“Analysis of the dynamic behavior of squat silos containing grain-like material subjected to shaking-table tests”

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PRESENTATION LAYOUT

• The test set-up

• The scientific background

• The shaking-table tests performed and the first results

• The comparison with theory expectations

OBJECTIVES

• To find out the pressure that the grain-like material produces on the silo walls due to time constant acceleration (for the experimental verifications of the analytical findings obtained in Silvestri et al., BEE 2012);

• To evaluate the influence of the base input (earthquake vs. sinusoidal)
SPECIMEN DATA

SILO:
H = 120 cm; D = 120 cm
\( t_{wall} = 3 \text{ mm} \)

Material: POLYCARBONATE
\( \gamma = 1200 \text{ kgf/m}^3 \)
E = 2300 MPa

CONTENT:
H = 120 cm ÷ 60 cm (slender silo and squat silo, respectively)

Material: BALLOTTINI GLASS
\( \gamma = 1481 \text{ kgf/m}^3 \)
E = 35000 ÷ 70000 MPa

Session 1

D. Foti - “Analysis of the dynamic behavior of squat silos…”

Final Meeting – ISPRA 28-30 May 2013
SPECIMEN GEOMETRY

SILO SPECIMEN (scale 1:10)

PARAMETERS

INTERNAL FRICTION ANGLE
\[ \varphi = 26^\circ \]

FRICIONT COEFFICIENT GRAIN-BASE
\[ \mu_{GB} = 0.45 \]

FRICIONT COEFFICIENT GRAIN-WALL
\[ \mu_{GW} = 0.3 - 0.45 \]

PRESSURE RATIO
\[ \lambda = 0.55 \]

INSERTION OF BALLOTTINI
**INSTRUMENTATION**

- mono-directional **accelerometers** located at the shaking-table foundation, glued to the silo walls and placed inside the Ballottini glass;
- vertical and horizontal **strain gauges** positioned on the exterior side of the walls at four different heights;
- **LVDT** placed at the top of the structure;
- **film** and **Flexi Force pressure sensors** placed on the interior side of the walls, in order to measure pressures.
FROM REALITY TO IDEALIZATIONS

REAL CASE

- Flexible
- Compressible grain
- Earthquake input

TEST SPECIMEN

- Flexible
- Uncompressible grain
- Earthquake input

IDEAL MODEL

- Flexible
- Uncompressible grain
- Sinusoidal input

- Infinitely stiff
- Uncompressible grain
- Constant input

A

B1

B2

C
PROBLEM FORMULATION

THE SPECIMEN MODEL IS SITUATED IN A CENTRAL POSITION WITH RESPECT TO THE REAL CASE AND THE IDEAL MODEL:

1. The silo **walls** are considered **not infinitely stiff** but with some flexibility associated to the acceleration profile;
2. The **grain** particles of the ensiled material are considered **uncompressible**;
3. The inputs used are:
   - **Sinusoidal** at low frequency that is comparable with the constant input used for the theory;
   - **Un-scaled Earthquake** closer to the real silo conditions
SESSION 1

20-22 August 2012:
- **Silo with smooth walls** (grain-wall friction coefficient $\mu_{GW} = 0.30$) and filled with Ballotini glass up to a height of 120 cm.
- **Input** – **white noises** (ampl. 0.05g, 0.1g, 0.2g, 0.3g), **sinusoidal** (low frequency) and **earthquake accelerograms** along Y direction.

**Objective:**
Analyze the behavior of the silo specimen under the specific conditions presented above with respect to the theory expectation.
SESSION 2

29-31 January 2013:

- **Silo with roughened walls** (grain-wall friction coefficient $\mu_{GW} = 0.45$) and filled with Ballotini glass up to a height of 60 cm.
- **Input** – white noises, **sinusoidal** at 1Hz and 2Hz along Y and Z directions and earthquake accelerograms (South Iceland records).

**Objective:**
Analyse the repeatability and the initial conditions of the silo and monitor the effect of a lower slenderness ratio.
SESSION 3

1-2 February 2013:

- **Silo with roughened walls** (grain-wall friction coefficient $\mu_{GW} = 0.45$) and filled with Ballotini glass up to a height of **120 cm**.
- **Input** – systematic **sinusoidal input** (ampl. 0.1g-0.6g) at 1Hz and 2Hz along Y direction.

**Objective:**
Analyze the behavior of the silo specimen under the specific conditions presented above with respect to the theory expectation and the results of the first session with particular attention on the effect of the increased roughness and the changed internal friction coefficient of the ensiled material.
Analysis of the dynamic behavior of squat silos...
ACCELERATION RESULTS

Session 1 – test S9

max/min horizontal accelerations. Filtered t=0- test - S9 - a =0.339g

SINUSOIDAL INPUT

max/min horizontal accelerations. Filtered t=0- test - E17 - a =0.415g

EARTHQUAKE INPUT
ACCELERATION RESULTS

Session 2 – test S50

Accelerometers $y=0.6$ (LEFT) test S50 $a = 0.2747$ g

Accelerometers $y=-0.6$ (RIGHT) test S50 $a = 0.2747$ g

max/min horizontal accelerations. Filtered $t=0$ test S50 $a = 0.2747$ g
ACCELERATION RESULTS

Session 3 – test S4

Accelerometers $y=0.6$(LEFT) test S4 $a = 0.325$ g

Accelerometers $y=-0.6$(RIGHT) test S4 $a = 0.325$ g

max/min horizontal accelerations. Filtered $t=0$ test S4 $a = 0.325$ g
STRAIN RESULTS

Session 1 – test S9

Vertical strain-gauges, y=0.6(LEFT) filt. t=0  test S9  a = 0.339g

Session 2 – test S50

Vertical strain-gauges, y=0.6(LEFT) filt. t=0 test S50  a = 0.2747 g
STRAIN RESULTS

Session 3 – test S4

Vertical strain-gauges, y=0.6(LEFT) filt. t=0   test  S4   a = 0.325 g

Vertical strain-gauges, y=-0.6 filt. t=0   test  S4   a = 0.325 g

COMMENTS
For all the sessions the maximum vertical strain is reached at height 0.18 m (the lowest one), on the contrary the lowest vertical strain is set for height of 0.92 m. This is concordant with the behavior of the silo under a sinusoidal input. Moreover the behavior of the two parts of the silo seems to be not identical; this may be due to a squeezing of Ballottini glass along the junction between the two polycarbonate semicircles.
Squeezing of Ballottini glass along the junction between the two polycarbonate semicircles
PHYSICAL BEHAVIOR FOR A CHANGE IN THE PGA

- by looking at the mean plot (black line - Figure 1a), there is a clear change in the physical behaviour for a value of PGA around 0.35 g.
- the same also for the case of input in Y and Z direction (Figure 1b)
- Figure 1c shows that for the case of rough walls surface the change in the physical behavior seems to appear around 0.25 g.

Figure 1a
Figure 1b
Figure 1c
INTERPRETATION OF EXPERIMENTAL RESULTS

The interpretation of the experimental results basically concerns the comparison between:

- the **experimental bending moment at the base of the silo**, as reconstructed from the strain values of the vertical strain gauges placed at a height $z = 0.14$ m from the table;
- the **predicted value** of the base bending moment, as given by the **analytical formulations proposed by the authors** (Silvestri et al. 2012);
- the **Eurocode 8 prescribed values**

The methodologies applied to reconstruct the experimental bending moment at the base of the silo (at a height $z = 0.14$ m) directly integrates the base vertical stresses multiplied by the corresponding lever arm over the whole circumferential cross-section.
METHODOLOGY

\[ M_{\text{exp}}(t) = \sum_{i} \sigma_{i}(t) \cdot A_{i} \cdot r_{i}^{2} \]

the experimental bending moment can be obtained by direct integration (discrete sum) of the base vertical stresses over the whole circumferential cross-section, where:

- \( A_{i} \) is the corresponding area;
- \( r_{i} \) is the lever arm
- \( \sigma_{i}(t) \) is the vertical stress computed assuming linear elastic behavior for the polycarbonate material of the silo;

\[ \sigma_{i}(t) = E_{\text{polycarbonate}} \cdot \varepsilon_{i}(t) \]
INTERPRETATION OF THE RESULTS:

Form the reconstruction of the experimental base bending moment it is possible to note that the wall-grain friction coefficient strongly affects the experimental base bending moment. This does not match with Eurocode 8 prescriptions which do not take into account the wall-grain friction coefficient at all.

\[ M(t) \text{ as re-constructed from base strains} - a=0.33g \]

\[ M \text{ [kgcm]} \]

All same conditions, except for the wall-grain friction coefficient
For $h = 120$ cm of the ensiled material the reconstructed experimental bending moment is much closer to the prediction given by the analytical formulas provided by the authors (Silvestri et al. 2012) than the Eurocode 8 provision.
END