

# Diagnosics for High-Speed Particulate Media Impacts

## An International Collaboration with Osaka, Tohoku & Chubu Universities, Japan



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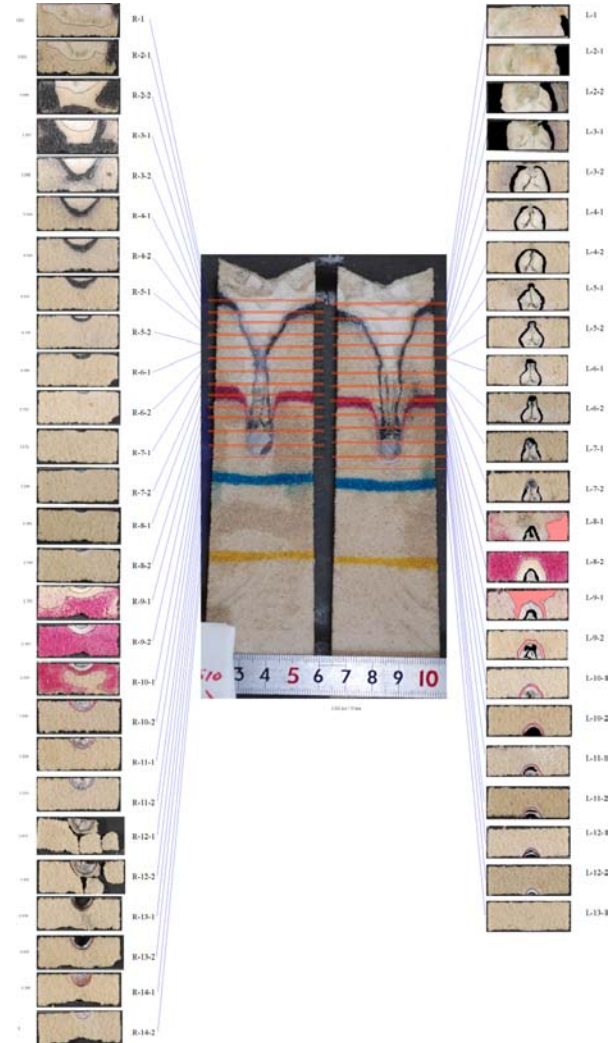
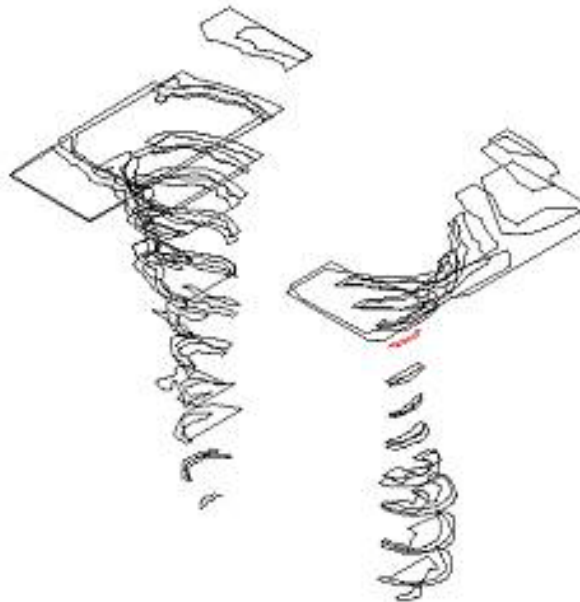


# Agenda



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- Objectives
- Why international?
- Timelines
- Successes



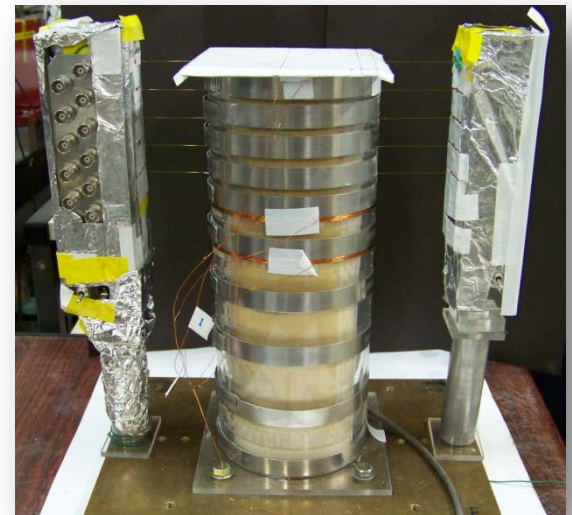


# Objectives



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- Develop diagnostics for high-speed impacts with particulate materials
- Leverage world-wide creativity & capabilities
- Learn to think in the way that particulate materials behave
- Shrink the world
- Timeline: 3-year projects administered in 1-Year renewable grants.





# Why International?



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- Access to creative thinkers
- Access to unique facilities
- Excellent research value/\$ ratio—Large teams for minimal \$
- Research immersion & focus time
- Access to Pacific Rim research community



# Payoff



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- **By the numbers:**

- 2 years nearly complete
- \$100K AFRL/RW funds invested
- \$100K AFOSR/AOARD funds invested
- 2 Senior professors
- 1 Associate Professor
- 1 PhD Research Associate
- 3 M.S. Students
- 4 Presentations
- 4 Journal Papers

- **International Exchange:**

- 3 months in Japan performing research (WoW—AFOSR/IO)
- Japanese PI visited USA for 3 months at no cost

- **150 page Tech Report:**

- 2-D Quasi-static Punch Experiment & Analysis
  - Mechanics models (1,2 & 3) for punch loading force
  - Analysis of rate and size effects
- Model 4: Force Chain Stability Modeling
  - Confining forces PDFs
  - Problems with assuming fixed coefficients of friction
  - Propagation of forces in curved chains w/ friction
  - Special case where inter-granular friction eliminates need for confining forces
    - Estimate of minimum required coefficient of friction
  - Special case of granular contact with rigid surface
    - Estimate of minimum coefficient of friction as function of chain angle relative to wall
- Dynamic Cylinder Impact Experiments & Analysis
  - Internal shearing layer and friction estimates
  - Observations regarding stability of false nose as function of coefficient of friction behavior
- Generalized shearing model for granular, crushed material, and solid surface interfaces
- Dynamic Sphere Impact Experiments & Analysis
  - Impact with glass beads
  - Impact with Eglin sand
  - Internal shearing layer and friction estimates
- Tohoku University High-Speed Impact Experiment
  - General Techniques
  - Triboluminescent Techniques
  - 3-D Sectioning & Mapping Techniques
- Osaka University High-Speed Impact Experiment General Techniques
- New Equipment Designs for Potential Collaborative Experiments
  - Osaka Gun Precision Container Catch Tank
  - Modular Particulate Material Container



# Presentations

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## 砂中への飛翔体高速貫入特性の計測 MEASUREMENT OF HIGH-SPEED PENETRATION PROPERTIES INTO SAND

K. Watanabe<sup>1</sup>, K. Tanaka<sup>2</sup>, K. Iwane<sup>1</sup>, S. Fukuma<sup>1</sup>, K. Takayama<sup>3</sup>, K. Kobayashi<sup>1</sup>

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### INTRODUCTION

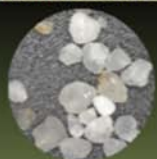
#### Background

Collisions between geological materials and rigid bodies occur in various situations, which are excavation, construction, military application and asteroid impact. Accordingly, the impact and penetration of projectiles in soil have long been studied extensively. However, for geological particulate materials such as sand, because the particle behavior is so complicated due to heterogeneity and instability of granular media, there have been few experiments investigating the impulse loading of these media, and the penetration properties on them are less understood.

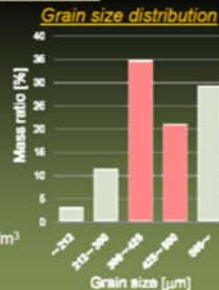
Dynamics of projectile penetration into sand depends greatly on the features of motion and state of the sand material at the interface with the projectile. Therefore, the goal of this study is to develop an understanding of behavior of projectile during penetration, condition and distribution of comminuted sands and pressure distribution in sand under the impulse loading and then evaluate the influence of impact velocity, initial porosity and particle size on behavior of comminuted sands.

### EXPERIMENTAL

#### Granular Material -Sand-



- Beach sand (Shirarahama sand)
- Silica: >90%
- Density:  $2.65 \times 10^3 \text{ kg/m}^3$
- Washed
- Completely dry



#### Vertical Powder Gun



#### Powder gun

Bore diameter :  $\phi 15 \text{ mm}$   
Impact velocity: 150~1400 m/s  
(Capacity: 100~2000 m/s)

#### Projectile

Body shape: Cylinder ( $\phi 15 \times 25 \text{ mm}$ )  
Nose shape: Flat  
Material: Impactor: **Brass SUS304**  
Sabot: Polycarbonate  
Mass: Brass+Sabot, 12.5 g  
SUS+Sabot, 12 g

#### Target Box Container A



Material: Polypropylene  
Size: 115x155x155mm  
Height: 125mm

#### Container B



Material: PMMA  
Inner dia.: 60mm  
Thickness: 5mm  
Height: 200mm

#### Container C



Material: PMMA  
Inner dia.: 190mm  
Thickness: 10mm  
Height: 200mm  
Packing density :  $1.49 \sim 1.56 \times 10^3 \text{ kg/m}^3$   
Porosity : 40~43 %

#### Fiber

Silica/Silica glass optical fiber  
Core diameter: 200μm  
Clad diameter: 220μm  
(Polyurethane jacket is removed by sulfuric acid)

2D pressure distribution of depth direction could be measured and the relationship between pressure and impact velocity was estimated by the pressure measurement sheet.

Glass optical fiber was used to measure the penetration speed of projectile and the slow down history became clear.

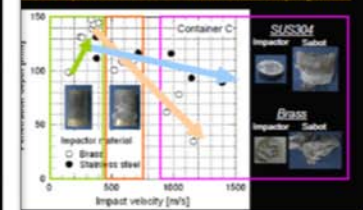
#### Objectives

- To establish experimental method and data analyzing method.

#### Investigation Items

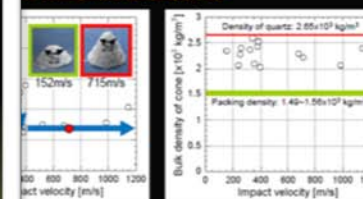
- Behavior of ejecta
- Relationship between impact velocity and penetration depth
- Fractured grain and its distribution
- Pressure distribution
- Behavior during penetration  
(Projectile trajectory, Penetration/ wave speed)

#### Effect of impactor material & condition of projectile



Degree of deformation of sabot and impactor velocity influenced the penetration depth.

#### Red sand (ahead of projectile)



Massive crashed sand (bulk density  $> 2 \times 10^3 \text{ kg/m}^3$ ) ahead of projectile and vertical angle  $2\alpha$  to around  $60^\circ$  as the velocity increases.

### SUMMARY

Some methods were proposed and tried for measurement of high-speed penetration properties into sand. As a result, although improvements must be made on many points, the validity of these methods was confirmed.



# Papers

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## 球の砂突入に関する研究

○山本新朗 (医療機構センター)  
大谷清博, 早坂正吉, 小川俊宏, 高山和壽 (東北大学流体科学研究所)

### A study of penetration of a sphere into sand layer

Yamamoto Hiroaki, Ohtani Kiyonobu, Hayasaka Shoichichi, Ogawa Toshikazu, Takayama Kazuyoshi  
Japan Association for the Advancement of Medical Engineering, 3-42-6 Hongo, Bunkyo-ku, Tokyo, 113-0033 JAPAN

#### Abstract

Paper reports the result of preliminary tests of a 10 mm diameter sphere penetrating into a sand layer. Using a vertical powder gun, we launched  $\phi$  10mm stainless spheres at speed ranging from 1.25 km/s to 1.94 km/s into sand layers. To preserve impacted specimens, we immersed them into inorganic silicone-sealing agent and succeeded to freeze the trajectory of sphere's motion and to identify the deformation of the sand layer structure.

Key Words: high-speed penetration, sand layer, vertical powder gun, freezing technique

#### 1. はじめに

砂や土のような微小粒状物体が充填された系に高速物体が衝突する現象は、微粒固体の運動ばかりでなく、砂層や土層崩壊などを伴うため、固体、液体、気体などの複相媒体に比べ複雑である。外力が加えられた微粒固体の運動について、さまざまな実験や理論解析[1]が行われているが、高速物体が砂層への突入する場合には、高速領域での粉流体の挙動に関する研究は実験的にも解析的にも完了したと云うにはほど遠い。

本報告は超高速大口径でフロリダ海岸砂を挿入した試験槽にステンレス鋼球を1.25 km/s~1.94 km/sで垂直に打ち込み、高速球の運動と砂層内部構造の変化などを観察する方法を開発する予備実験結果の連絡である。

#### 2. 実験方法 2-1 供試砂

実験には、フロリダ海岸砂、造粒エグリン砂 (Quikrete Commercial grade Fine Sand No.1961) を用いた。図1に顕微鏡写真を示す。粒子は主に球形からなり、やや角が取れたいびつな形状を示す。図2に粒度分析結果を示す。グラフは縦軸粒度重量比%、横軸粒度mmの対数表示である。エグリン砂は355 $\mu$ mから500 $\mu$ mに幅値を持ち、母平均361 $\mu$ m、母分散0.733の正規分布に近い粒径分布を示す。

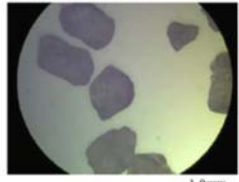


Fig. 1 Eglin sand

#### 2-2 実験装置

ステンレス鋼球は直径10mm重量6.63gのベアリング球である。図3は東北大学流体科学研究所の超高速1段式大口径銃であり、過去に高速材料破壊発生実験に用いた装置を改造した。この回収部に、砂を充填した供試媒体を置いた。筒周用ライフルの薬室に、無煙火薬約3gを封入し、端部の雷管を空気圧駆動の撃針で起爆した。薬室の下部に鋼管を介して、ポリカーボネートのサポに挿入した球をおいた。サポ形状は後述にフレイアをもち、先端はやや斜めの切り込みをもつ形状で、試験結果で最適化されている。なお工夫の余地があるが、サポは加速管下部に衝突して静止し、爆発生成気体の回収部への流入を阻止し、また、球だけが加速管軸心にほぼ一致することで、回収部への打ち出しを許す形状を持っている。図3に衝突して回収されたサポを示す。サポは加速管末端の回りに、きつく嵌入している。

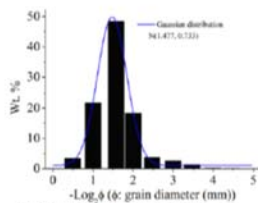


Fig. 2 Grain size distribution of Eglin sand

サポ分離した球は、1.25km/sから1.94 km/sで、回収部を自由落下する。回収部空間には、半導体レーザー光線と受光部を組み合わせて、60mm間隔に取り付けた飛行時間計測部が配列され、球の速度を推定した。砂は内径100mm、長さ150mm、肉厚5mmのアルミ樹脂筒内に、予備実験なので、特別な配慮なしに充填した。得る、砂粒径を整えて、衝撃させながら充填することで砂層度の制御を視野に入れている。

## Behavior Induced by High-Speed Penetration of Projectile

Watanabe<sup>1</sup>, Koichi Tanaka<sup>2\*</sup>, Keisuke Iwane<sup>3</sup>, Syungo Fukuma<sup>4</sup>, Kazuyoshi Takayama<sup>5</sup> and Hidetoshi Kobayashi<sup>6</sup>

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primary objective is establishing tangible experimental methods and data methods in order to grasp various phenomena, which were the behavior of projectile, the penetration depth and speed of projectile, fractured grains and distribution, induced by high-speed impact of projectile on sand. The plate experiments were conducted using vertical powder gun. The principal results are as follows: Sands around the penetrated projectile were smashed to fine  $\mu$ m or less like a potato starch. Circumferential crashed sands were abraded and generated at impact velocity above 300 m/s. Conical massive was produced ahead of projectile and vertical angle converged to around  $45^\circ$  increases. The projectile penetrated at a speed about equal to the  $v$  in the initial penetration and decelerated rapidly over since.

#### INTRODUCTION

Disturbances between geological materials and rigid bodies occur in various fields such as excavation, construction, military application and asteroid impact. The impact and penetration of projectiles in soil have long been studied. However, for geological particulate materials such as sand, because the behavior is so complicated due to heterogeneity and instability of granular media there have been few experiments investigating the impulse loading of these penetration properties on them are less understood. Dynamics of penetration into sand depends greatly on the features of motion and state of the projectile at the interface with the projectile.

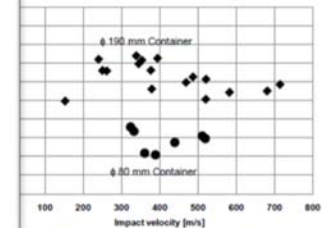
The main goal of this study is to develop an understanding of behavior of projectile penetration, condition and distribution of comminuted sands and penetration in sand under the impulse loading. As the first step, the primary objective is establishing tangible experimental methods and data analyzing methods in various phenomena induced by high-speed impact of projectile on sand.

## Stresses by Chains of Grains in High-Speed Particulate Media Impacts

Watanabe<sup>1</sup>, Koichi Tanaka<sup>2\*</sup>, Keisuke Iwane<sup>3</sup>, Syungo Fukuma<sup>4</sup>, Kazuyoshi Takayama<sup>5</sup> and Hidetoshi Kobayashi<sup>6</sup>

primary objective is establishing tangible experimental methods and data methods in order to grasp various phenomena, which were the behavior of projectile, the penetration depth and speed of projectile, fractured grains and distribution, induced by high-speed impact of projectile on sand. The plate experiments were conducted using vertical powder gun. The principal results are as follows: Sands around the penetrated projectile were smashed to fine  $\mu$ m or less like a potato starch. Circumferential crashed sands were abraded and generated at impact velocity above 300 m/s. Conical massive was produced ahead of projectile and vertical angle converged to around  $45^\circ$  increases. The projectile penetrated at a speed about equal to the  $v$  in the initial penetration and decelerated rapidly over since.

Watanabe 2010] conducted experiments to observe the high-speed impact of right-circular projectiles (polycarbonate body) with quartz Eglin sand ( $\phi$  75-1,400  $\mu$ m grains,  $d_{50}$  = 400  $\mu$ m,  $\sigma$  = 10). Projectiles were launched vertically downward and impacted the sand surface at 150-720 m/s. Projectile velocities were measured using induction loops and impact  $\phi$  photography. Two containers were used:  $\phi$  80 mm &  $\phi$  190 mm internal diameter, depth did not vary appreciably with impact velocity, but was strongly affected by the inner size from 190 mm to 80 mm cut the penetration depth in half as shown in Fig. 1. Particle communication with the container—the stresses at the projectile surface and the drag container size. The goal of this analysis is to examine the mechanics that enable the penetration.



Projectile penetration depth as function of impact velocity



# Questions?