The Dynamic Compaction of Sand and Related Porous Systems

Quasi-static to Shock

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Aims

• Apply techniques to determine the high-pressure and low-pressure response of sand
• Use a natural sand (marine)
• Present data on sand over a wide range of strain rates.
• Establish trends
• Provide data for validation of models
• Increase predictive capability
Modelling

Several groups of models exist -

- P-alpha model (volume-based)
- P-lambda model (length-based)
- Porter-Gould (potential-based)
- Thouvenin (laminar-based)
Parameters / Techniques

- Dry Sand - heated in oven.
- 5%, 10%, 20%, 22% by mass water,
- Instron
- Dropweight
- Hopkinson Bar
- Plate Impact
Size Distribution (natural sand)

Grain Size Distribution

Mass %

Minimum Grain Size
Sand - bi-modal mix

- Bimodal sand - 150-210 micron + 50-63 micron particles
- No significant difference found with the natural “mix”.
- Both materials will be referred to as “sand”
Instron - Quasi-Static
Parameter Space

- 10 kN load capacity
- Water content 0, 5 or 10 %mass.
- 6 g samples
- Stainless steel cell
  - 13 mm inner diameter
- Piston driven in at 5 mm/min.
Instron - Results

![Graph showing density vs. pressure for different conditions.](image-url)
**Starting Density**

- Obviously important
- In range the materials move closer together
- Do not become identical
- Friction between the grains
- Lock-up with pressure
- Movement of particles
- Force Chains within the sample
- Skeletal Strength
Moisture Content

![Graph showing moisture content vs pressure with different markers for dry and water samples.](image)
Water Content

- Starting density order
  - Dry > 10% Wet > 5% Wet
- Dry = limited change in density
- Wet = movement in grains
- Wet = move along parallel paths
Drop-weight Parameters

- 4 orders strain-rate faster than Instron
- 6.414 kg weight
- Maximum height of 120 cm.
- Guided
- Velocities of up to 5 ms$^{-1}$
- Sample cell and size - same as Instron
Schematic Drop-weight

- Weight
- Steel Plate
- Electromagnet
- Steel guide rod
- Light gates and trigger point
- Force transducer
- Impact point
- Impact rig base (cone supported by a hydraulic shock absorber)
Sample Cell - Stress monitoring

- Impact rod
- Steel tube
- Sample
- Anvil
- Strain gauges
Force transducer
Raw Strain Signal

Stress + Deceleration (distance)
... and the results
Trends

- Trends
  - Dry sand - little compaction
  - Wet sand - grain movement
  - Lubrication
  - In all cases limited fracture

- In Wet samples - see some water flow out of pores
Comparison -
Comparison - Quasi to Dropweight


Intermediate Rates

Hopkinson Bar

- Strain rate up to $10^4 \text{ s}^{-1}$
- Kolsky / Hopkinson Bar technique
- Bars - elastic waveguides
- Strain gauges on bars
- Stress-time / strain - time
Set Hopkinson pressure bars
Diameter of 10/20 /60mm
Modified Kolsky method for poorly coherent and low-density materials
Stress / Strains in the System

Stress components in a specimen and in the confined jacket
Data from Jacketed Hopkinson System

![Graph showing data from Jacketed Hopkinson System]

- Lateral trust
- Tangential stress

Pressures range from 0 to 300 MPa, and stresses range from 0 to 180 MPa.
The Governing Relationships

- \[ \tau = \frac{(\sigma_x - \sigma_r)}{2} \]
- \[ P = \frac{(\sigma_x + 2\sigma_r)}{3} \]
- \[ \tau = C + (\tan \psi)P \]
- \[ P = \frac{(\sigma_x - \frac{4}{3}C)}{\left(1 + \frac{4}{3} \tan \psi\right)} \]
- Loose soils - C is small - little static shear strength
Data obtained
The Cavendish Gas-Gun Facility

- 50 mm bore / 5 m long barrel
- 20 l gas reservoirs
- 350 atm. max. driving pressure
- 150 - 600 g projectiles
- Velocities up to 1.2 km s$^{-1}$
Manganin Foil Stress Gauges

Gauges - piezoresistive
Time resolution 30 - 200 ns dependant on geometry
Accuracy ± 2.5%
Different sizes available

Encapsulated Gauge

2.3 mm
6.0 mm
Copper Impactor on Copper Target

- Impact Velocity = 498 m s\(^{-1}\), 10 mm Cu Flier
- Target = Impact Face /10 mm Cu/Gauge/20 mm Cu

![Graph showing pressure versus time with a peak pressure of 9.46 GPa and risetime ~200 ns.](attachment:image)
Sample Arrangement

Sabot

50 mm diameter

2 mm 2 mm

3 mm 10 mm

90 mm diameter

Drawing not to scale
Wave reflection in cell

- Shock waves - black lines
- Release waves - blue lines
- Dashed line - indicates compaction
Impact at 200 m s$^{-1}$

Pressure / GPa

Time / µs

Front
Rear
$500 + 505 \text{ m s}^{-1}$
812 m s$^{-1}$
Rear Gauge Variation
Features in Output Traces

- Ramping region - pore collapse
- Shock velocity on principal Hugoniot
  time difference between gauges
- 1\textsuperscript{st} Plateau - secondary Hugoniot
- 2\textsuperscript{nd} Plateau - ring-up, wave reflection
- Shock velocity in pre-compressed sand
  (gauge comparison)
Shock thickness / particle size

- Rise time of first pulse
- Shock velocity

- 200 m s$^{-1}$
  - 1 $\mu$s rise time and $U_s$ 1 mm $\mu$s$^{-1}$
  - 1 mm or 4 grain particles

- 500 m s$^{-1}$
  - 0.5 $\mu$s rise time $U_s$ 1.4 mm $\mu$s$^{-1}$
  - 0.7 mm or 3 grain particles

- 800 m s$^{-1}$
  - 0.2 $\mu$s rise time and $U_s$ 2 mm $\mu$s$^{-1}$
  - 0.4 mm or 2 grain particles

- Need appropriate length-scale model (mesoscopic)
Comparison -

Intermediate to High-rate

• Assume relationship lateral vs. longitudinal stress ~same in shock

• Overlap of stress range of Hopkinson bar with the shock study
Results Combined Stress + Pressure

Stress or Pressure / GPa

\[ y = 0.0203 e^{10.691x} \]

\[ y = 0.011 e^{10.691x} \]

\[ y = 0.02 e^{10.827x} \]
Water content

Particle Velocity Space

Shock Velocity (km s⁻¹)

- 22% sat. 1.84 g cm⁻³,
  Us = 0.32 + 4.92 Up
- 20% sat. 1.81 g cm⁻³,
  Us = 0.71 + 2.90 Up
- 10% sat. 1.53 g cm⁻³,
  Us = 0.23 + 2.26 Up
- Dry 1.43 g cm⁻³,
  Us = 0.53 + 1.64 Up

Particle Velocity (km s⁻¹)
Stress Space

Long stress

- 22% sat. 1.84 g cm$^{-3}$
- 20% sat. 1.81 g cm$^{-3}$
- Dry 1.43 g cm$^{-3}$
- Dianov et al. [1], 23% sat. 1.93 g cm$^{-3}$
- Dianov et al. [1], dry 1.52 g cm$^{-3}$

Particle Velocity (km s$^{-1}$)
Effect of Water Content

- 0-10% water (weight) ~ dry
- 10 - 20% marked change
  - Higher level, faster sound speed
- Change 20 to 22% as large as from 10 - 20%
Conclusions

- Sand characterised over a range of conditions
- Low rate = friction / grain movement
- High rate = fracture
- Water content = strain rate dependant,
  - Low rate few % - big effect - lubrication
  - Intermediate rate - stronger effect at higher levels
  - High rate - small % water, no effect (>10%)
  - Large effect small % change at high saturation
- Measured Bulk Response
- Low-density sample shows different strain rate dependance, compaction processes
Recent / On-going Areas

- Grain size over a wider interval
- Find size / volume element that can be used to describe bulk response
- Model the fracture, collapse process
- Meso-level modelling
- Ductile grains
**Dyanmic Impact - Longitudinal and Lateral components**

1. Expanding cone shaped area of material moving longitudinally
2. Fixed angle of cone through all images

1. Lateral displacement roughly uniform along rod
2. Same lateral extent of deformation throughout

250us after impact

**Quasi-static penetration**

- Penetration carried out at a rate of 1.5 mm/min (2.5 x 10^{-5} m/s) using an Instron compressive tester.

- Same sample geometry, projectile, x-ray setup etc.

- Looking for rate dependence in the penetration process - will give a fuller understanding of the behaviour of the material
Longitudinal and Lateral components
In the quasi-static case most of the material down to the rod tip is moving upwards.

There is no travelling compaction wave in the material.
Theoretical Construct
R. Blumenfeld

\[ C_{ij}^{cgp} = \left( \tilde{\xi}_{cgp} \times \tilde{r}_{cgp} \right)_i R_{ij}^{cg} \]

\[ V^q = V^{cgp} = \frac{1}{3} \text{Tr}\{\tilde{C}_{cgp}\} \]
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