2D Silo Discharge of Soft Slippery Spheres and Mixtures with Hard Grains

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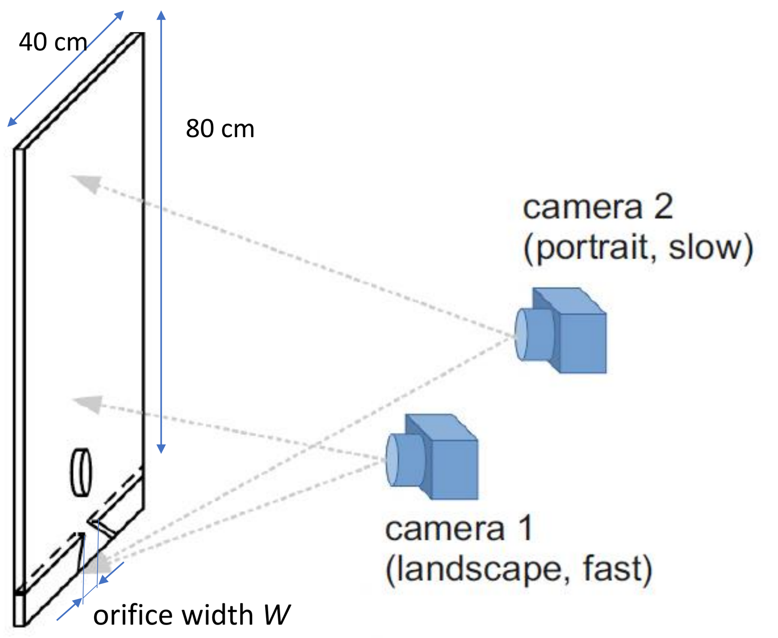
Background and Motivation

- Mechanical aspects of the storage of granular matter in silos and their discharge characteristics are of considerable practical value.
- Silo discharge has been in the focus of scientific research since decades (Beverloo1969).
- Most studies have considered the simplest case of hard,spherical grains.
- Other particle shapes like rods, prolate or oblate ellipsoids and more complex shapes have become increasingly fashionable in recent years.

- This study deals with the influence of particle elasticity on the discharge and clogging characteristics.
- We explore a quasi two-dimensional(2D) silo geometry, in order to simplify optical observations.

Experimental Setup & Material

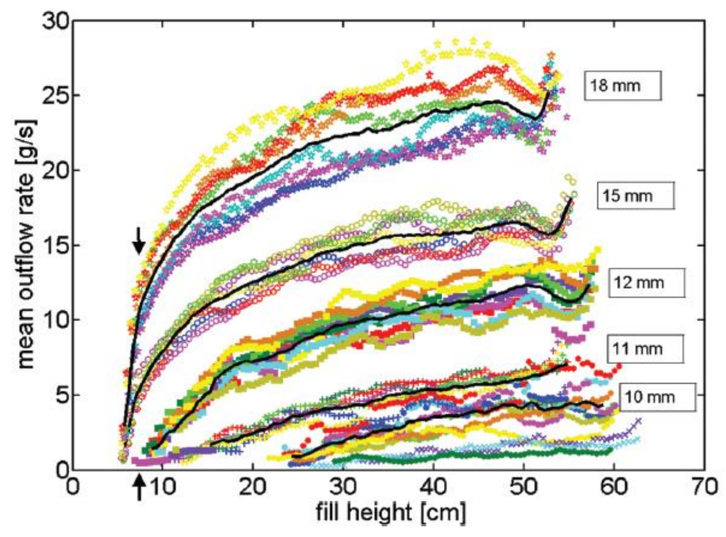


- Quasi-2D container with resizeable opening at the bottom.
- Bin width is adjusted to particle diameters.
- Two cameras record videos of the complete front view and a detailed image of the region near the outlet.
- The mass of discharged material is continuously recorded by means of an electronic balance.

- We investigate ensembles of monodisperse spheres and their mixtures
- Hydrogel spheres with ~6 mm diameter as soft,elastic slippery grains, elastic modulus in the 10 … 100 kPa range. Many different colors.
- Hard plastic bullets with 6 mm diameter, friction coefficient 0.3, available in two colors

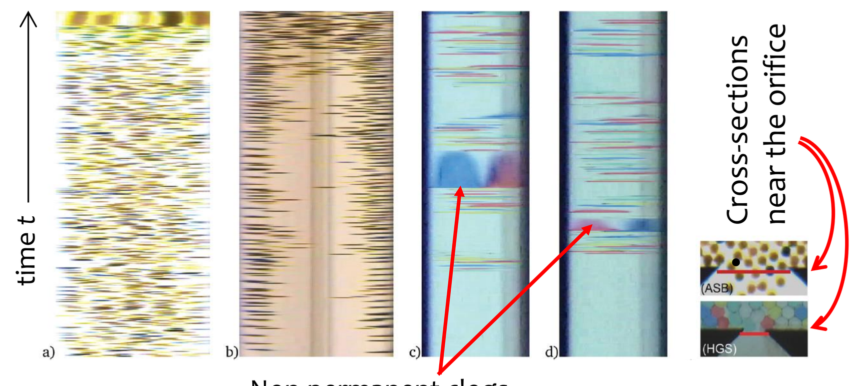
Silo Discharge of Soft Slippery Grains [1]

- The outflow rate of *soft* particles is fill-height dependent. This is in clear contrast to hard grains where the discharge rate is independent of the fill level as long as the fill height is larger than roughly the silo width.
- For hard grains, the pressure at the container bottom is independent of fill height (Janssen´s law). Even when the pressure is changed, the fill rate is not influenced significantly.
- The graphs show the dependence of the discharge rate of *hydrogel spheres* on the momentary fill height for different orifice sizes.



- Soft particles exhibit a new feature that was found earlier only for animate objects, like the passage of animals through narrow gates or egress of people through narrow doors: **non-permanent clogs**

a) Space-time plot of a cross-section at the orifice for hard grains in the beginning of discharge. The outflow is continuous with only little fluctuations.
b) Same near the end of discharge. Flow rate is still continuous.
c) Soft grains form clogs that dissolve spontaneously.
d) Same near the end of discharge. Flow is intermittent.

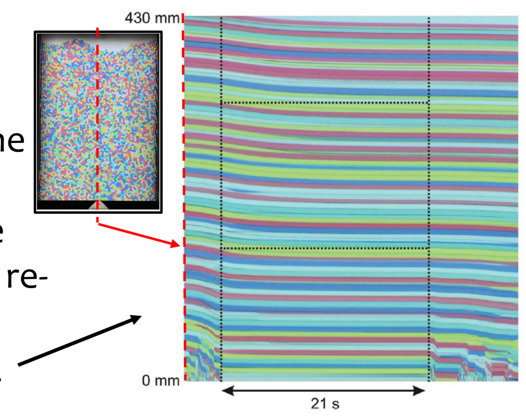


Non-permanent clogs

- Explanation of non-permanent, spontaneously dissolving clogs:

When the outlet is clogged, there is still a reorganization of the grains inside the silo. For the present material, this can take up to a minute. The statics and pressure distributions in the container may change continuously. The material compactifies by a local reorganization of the packing structure. This can finally lead to the imbalance of the clog and re-iteration of the outflow.

Space-time plot of a vertical central cross section of hydrogels during a clogged state.

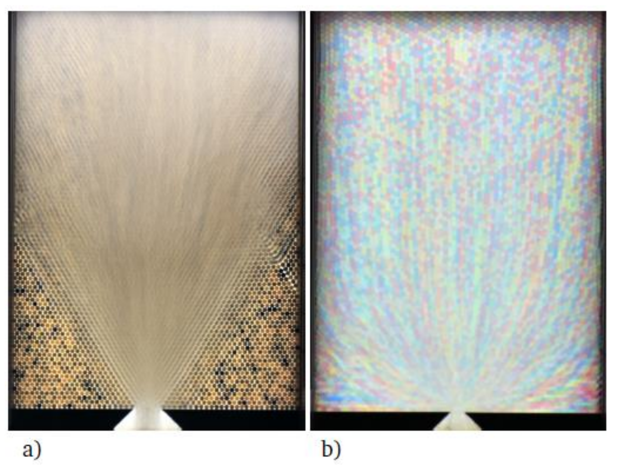


- Hard spheres

Internal flow field visualized by superposition of images from a time series. One identifies the stagnant zones at the two sides of the orifice, where the material never participates in the outflow.

Flow starts immediately in the whole silo after the outlet was opened.

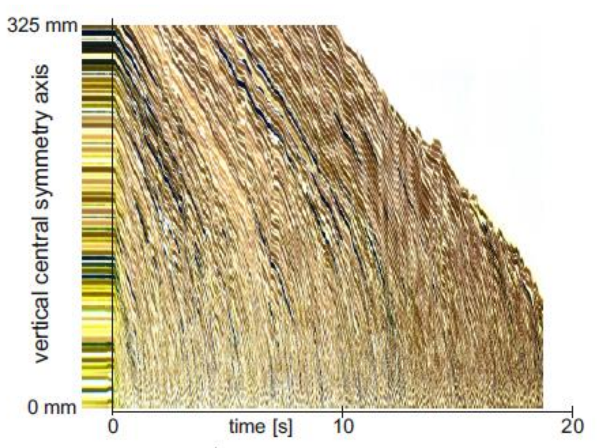
- Comparison of Internal flow profiles

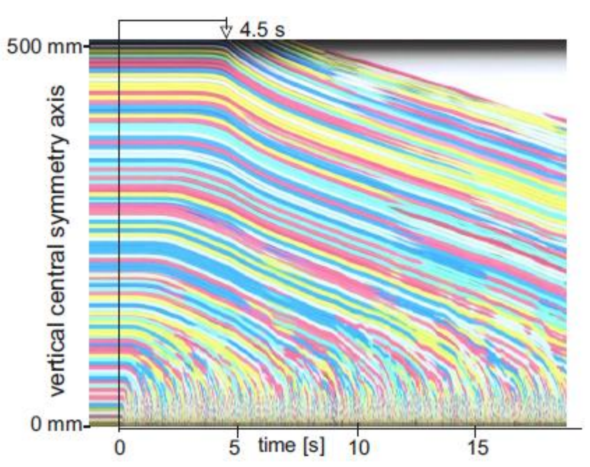


- Soft spheres

A superposition of subsequent images shows that the soft, slippery grains practically don‘t develop stagnant zones at the sides. All particles participate, in a more or less effective fashion, in the outflow.

Flow in the top layers starts with several seconds delay rafter the outlet was opened.



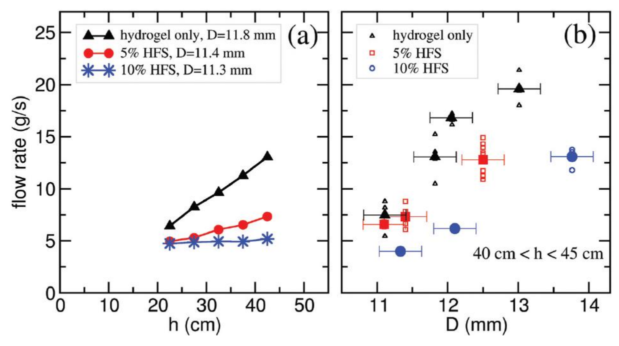


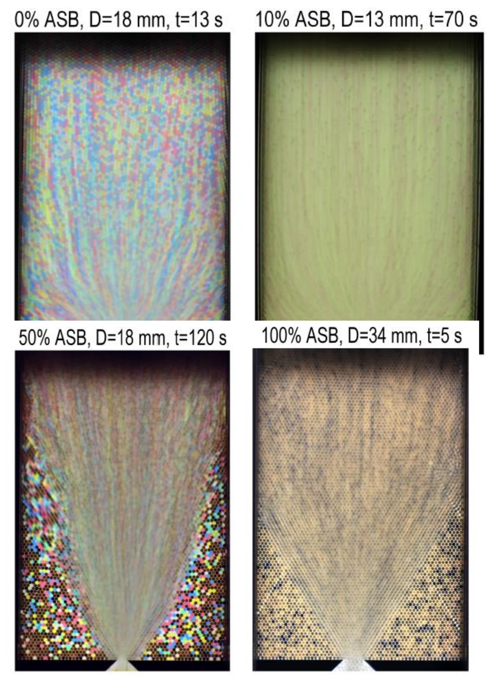
Mixtures of hard and soft grains [2,3]

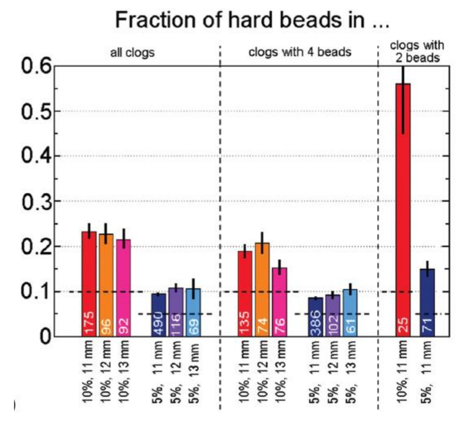
Important differences of hard and soft slippery grains:

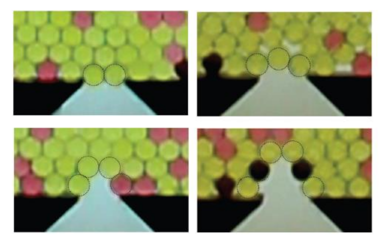
- flow profiles: soft grains → plug flow, practically no stagnant zones, fill-height dependent flow rate
  hard grains → funnel formation, stagnant zones, flow rates indep. of fill height
- clogging: soft grains → intermittent flow, transient congestions when W≈2…3 x grain diameter
  hard grains → permanent clogs for W< 5 x grain diameter

→ Which properties dominate the flow of mixtures? Soft or slippery, what matters more?



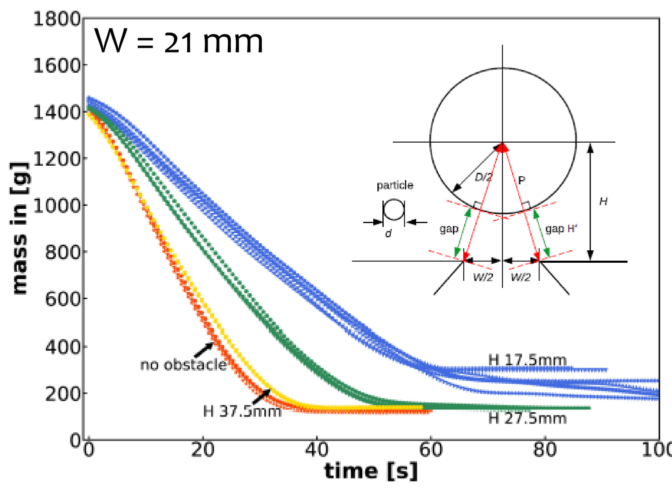




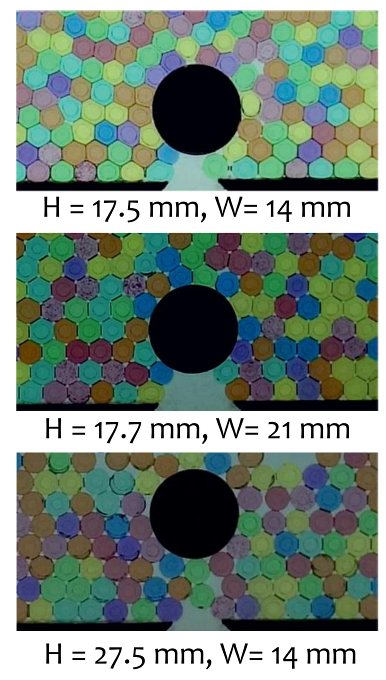


- funnel-flow at ~50%
- flow rate is height-dependent & affected by presence of hard particles near orifice
- clog structure statistics reveal 2x as many hard grains in clogs as in the bulk mixture

Effect of an obstacle



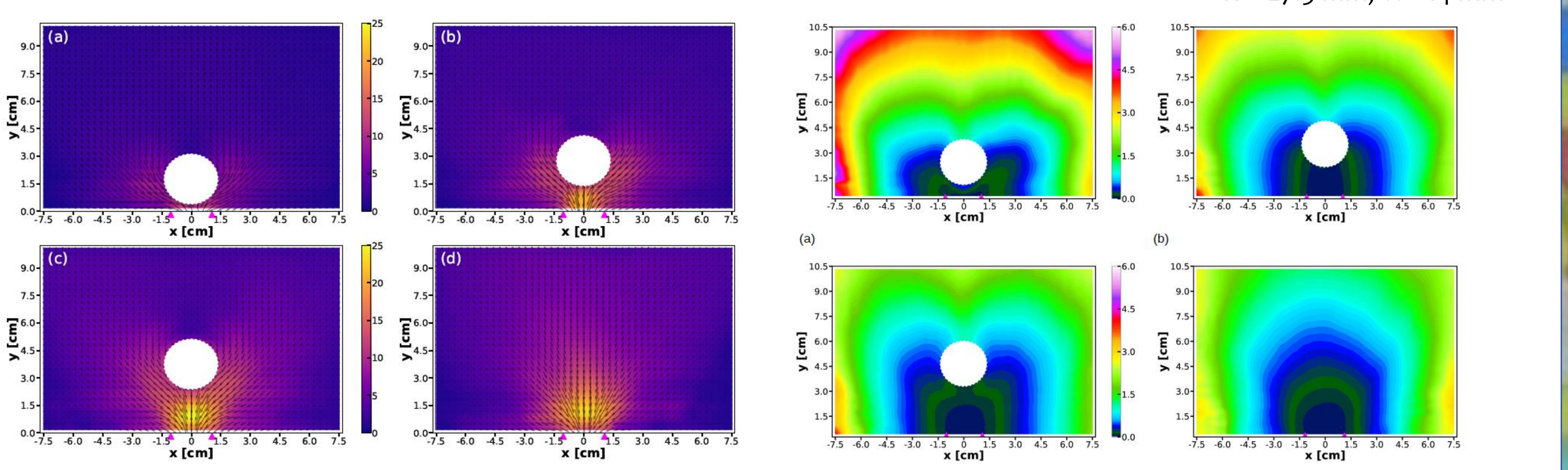
- In all experiments, discharge is slowed down by the obstacle
- clog structures and locations change with the gap width H':
  - for small gaps H', clogs span from the silo bottom to the obstacle
  - for large H', clogs span the container opening



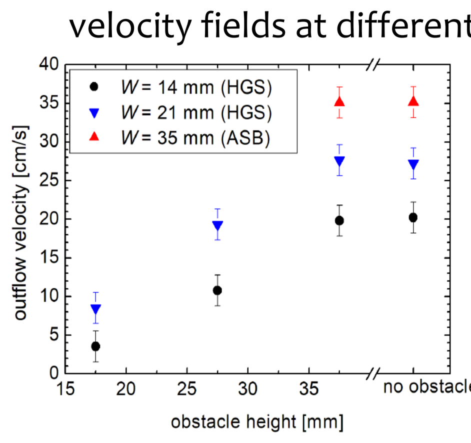
H = 17.5 mm, W= 14 mm

H = 17.7 mm, W= 21 mm

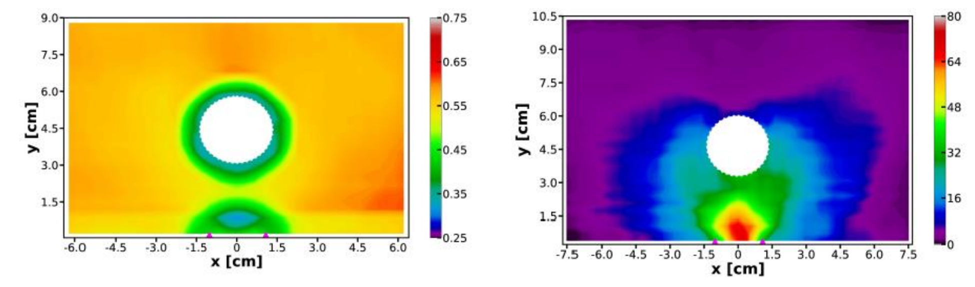
H = 27.5 mm, W= 14 mm



velocity fields at different obstacle positions, and corresponding escape time maps for W=21 mm



increasing outflow velocity with obstacle height at the orifice

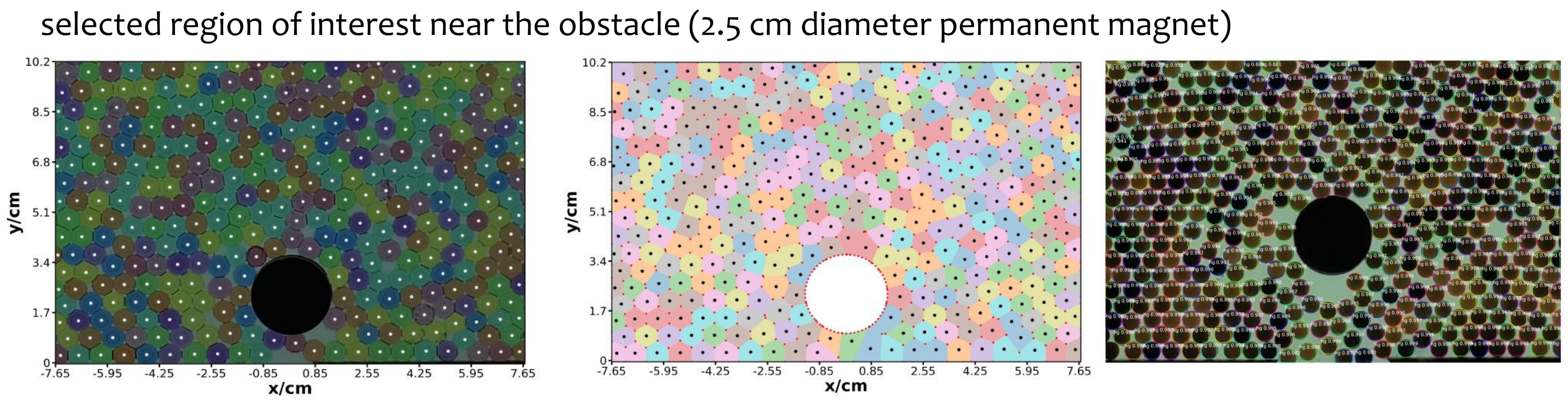


local 3D packing fraction for W=21 mm, H=37.5 mm

time-averaged kinetic stress for W=21 mm, H=37.5 mm

Particle detection and tracking

selected region of interest near the obstacle (2.5 cm diameter permanent magnet)



(a) soft spheres and detected centers (b) Voronoi tesselation based on a (c) detected hard particles

- Detection of all particles in the region of interest using a Mask R-CNN neural network
- Particle tracking using the python *trackpy* package
- evaluation of velocities, local 3D packing fractions, escape times, and the time-averaged kinetic stress $\overline{\sigma_K}(x) = \overline{\phi(x,t) \cdot [v(x,t) - \bar{v}(x,t)]^2}$, coarse-grained values of the quantities

Conclusions

- Hydrogel particles were used as convenient templates for soft,elastic materials with low friction
- Such soft grains behave visco-elastically which can cause **non-permanent clogging** and **intermittent flow** in silo discharge
- After initiation of the container discharge, the pressure is released and the material expands, leading to a **retarded onset of flow** in the upper part of the container
- Admixture of few percent of hard grains to a soft particle ensemble has tremendous effects on the discharge and clogging characteristics.
- Obstacles near the outlet retard the outflow and may change the structure and position of clogs formed

References

[1] K. Harth, J. Wang, T. Börzsonyi, R. Stannarius, *Soft Matter* **16** 8013 (2020)
[2] J. Wang, K. Harth, T. Börzsonyi, B. Fan, R. Stannarius, *Soft Matter* **17** 282 (2021)
[3] J. Wang, K. Harth, T. Börzsonyi, B. Fan, R. Stannarius, *EPJ Web of Conf.* **249** 03002 (2021)