Computational Fluid Dynamics

Takayuki Aoki

Global Scientific Information and Computing Center
Tokyo Institute of Technology

Schedule (1)

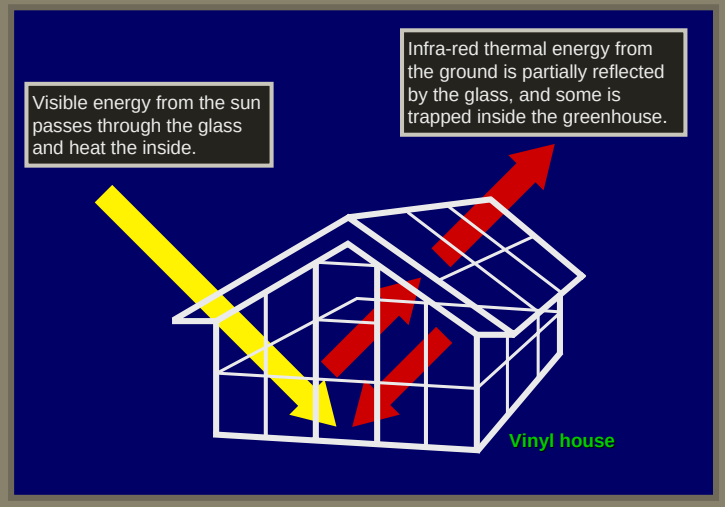
- **Classification of Partial Differential Equations**
- **Discretization in space and time**
- **Finite Difference Method**
- **Diffusion Equation**
- **Advection Equation**
- **Poisson Equation**

Schedule (2)

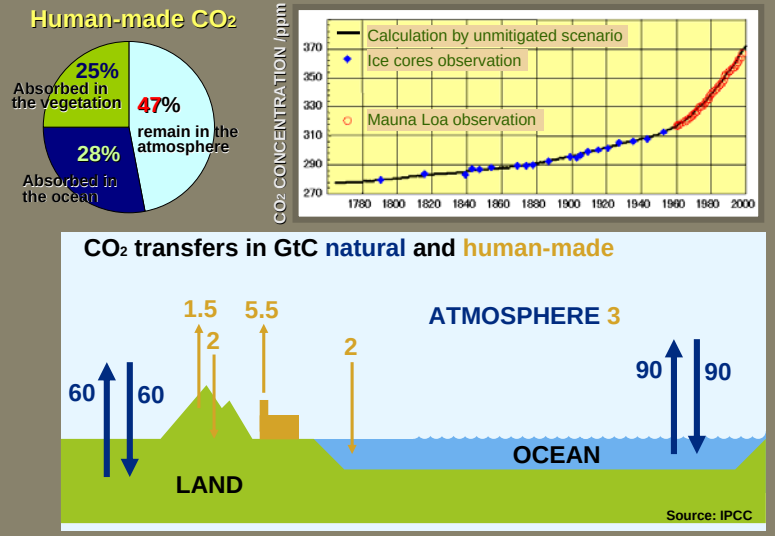
- **1-D and 2-D Burgers Equations**
- **Shallow Water Equation**
- **Incompressible Navier-Stokes Equation**
- **Visualization**

In XXXX, Manhattan, New York

GREENHOUSE EFFECT



NATURAL AND HUMAN-MADE CYCLE OF CARBON



Environmental Problems

Human activity

- Climate Change
  - global warming
- Air pollution
  - Acid rain
  - Ozone hole

Natural Phenomena

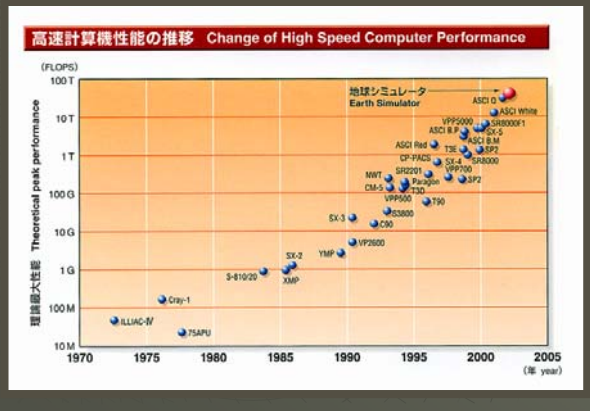
- Meteorological Disasters
  - Heavy rain, Drought
- Diastrophism
  - Earthquake
  - Volcanism

Fastest Supercomputer
in the world

TOP500 SUPERCOMPUTER SITES

In 2002 June

No.1	Earth Simulator	Japan (Jamstec) (NEC)	35.86 TFlops
No.2	ASCI White	USA (LLNL) (IBM Power 3)	7.23 TFlops
No.3	Alpha Server	USA (Pittsburg SC) (Alpha)	4.46 TFlops



Latest Top500

2005 November

No.1	BlueGene/L	USA (DOE) (IBM)	280.60 TFlops
No.2	BlueGene/L	USA (IBM Watson) (IBM)	91.29 TFlops
No.3	ASCI -Purple	USA (DOE) (IBM)	63.39 TFlops
No.4	Colombia	USA (NASA) (SGI)	51.87 TFlops
No.5	Thunderbird	USA (Sandia) (Dell)	38.27 TFlops
No.6	Red Storm d	USA (Sandia) (Cray)	36.19 TFlops
No.7	Earth Simulator	Japan (Jamstec) (NEC)	35.86 TFlops
No.8	MareNostrum	Spain (Balserona) (IBM)	27.91 TFlops

BlueGene/L - eServer (IBM) Power 4 × 131,072 CPU

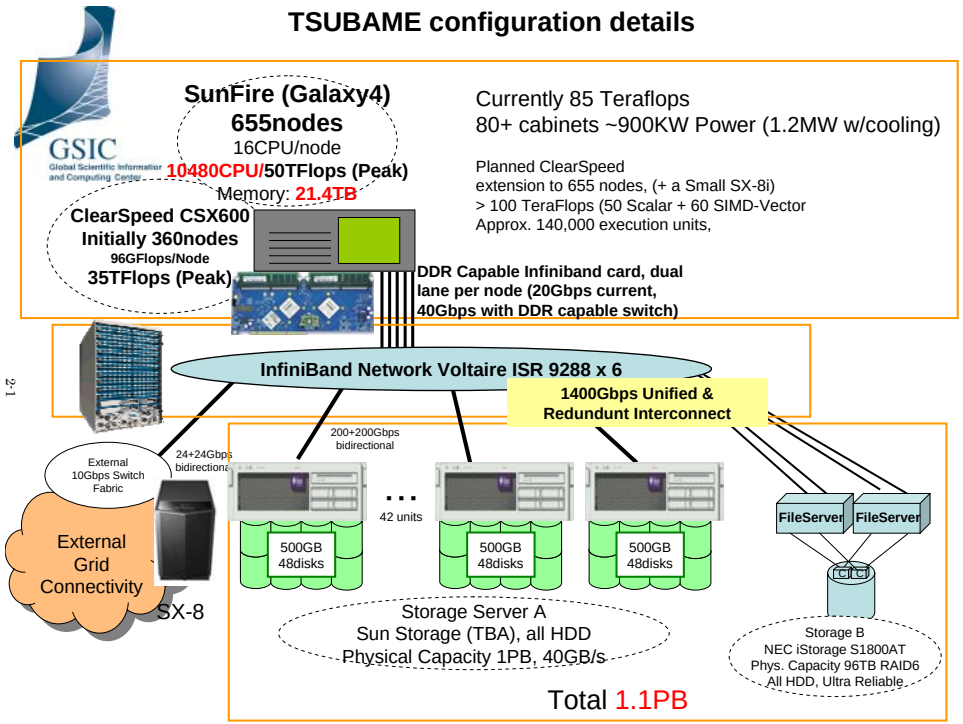
GSIC
Global Scientific Information and Computing Center

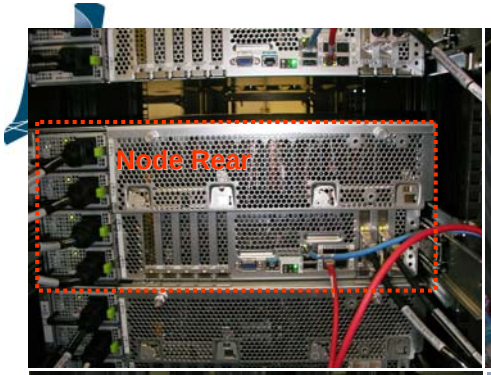
TSUBAME Grid Cluster

- **T**okyo-tech
- **S**upercomputer and
- **UB**iquitously
- **A**ccessible
- **M**ass-storage
- **E**nvironment

TSUBAME means swallow in Japanese,
Tokyo-tech symbol is swallow.

TSUBAME configuration details





TSUBAME is #7 Fastest in World

Linpack is used as a performance measure in ranking

T/V	N	NB	P	Q	Time	Gflops
WR10R2R4	1334160	240	36	144	41462.22	3.818e+04

Rank	Site	Computer	Processors	Year	R_{max}	R_{peak}
1	DOE/NNSA/LLNL United States	BlueGene/L - eServer Blue Gene Solution IBM	131072	2005	280600	367000
2	IBM Thomas J. Watson Research Center United States	BGW - eServer Blue Gene Solution IBM	40960	2005	91290	114688
3	DOE/NNSA/LLNL United States	ASC Purple - eServer pSeries p5 575 1.9 GHz IBM	12208	2006	75760	92781
4	NASA/Ames Research Center/NAS United States	Columbia - SGI Altix 1.5 GHz, Voltaire Infiniband SGI	10160	2004	51870	60960
5	Commissariat a l'Energie Atomique (CEA) France	Tera-10 - NovaScale 5160, Itanium2 1.6 GHz, Quadrics Bull SA	8704	2006	42900	55705.6
6	Sandia National Laboratories United States	Thunderbird - PowerEdge 1850, 3.6 GHz, Infiniband Dell	9024	[illegible]	38270	64972.8
7	GSIC Center, Tokyo Institute of Technology Japan	TSUBAME Grid Cluster - Sun Fire X64 Cluster, Opteron 2.4/2.6 GHz, Infiniband NEC/Sun	10368	2006	38180	49868.8
8	Forschungszentrum Juelich (FZJ) Germany	JUBL - eServer Blue Gene Solution IBM	16384	2006	37330	45875
9	Sandia National Laboratories United States	Red Storm Cray XT3, 2.0 GHz Cray Inc.	10880	2005	36190	43520
10	The Earth Simulator Center Japan	Earth-Simulator NEC	5120	2002	35860	40960

- N : 1334160
- NB : 240
- PMAP : Row-major process map
- P : 36
- Q : 144
- PFACT : Right
- NBMIN : 4
- NDIV : 2
- RFACT : Right
- BCAST : 1ring
- DEPTH : 1
- SWAP : Mix (threshold = 240)
- L1 : transposed form
- U : transposed form
- EQUIL : yes
- ALIGN : 8 DP words

38.18 TeraFlops

- **Opteron Only, 648 nodes**
- **~14 Terabytes memory**
- **76.56% Efficiency**

High-resolution Typhoon Simulation

CReSS: Cloud Resolving Storm Simulator

Non-hydrostatic and compressible equation

Terrain-following in three dimensional geometry

Prognostic variables:

- three-dimensional velocity components
- perturbation of pressure
- perturbation of potential temperature
- subgrid-scale turbulent kinetic energy, TKE
- mixing ratios for water vapor and several hydrometeors

Cloud Physics Process

Bulk method of cold rain.

Prognostic variables for mixing ratios :

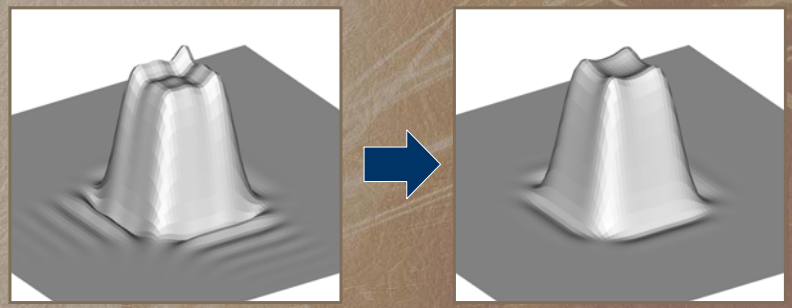
- water vapor
- cloud water
- rain water
- cloud ice
- snow
- graupel

Improved Dynamic Process

$$\frac{\partial \bar{\rho} u}{\partial t} + \bar{\rho}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} \right) = -\frac{\partial p'}{\partial x} + \bar{\rho}(f_s v - f_c w) + Turb.u$$

4thFDM+Leap-flog method
(with Asselin filter)

Semi-Lagrangian Scheme
Cubic-Lagrange, CIP Method

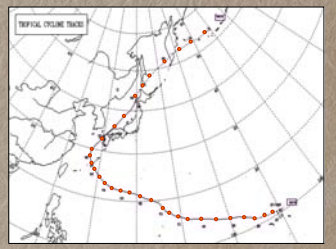


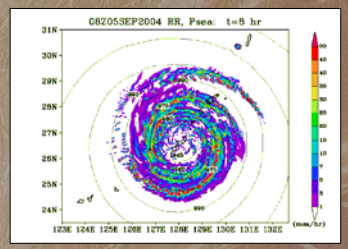
CFL = 0.15

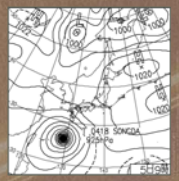
CFL= 0.6

Typhoon Simulation

#18-typhoon Sep 2004, Sever Damage in Kyushu

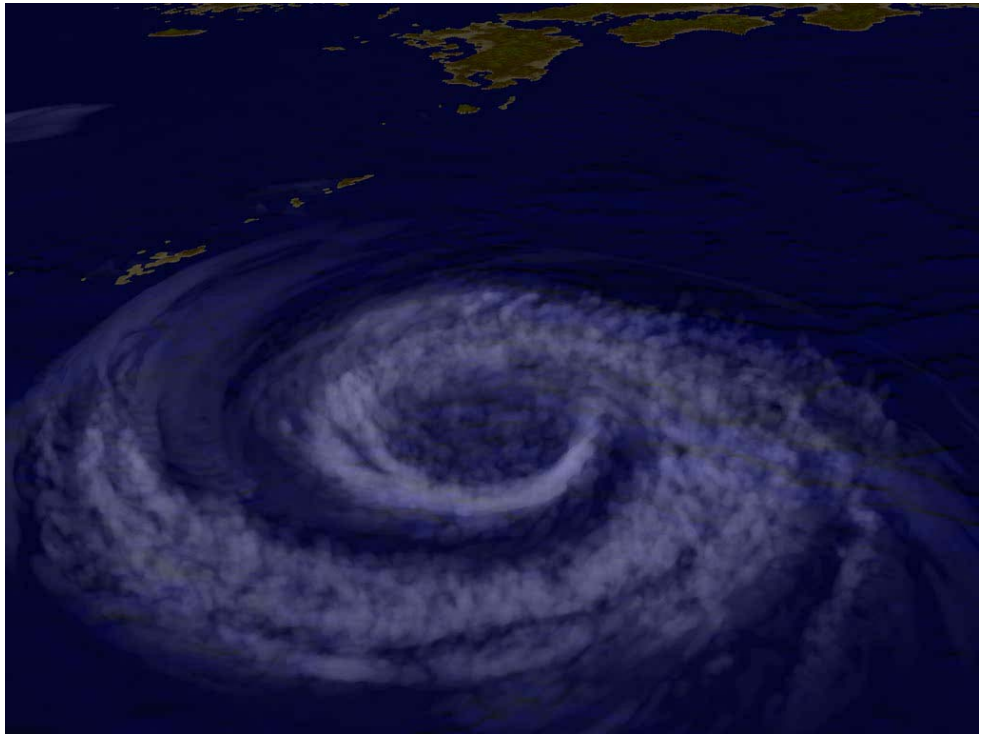




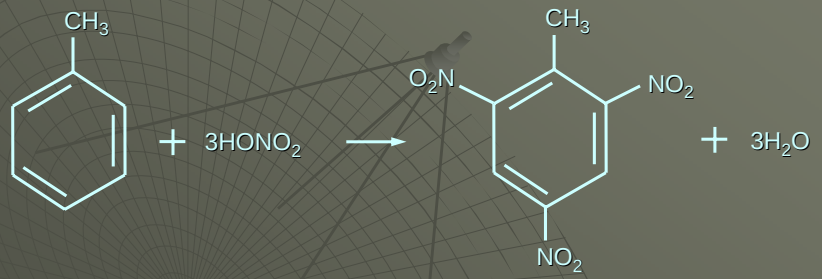


Calculation Conditions:

Domain	H: 1000 km × 1000 km × V: 18 km
H-gird size	1000 m
V-grid size	200 ~ 300 m (stretched)
Grid numbers	H: 1003 × 1003 × V: 63
Integration time	48 hours
Micro-physics	the bulk cold rain type
Initial condition	JMA Regional Spectral model output
Boundary	JMA Regional Spectral model output
Surface	real topography and observed SST
Earth Simulator	100 nodes (800 CPU)



Explosion Simulation

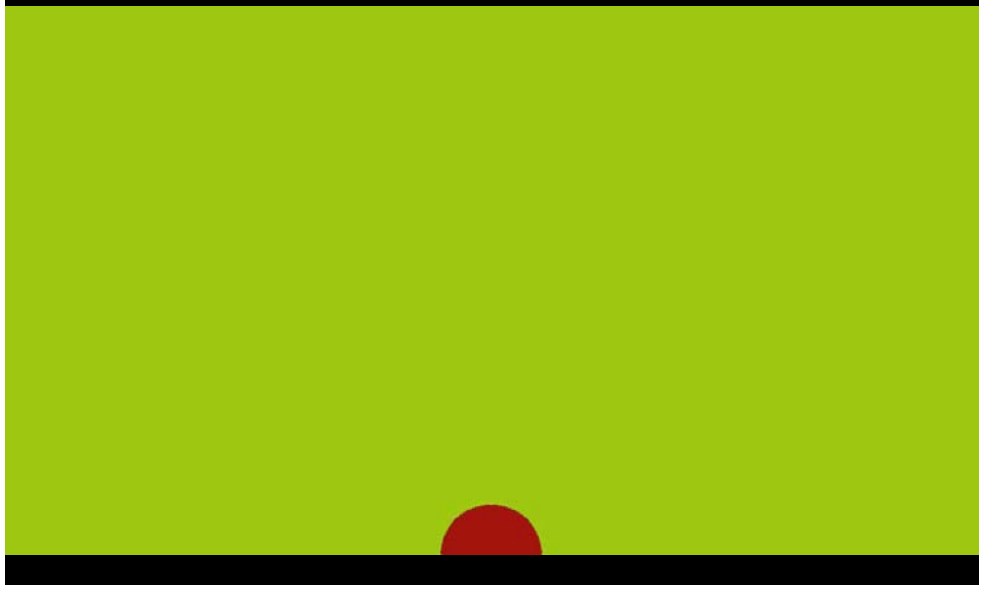


1kg-TNT explosion : 3.22 MJ
30kg-TNT explosion : 100 MJ

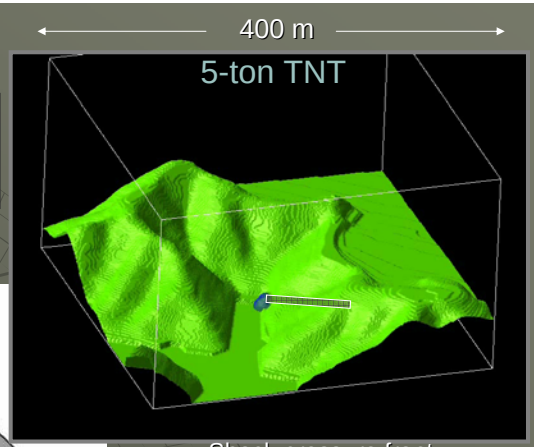
Dangerous and difficult experiment → Numerical Simulation

Blast wave just after explosion

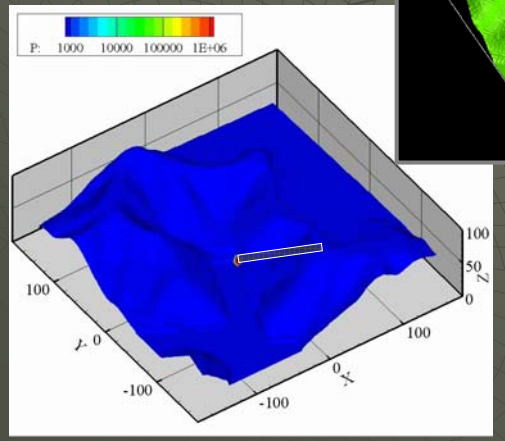
in Cylindrical 2-D geometry



Shock Propagation on Complex Terrain

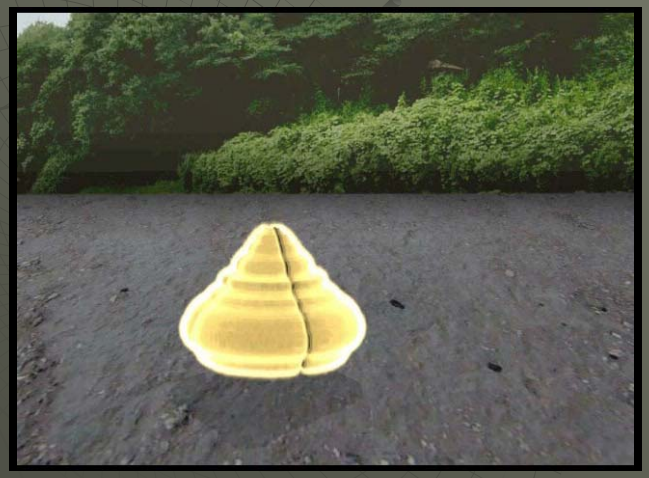


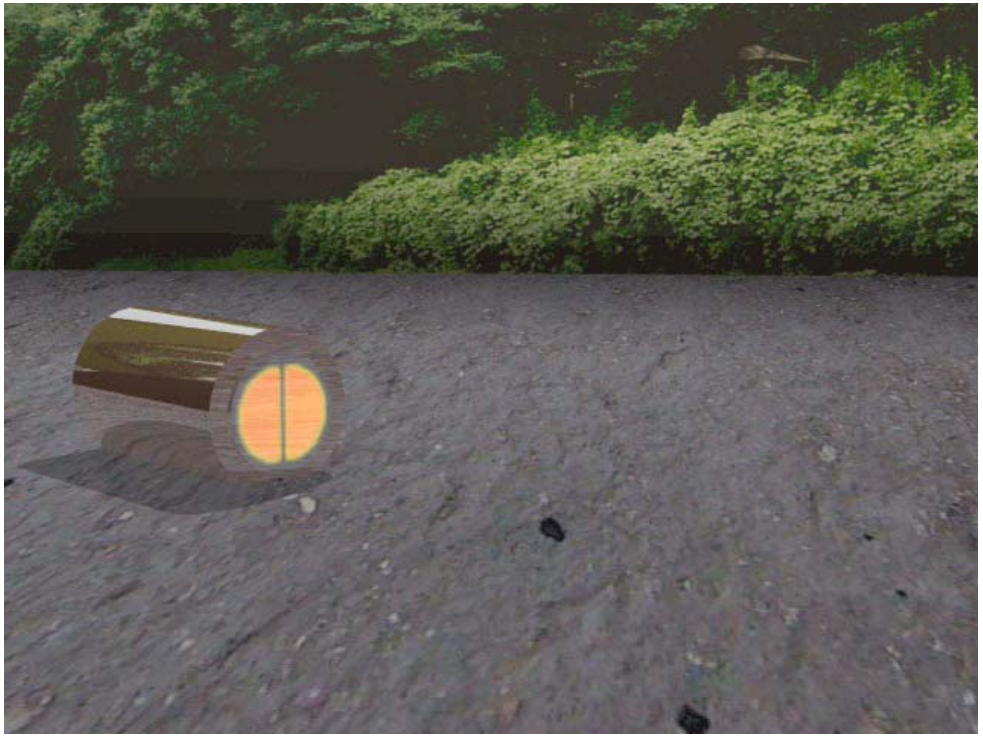
Shock pressure front



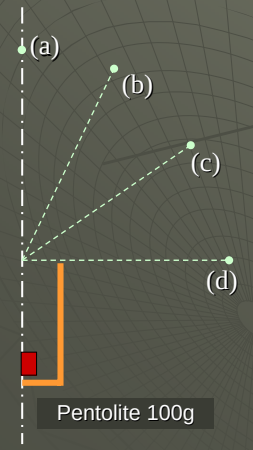
Pressure history
on the ground surface

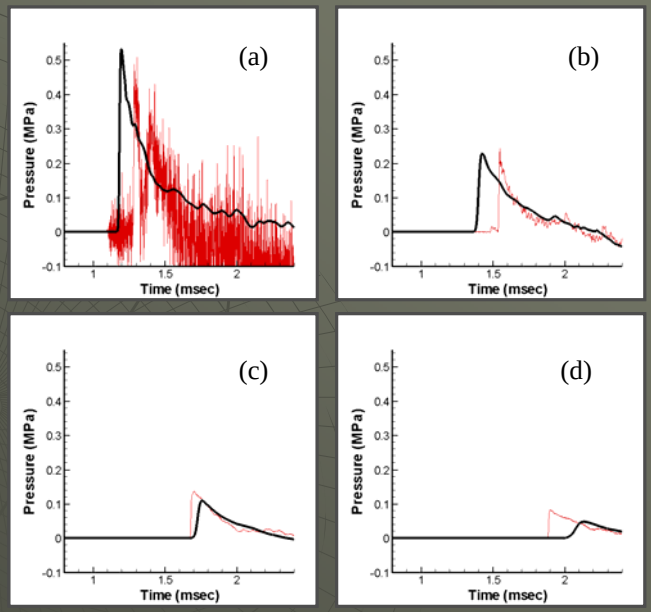
32kg-TNT EXPLOSION ON THE GROUND





Comparison with Experiment





32kg-TNT Explosion Experiment

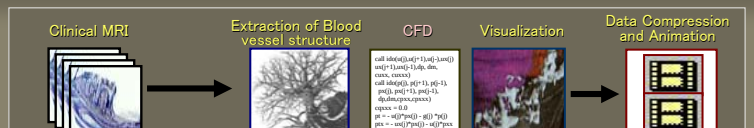
Safety test for 32kg-TNT Explosion on the ground.

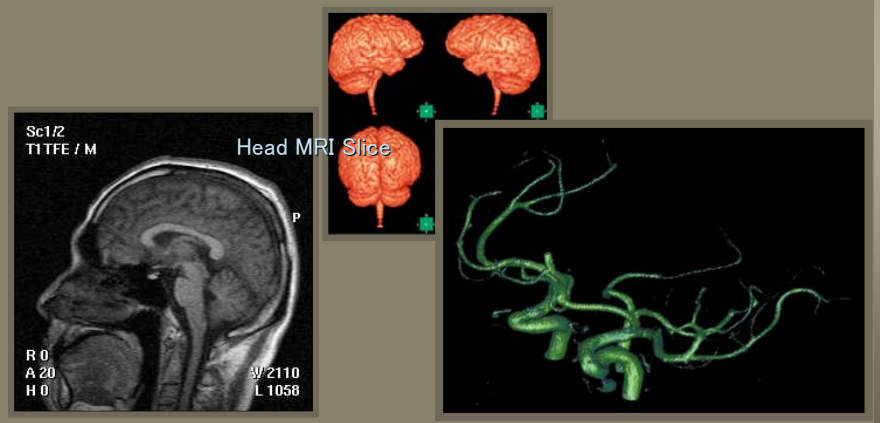
In 2002, December 3,
In Ooita Pref., Hijuu-dai, at Japan Ground Self-Defense Force,

The experiment was done by the Research Center for Explosion and Safety, National Institute of Advanced Industrial Science and Technology.

Recorded by High Speed Camera.

Blood Flow Simulation System

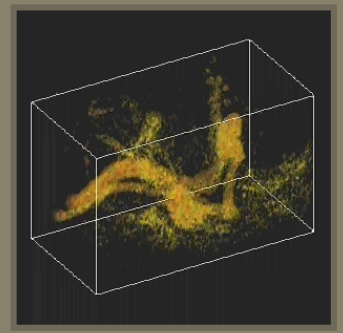




MRI Facility

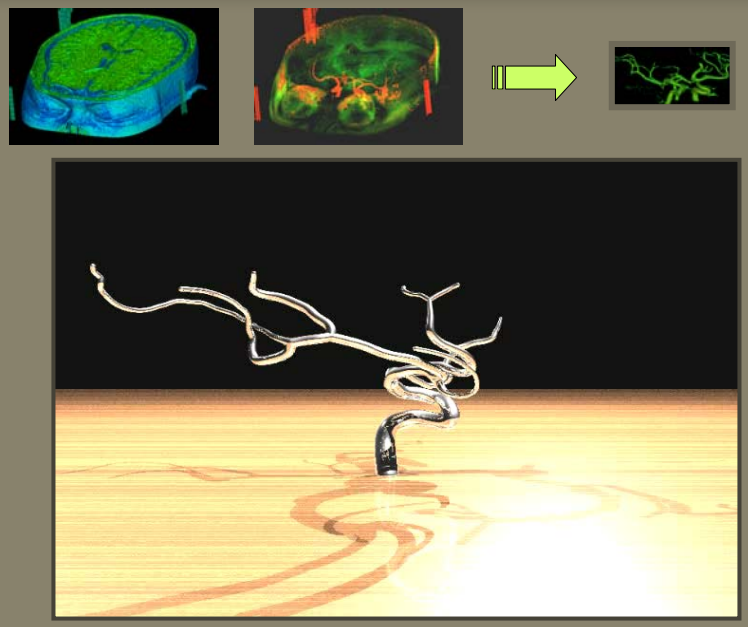
Collaboration : Division of Medical Imaging, National Institute of Radiological Sciences, Ikehira Lab.

Gyroscan Intera
1.5T Philips

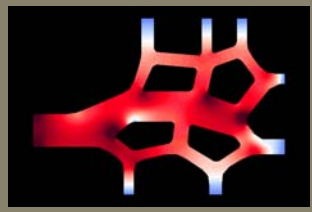


4-D MRI processing synchronizing electrocardiograph

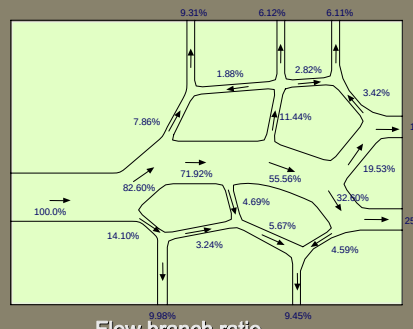
Extraction of Blood Vessel Structure from Voxel data



Blood Flow With Complex Branches

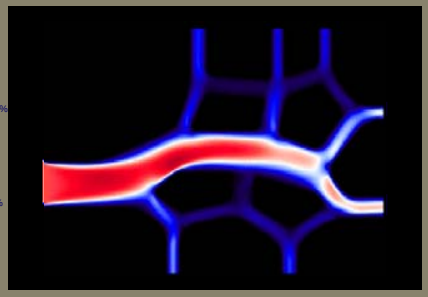


Pressure Profile



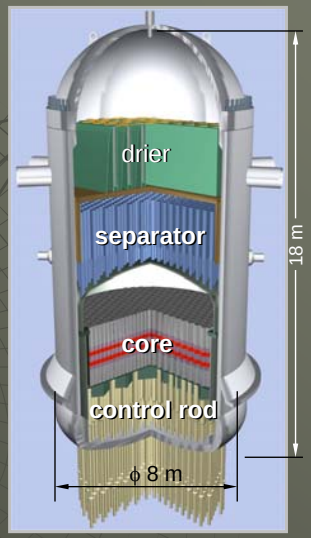
Flow branch ratio

Flow Velocities

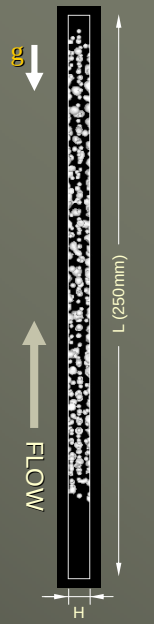


Bubbly Flow Simulation

- Channel Width (H) 10 mm
- Channel Length (L) 250 mm
- Mesh Size : 0.25 mm
- Mesh Number : 40 × 40 × 1000
- Equal grid spacing
- Incoming Flow Velocity : 0.5 m/sec
- Wall Boundary condition: non-slip
- Periodic in the gravity direction
- Room Temperature
- No thermal process
- Initial Condition
  - —Average Void Ratio : 0.1
  - —Diameter of bubble : 2 mm
  - —Number of bubbles : 594
  (=66 stages X 9)



BWR



Computational Methods

- Gas – Liquid Unified Solver : CIP (CCUP) method
- 3-dimentional Compressible / Incompressible fluid
- Surface Tension : CFS model
- Contact angle between wall and bubbles
- Surface tracking method : improved VOF method

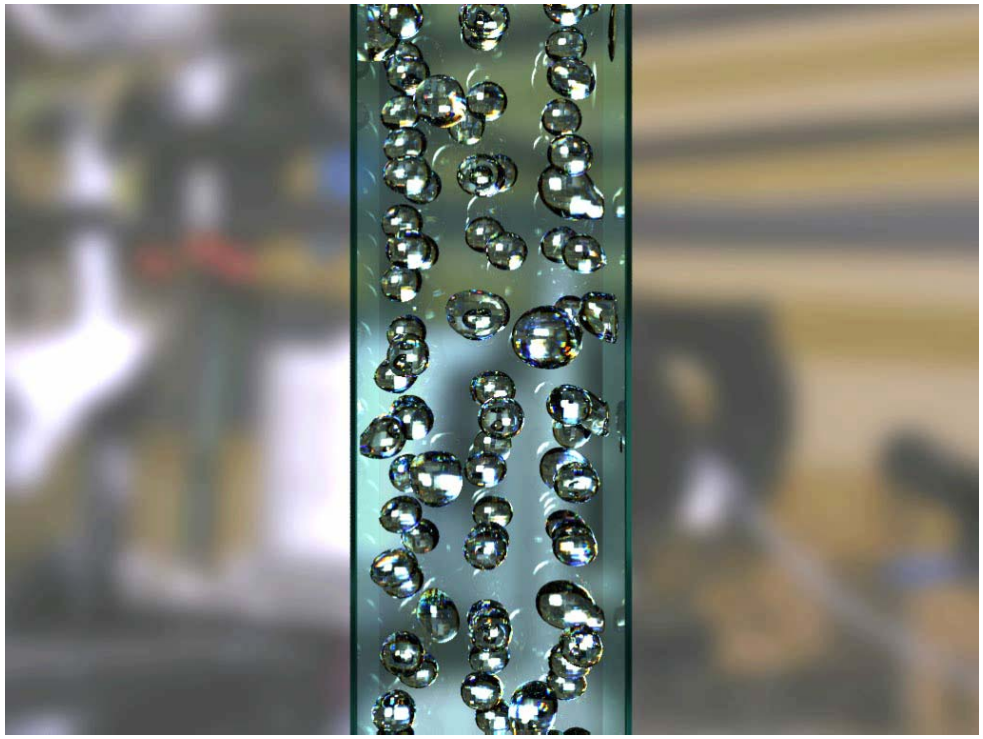
$$\frac{\partial \rho_l \phi_l}{\partial t} + \nabla \cdot (\rho_l \phi_l \boldsymbol{u}) = 0$$

$$\frac{\partial \rho_g \phi_g}{\partial t} + \nabla \cdot (\rho_g \phi_g \boldsymbol{u}) = 0$$

$$\rho = \rho_l \phi_l + \rho_g \phi_g \qquad \phi_l + \phi_g = 1$$

$$\frac{Du_i}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} + g_i + \sigma_i$$

$$\frac{De}{Dt} = -\frac{p}{\rho}\frac{\partial u_i}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) + q$$



Ray Tracing Visualization

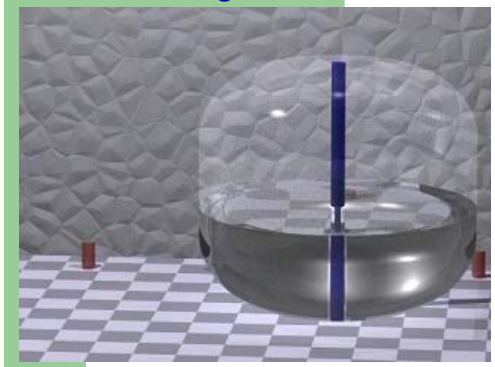
Free Software

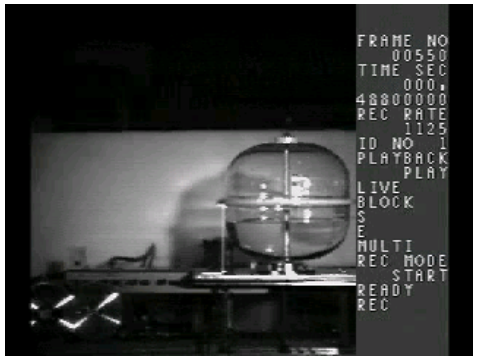
POV-Ray 3.6

Tracing light ray correctly
and reproducing optics.

Void Ratio data → Voxel DF3 format

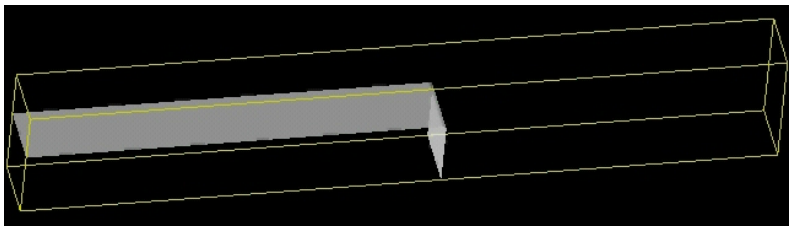
Sloshing





Prof. Takehiro Himeno (Univ. of Tokyo)

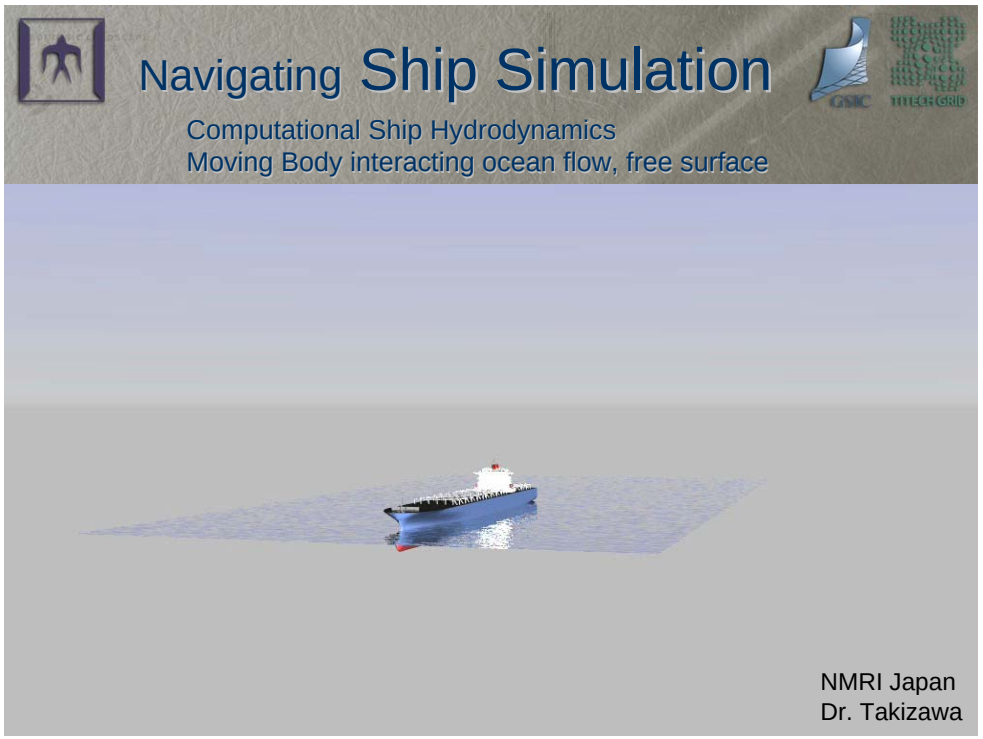
Non-linear wave



Prof. F. Xiao
(Tokyo Tech)

Navigating Ship Simulation

Computational Ship Hydrodynamics
Moving Body interacting ocean flow, free surface



NMRI Japan
Dr. Takizawa

Simulation for Falling Leaves

Major difficulties:

- Fluid-structure interaction
- Complex shape of leaves
- Very thin structure

Shape of the leaf :
modeled by
Geometry data
200 polygons
DXF or STL CAD format

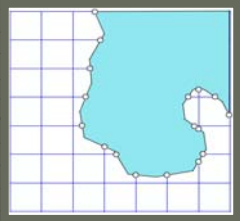
Computational Mother Domain: 50x50x80
Computational Sub-Domain: 40x40x30

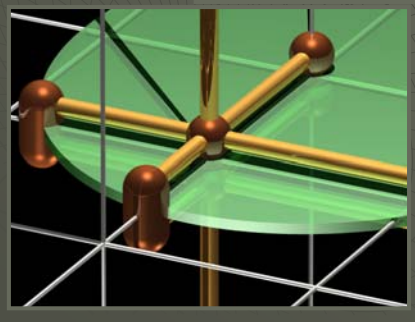
Some techniques

InterGrid (Cut Cell)

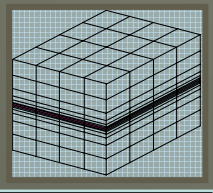
Two values at the same position,

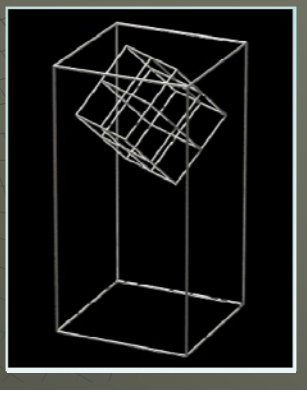
representing the front and the rear surface pressure.





Overset grid

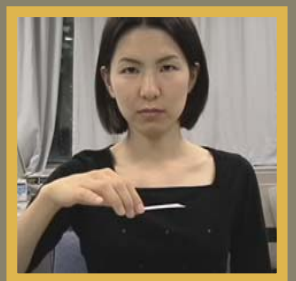




DO Experiment

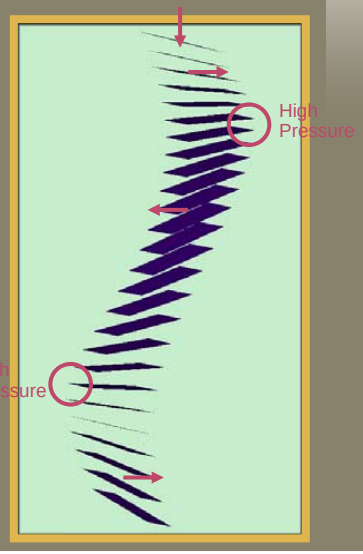
A Preliminary Simulation:

A Falling Piece of Paper
for example, a Name Card

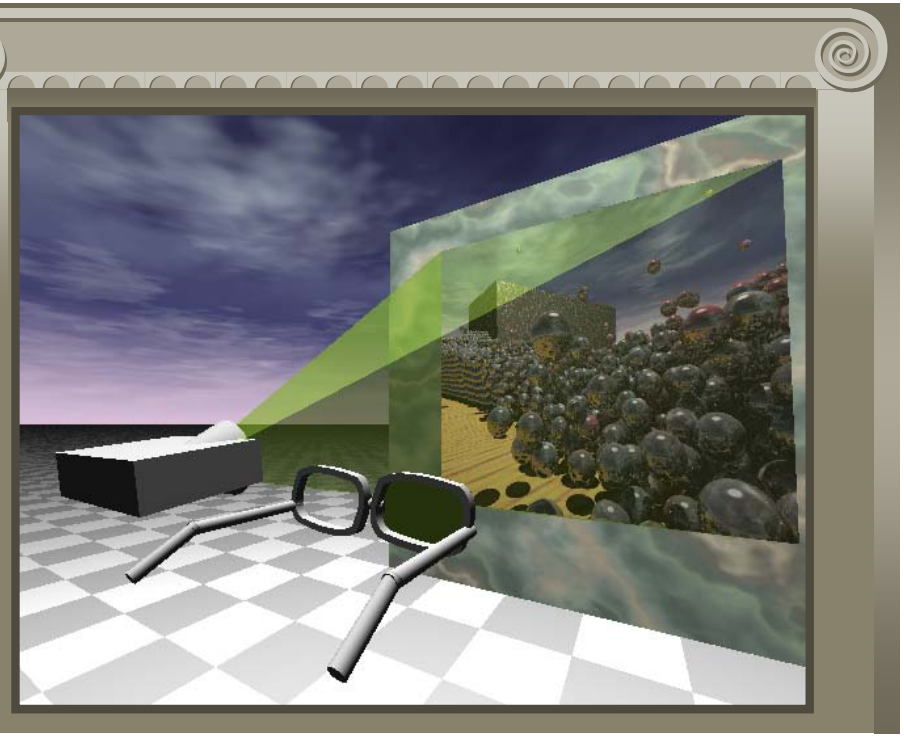


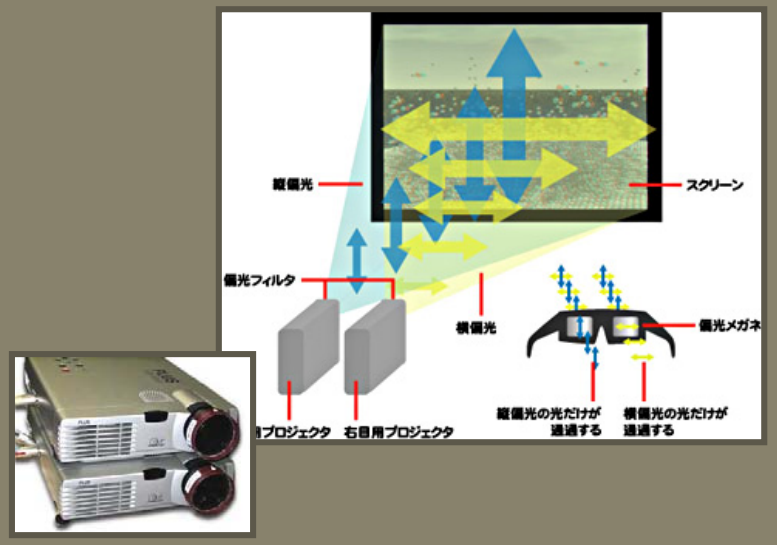
Mechanism of Flattering

- Start to fall with gravity acceleration
- Transverse acceleration by the lift force due to an attack angle
- Deceleration by the drag due to pressure and friction
- Torque Generation
- Inverse attack angle
- Transverse acceleration in the inverse direction



3D Visualization





Anaglyph
2

Particle Simulation for Disasters

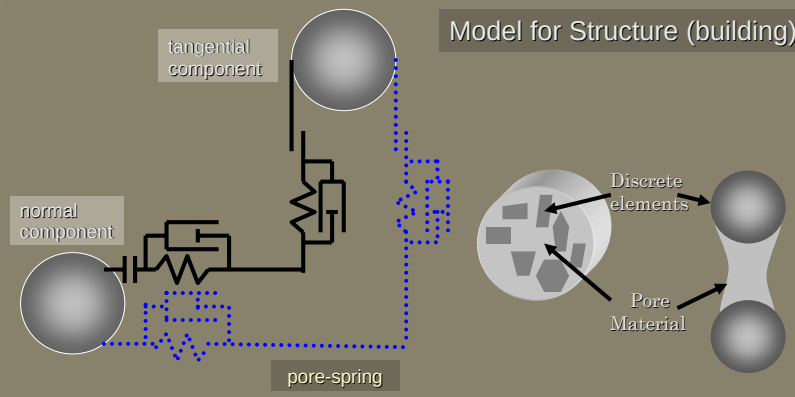
Structure destruction by Landslide, Boulder flow,
Crater formation by a meteorite impact

- **Fluid like behavior of Granular**
- **Structure Destruction**
  (Continuous model is not applicable)
  - Crack growth
  - Amputation
  - Shear
  - Smashing

eDEM
(Extended Discrete Element Method)

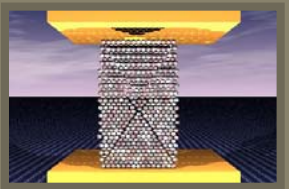
Model for Granular (Sand, etc)

Model for Structure (building)

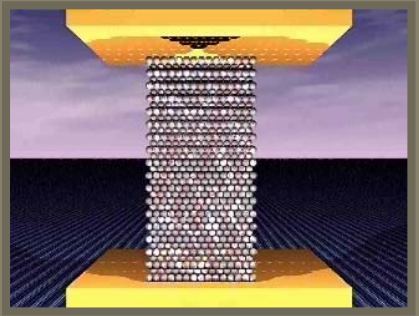


Compression Test of Concrete Structure

Check for Destruction model



Shear Band (Dilatancy)



離散要素法シミュレーションのアナグリフ立体表示

青木尊之 あおきたかゆき
東京工業大学学術国際情報センター
古市潔 ふるいちきよし
東京工業大学大学院理工学研究科
高橋通 たかはしとおる
(株)有沢製作所３Ｄ推進室

Visual Science Festa 2002 Grand Prix

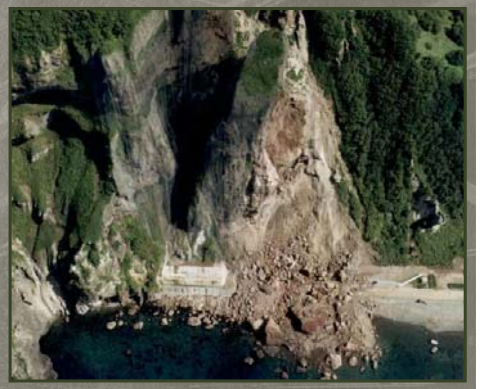
Rock Fall Simulation

Rock Fall : One of slope disasters

Prevention

- Control of Sediments
  exp : fence, wall, net
- Improvement of Hazard Map

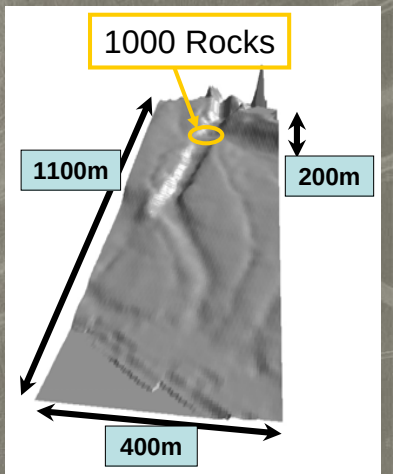
Numerical Simulation :
effective tool



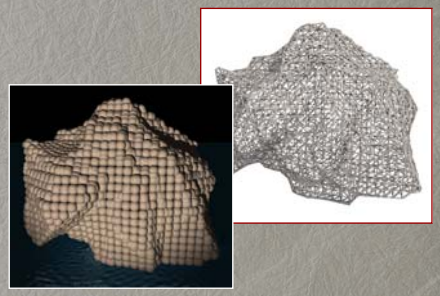
Aug 25, 1997

Rock Fall Simulation

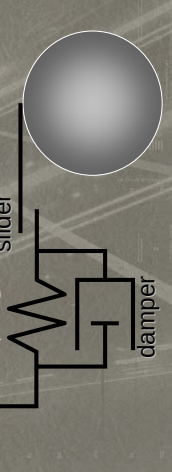
Digital Elevation Data



Non-Spherical Rock Model



DEM Discrete Element Method



Summation for all the particles

normal component

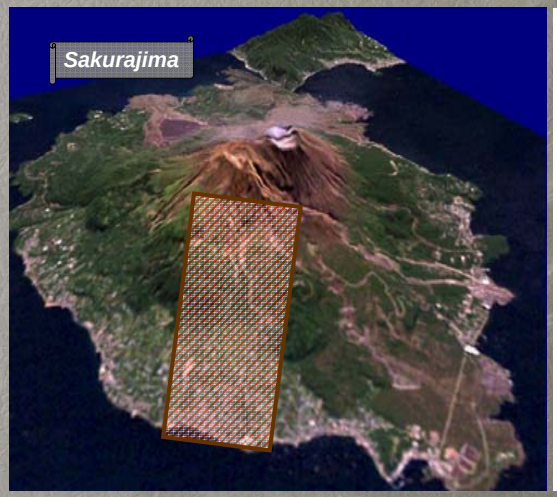
Translational and Rotational motion of rocks

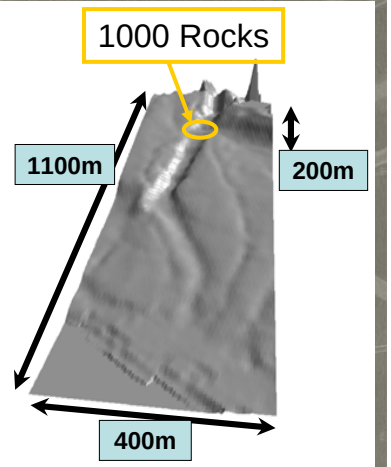
Quaternion

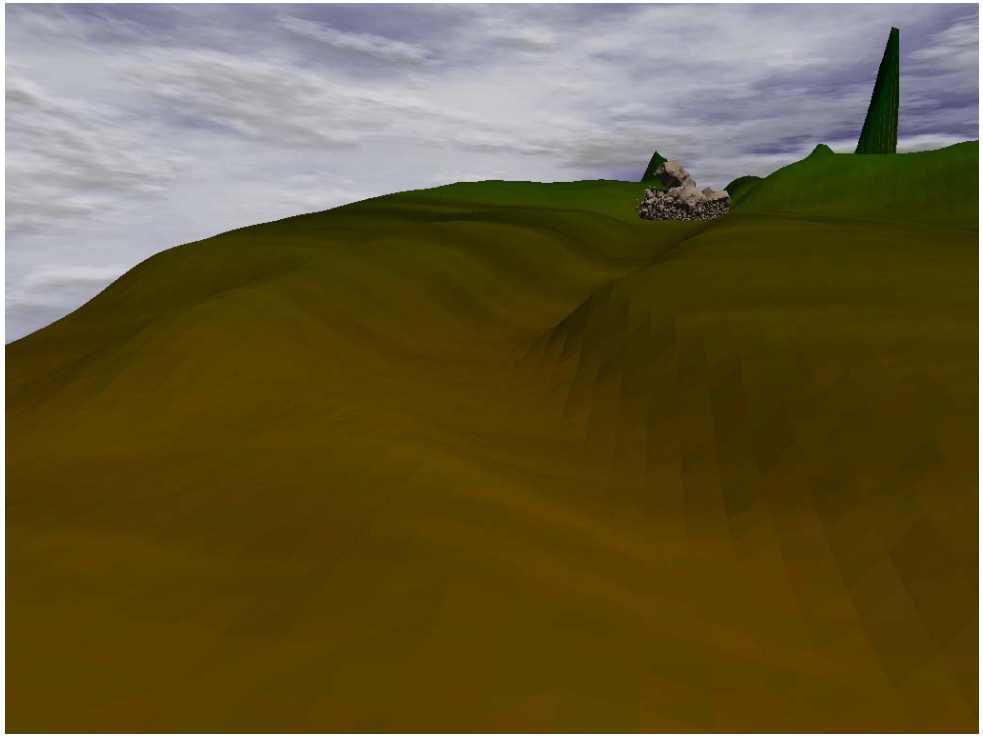
$$\tilde{Q} = Q_s + Q_i \mathbf{i} + Q_{ii} \mathbf{j} + Q_v \mathbf{k}$$

Rock Fall Simulation

Digital Elevation Data







Guard Fence for Rock Fall

Digital Elevation Data