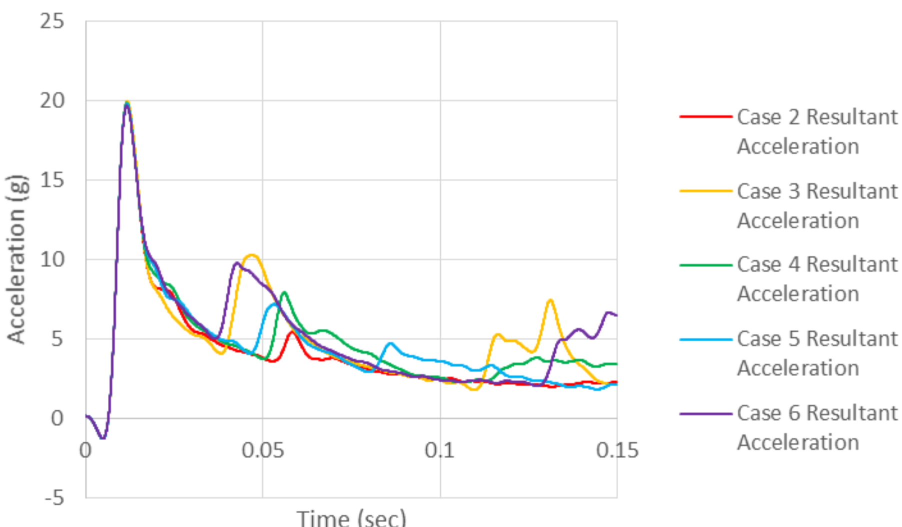
Results: G-Loads

Drag Plate Case 2 (vertical only) LS-DYNA compared to analytical

- Drag plate not modeled analytically
- LS-DYNA sees second peak due to drag plate

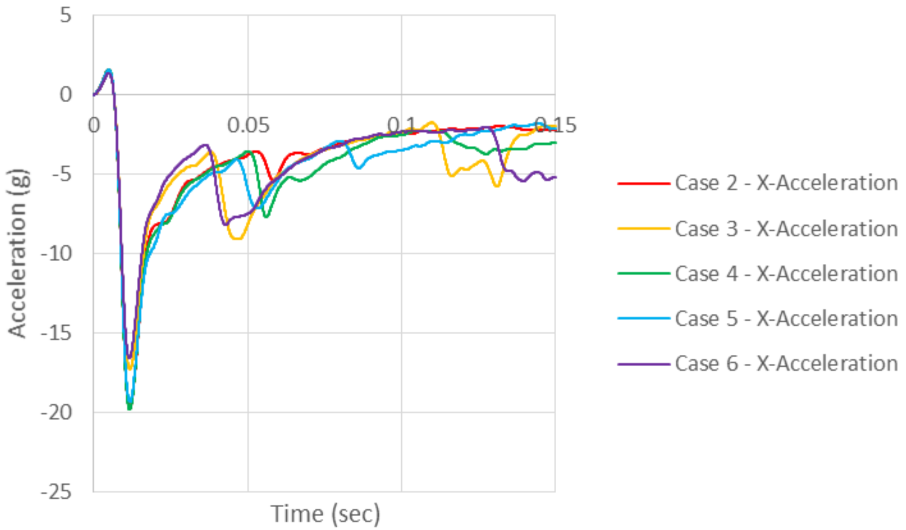


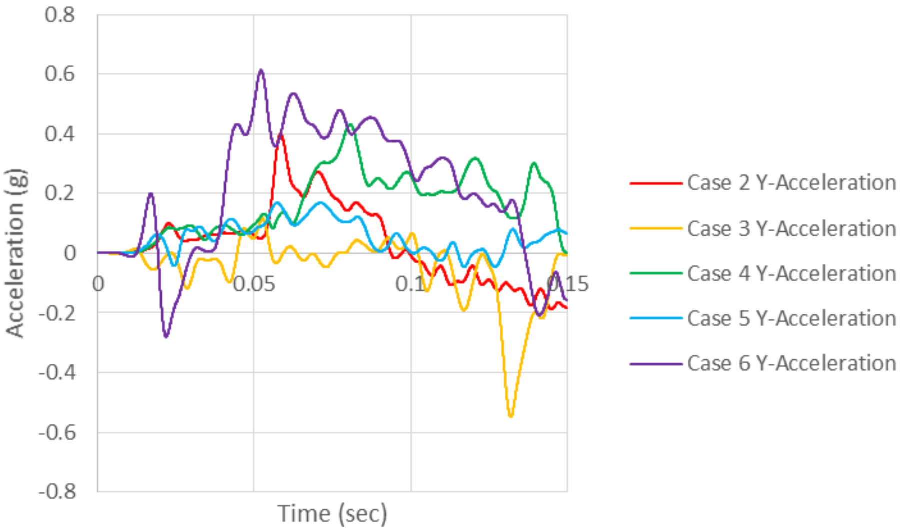
Method	Peak Acceleration [Earth G's]
Closed Form Spherical	21.9
Numerical Integration	19.7
LS-DYNA	20.0

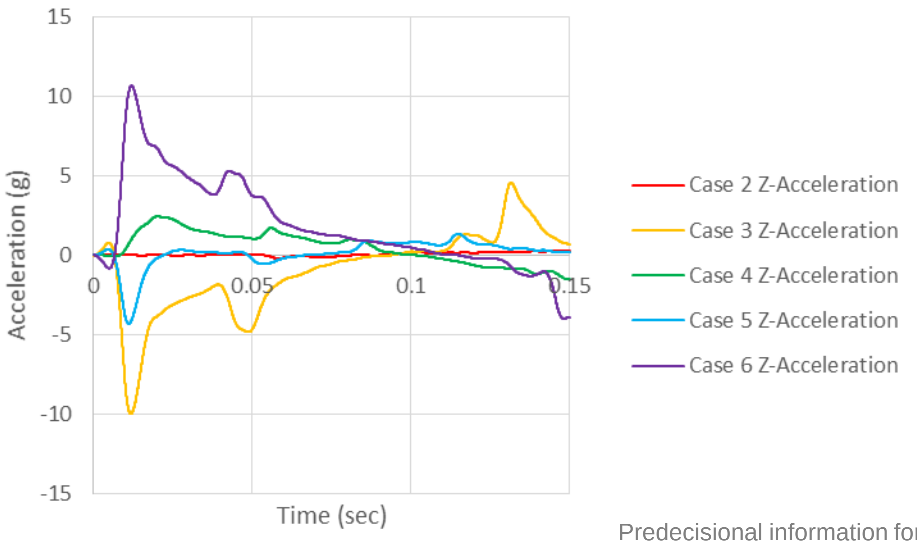


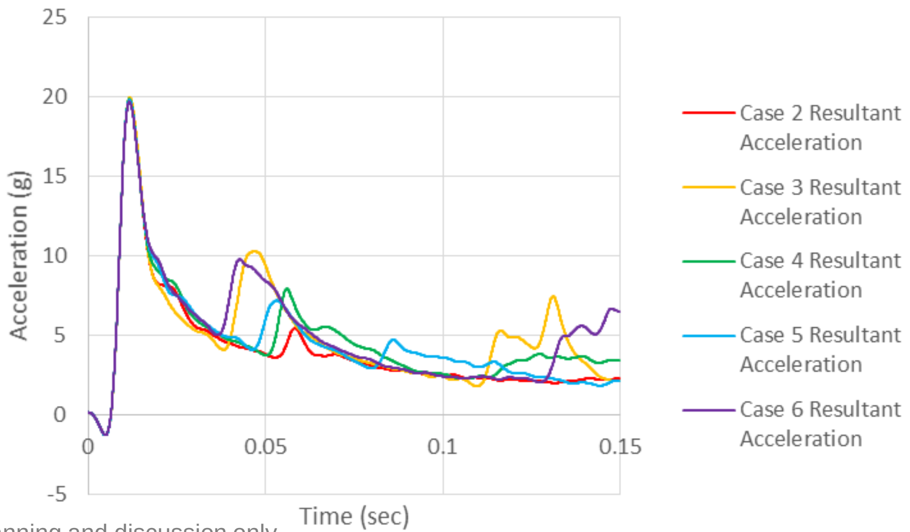
Results: G-Loads

Drag Plate, LS-DYNA for all cases. X-axis is out the nose of vehicle

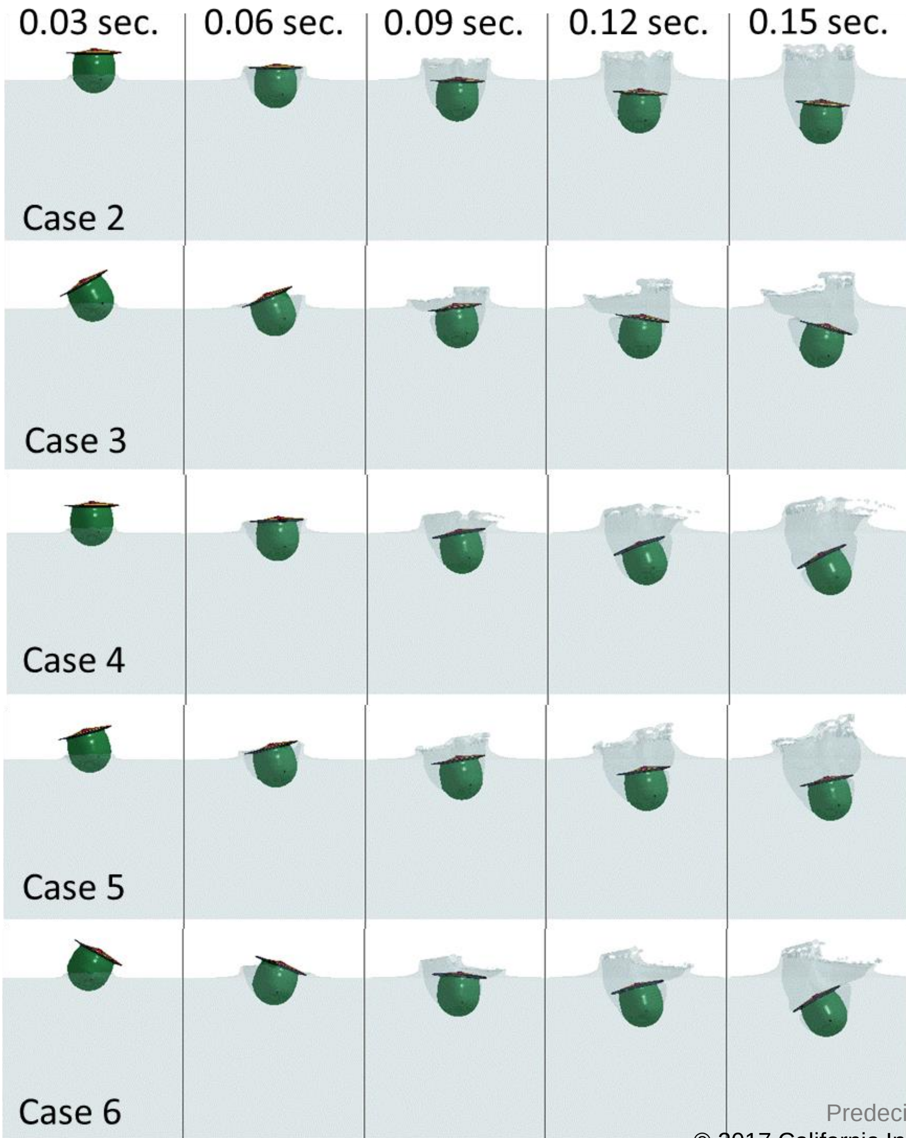






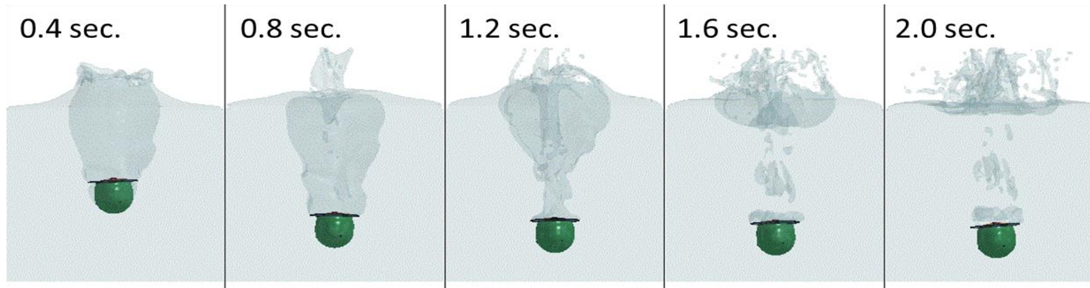


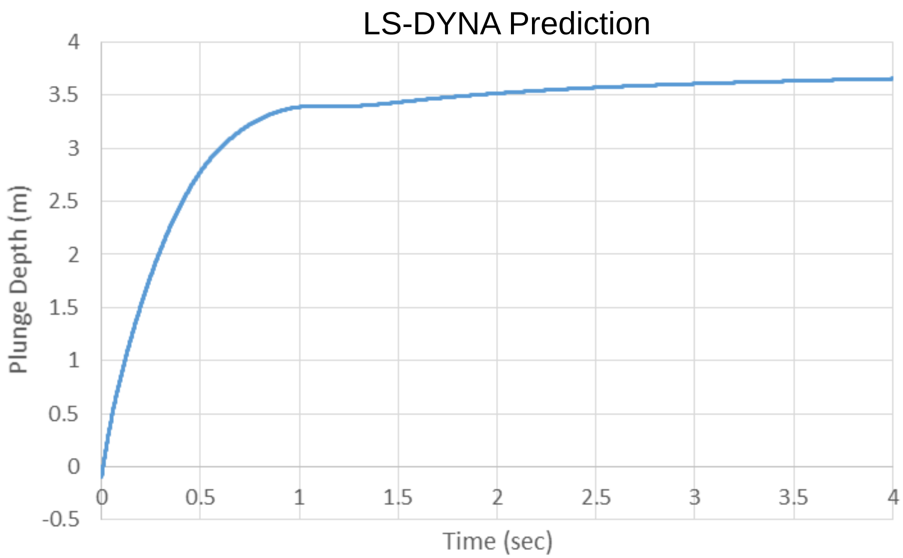
Results: G-loads Response Sequence

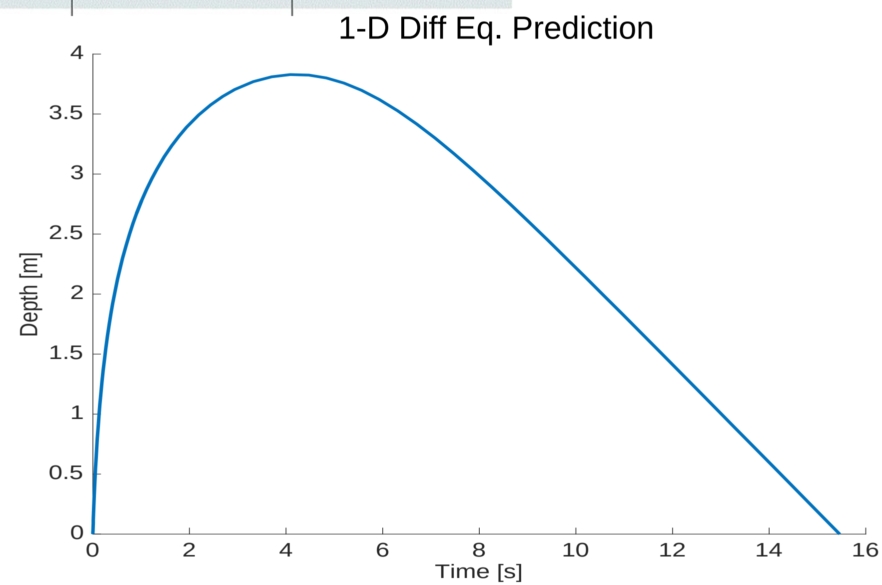


- Fluid impact phenomena predicted well compared to other experiments
- Note void above the plunging body

Results: Plunge Depth







Method	Plunge Depth [m]	Resurge Time [s]
Conservation Equations	4.2	10
Numerical Integration	3.8	15
LS-DYNA	3.7	-

Conclusions

- Analytic expressions, LS-DYNA, and experiments (on other test articles) yield results within 20% of each other for normal impacts
  - Analytics useful for rapid initial scoping/screening of designs
- LS-DYNA accurately predicts impact loads and impact flow phenomena
  - Useful for determining lateral loads of off-vertical impacts
  - Valuable in calculating margin for instrument accelerations for off-nominal sea entries
    - Includes pitch angles and horizontal winds
- Resurge difficult to predict due to complex flow
  - Behavior of cavity is important
  - Solution also degrades over time
  - Run time becomes computationally expensive
  - Scale model tests and correlations may be useful
  - CFD may be more effective
- Simple models suggest plunge depth of ~4m and resurge time of ~10 s for baseline Titan probe design in this study
  - May permit measurement of conditions at depth
  - Tests and/or CFD needed to better understand vehicle depth and entrainment of liquid adjacent to probe surface

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Back-up

Related Work

- Von Karman: derived momentum approach for wedges entering water
  - To find max impact load for seaplane floats
- McGehee, et al: Theoretical and experimental water impact accelerations results for Mercury program
- Stubbs, et al: Experimental results for Apollo program
- Hirano and Miura: Closed form solution for peak load of spherical and conical shapes related to experimental results
- Lorenz, et al and Seiff, et al: Conducted experimental impact tests into water and kerosene for Titan probes Huygens and TiME

Test Results: