Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Design of an enclosed and automated sand rainer system to reduce respirable silica dust exposure

Yifa Wang
The University of Melbourne, Melbourne, Australia, yifa.wang@unimelb.edu.au

Steve Beard, Shiaohuey Chow, Mark J. Cassidy
The University of Melbourne, Melbourne, Australia, sbeard@unimelb.edu.au, shiaohuey.chow@unimelb.edu.au, mark.cassidy@unimelb.edu.au

ABSTRACT: Sand raining is widely used in physical modelling to prepare uniform sand samples; however, the process can generate airborne respirable crystalline silica (RCS), presenting a significant occupational health risk in laboratory environments. Increasing regulatory scrutiny and tightening exposure limits have highlighted the limitations of reliance on personal protective equipment (PPE) and administrative controls alone. This paper presents the safety-in-design–driven development of a purpose-built enclosure and automated hopper system for an Acutronic sand rainer to reduce operator exposure during sand raining operations. Early hazard identification, informed by material safety data and observations of sand rainer use, identified dust generation during sand flow control and sand spread beyond the raining zone as key exposure pathways. The engineering solution integrates three complementary control measures: (i) a fully enclosed raining volume, (ii) a negative-pressure mechanical extraction system incorporating HEPA Class H filtration to prevent airborne particles escaping the enclosure, and (iii) an automated pneumatically actuated hopper door operated remotely from outside the enclosure. Electrical interlocks link the hopper actuation, enclosure doors, and filtration system, with fail-safe logic ensuring automatic hopper closure under unsafe or loss-of-signal conditions. The enclosure was designed and constructed around a pre-assembled sand rainer commissioned at the University of Melbourne. Operational experience indicates a qualitative reduction in visible dust, improved control of sand spread, and reduced operator proximity during high-exposure tasks. The paper outlines key design considerations for implementing engineering controls to mitigate silica risks in physical modelling laboratories.

1 INTRODUCTION

Sand raining is widely used in physical modelling laboratories to prepare uniform and repeatable sand samples for geotechnical testing (Butterfield and Andrawes, 1970; Garnier and Cottineau, 1988; Stuit, 1995; Cresswell et al., 1999; Zhao et al., 2006; Choi et al., 2010; Tabaroei et al., 2017). The method is well established for both 1g and centrifuge modelling and remains an essential technique for investigating the behaviour of granular soils under controlled conditions. Despite its widespread use, sand raining involves the handling and free fall of dry sand, which can generate airborne fine particles during operation, particularly during sand flow initiation, termination, and interaction with surrounding surfaces.

Many sands commonly used in physical modelling contain crystalline silica, and the generation of respirable crystalline silica (RCS) during sand raining presents a recognised occupational health risk (Safe Work Australia, 2023). Exposure to RCS has been linked to serious long-term health outcomes, leading to increasing regulatory scrutiny and progressively tighter workplace exposure limits in many jurisdictions (Safe Work Australia, 2023; WorkSafe Victoria, 2024). In Australia, the current workplace exposure standard for RCS is 0.05 mg/m^3 (8-hour time-weighted average), with WorkSafe Victoria recommending a precautionary approach targeting exposures below 0.02 mg/m^3 to prevent silicosis and minimise the risk of lung cancer. Within laboratory environments, these developments have highlighted the limitations of traditional reliance on personal protective equipment (PPE) and administrative controls, particularly for repetitive or prolonged sand raining operations.

In response, there is growing emphasis on the implementation of engineering controls to reduce airborne dust generation and limit operator exposure at source. However, while sand raining equipment is widely used internationally, there is limited published guidance describing the practical design and integration of engineering controls – such as enclosures, automation, and active filtration – specifically tailored to physical modelling laboratories. As a result, laboratories often address silica risk through ad hoc or locally developed solutions, with limited documentation of design rationale or performance.

This paper presents the safety-in-design–driven development of an enclosed and automated sand rainer system for an Acutronic sand rainer. The system was designed to contain sand and dust, actively control airborne particles, and minimise operator proximity during high-exposure tasks through remote operation and interlocked controls. The paper focuses on the identification of key exposure pathways, the derivation of functional safety requirements, and the resulting engineering design, with the aim of providing transferable guidance for improving silica dust mitigation in physical modelling laboratories.

2 SAND RAINING AND HAZARD IDENTIFICATION

The sand raining technique involves the controlled release of dry sand from a hopper, allowing particles to fall under gravity into a model container. Commercial sand rainers, including those supplied by Acutronic (Figure 1), are commonly used in both 1g and centrifuge laboratories. During operation, interaction with the hopper and flow control mechanisms is required, particularly during the initiation and termination of sand flow. In addition, the falling sand stream can interact with surrounding surfaces, generating fine airborne particles, with dust generation often most pronounced during non-steady flow conditions and handling of dry sand.

Many sands used in physical modelling contain crystalline silica, and a review of material safety data identifies RCS as a potential hazard during handling and processing. Early consultation with laboratory safety specialists and observations of sand rainer operation highlighted the potential for airborne silica generation during sand raining, particularly during sand release, surface impact, and subsequent cleanup. Practical observations also identified the spread of sand beyond the immediate raining zone and the need for operators to remain in close proximity to the sand stream during hopper operation, increasing the likelihood of inhalation exposure.

Based on these observations, several exposure pathways were identified. The primary pathway was airborne dust generated during sand flow initiation and termination, when transient conditions promote the release of fine particles. Secondary pathways included the escape of dust-laden air from the raining zone into the surrounding laboratory and operator exposure associated with manual hopper operation in close proximity to the rainer. These findings indicated that reliance on administrative controls or PPE alone would be insufficient to manage exposure risk. Instead, effective mitigation required integrated engineering controls capable of containing sand and dust, preventing the escape of airborne particles, and reducing operator proximity during high-exposure tasks. These considerations directly informed the safety-in-design requirements and engineering solutions presented in the following sections.

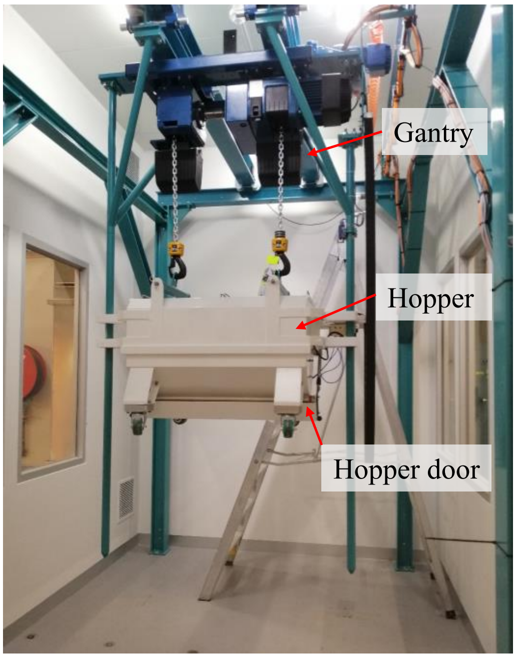

Figure 1. Acutronic sand rainer installed at the University of Melbourne geotechnical modelling laboratory.

3 SAFETY-IN-DESIGN PHILOSOPHY AND FUNCTIONAL REQUIREMENTS

The sand rainer enclosure and automated hopper system were developed using a safety-in-design approach, in which potential hazards associated with sand raining operations were identified early and addressed through engineering controls. Table 1 summarises the key hazards identified, the corresponding functional requirements, and the implemented design measures. The functional requirements directly informed the design of the enclosure, automated hopper, interlocked control logic, and filtration system described in the following section.

Table 1. Summary of safety-in-design hazards, requirements, and responses.

Identified hazard	**Functional requirement**	**Design response**
Airborne silica generated during sand raining	Contain sand and dust within the raining zone	Fully enclosed sand rainer
Escape of dust-laden air into laboratory	Prevent outward airflow from enclosure	Negative-pressure enclosure with HEPA Class H filtration
Operator proximity during sand flow control	Enable remote operation of sand flow	Pneumatically actuated automated hopper door
Unsafe operation with enclosure access open	Prevent hopper actuation unless enclosure is safe	Electrical interlocks between doors, hopper, and controls
Loss of power or control signals	Ensure safe system state under fault conditions	Fail-safe hopper closure on signal loss

4 ENGINEERING DESIGN SOLUTION

4.1 Enclosure concept

A purpose-built enclosure was designed to house a pre-assembled Acutronic sand rainer within the geotechnical modelling laboratory at the University of Melbourne, as shown in Figure 2. The enclosure fully surrounds the sand raining system and defines a controlled raining volume, providing primary containment of sand and dust generated during operation. The design allows construction around the installed sand rainer without modification to the core equipment, minimising disruption to established experimental procedures. Transparent panels provide visual access for monitoring sand flow and raining uniformity, while access doors enable loading, inspection, and maintenance when the system is in a safe state.

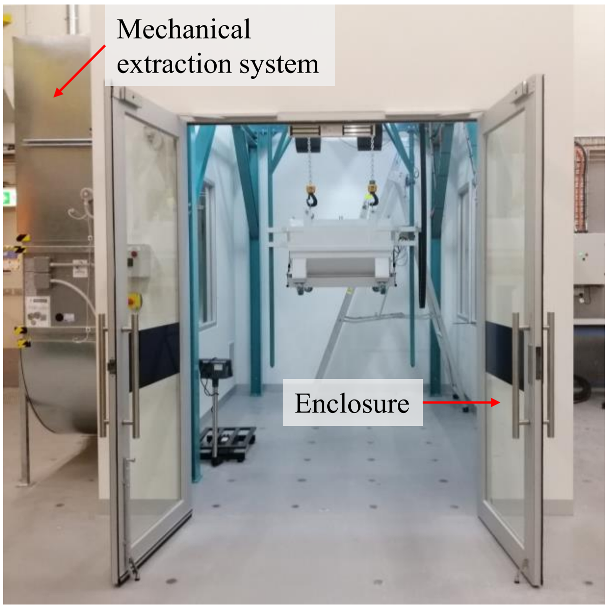

Figure 2. Purpose-built enclosure housing the sand rainer for dust containment and exposure control.

4.2 Dust containment and operational zoning

The enclosure establishes a clear separation between high-exposure and low-exposure zones. Sand raining operations are confined to the enclosed volume, containing both airborne dust and sand spillage within the enclosure footprint. Operator access is restricted during active raining, reducing the likelihood of direct exposure to airborne particles. This spatial zoning supports safe work practices by physically separating sand raining from surrounding laboratory activities and preventing the uncontrolled spread of sand across the laboratory floor.

Following pluviation, settled dust and spilled sand remain confined within the enclosure footprint. Cleaning is undertaken using HEPA-filtered vacuum equipment after a defined settling period, with the extraction system operating where appropriate to minimise re-suspension. Dry sweeping is avoided to prevent secondary airborne dust generation.

4.3 Negative-pressure HEPA filtration system

Airborne dust within the enclosure is managed using a mechanical extraction system that maintains a negative pressure relative to the surrounding laboratory. Figure 3 illustrates the ductwork layout of the extraction system. Air is continuously extracted from the enclosure during operation, passed through a HEPA Class H filter, and discharged back into the laboratory. The system is designed to maintain a pressure differential of at least 12 Pa (water gauge), ensuring inward airflow at any leakage paths and preventing airborne particles from escaping the enclosure. Defined inspection and filter replacement intervals are incorporated to maintain long-term filtration performance and safe ongoing operation.

The potential influence of enclosure airflow on sand deposition was considered during design. The extraction rate was selected to maintain negative pressure while limiting internal air velocities within the raining zone. Extraction points are positioned away from the falling sand stream to minimise cross-flow.

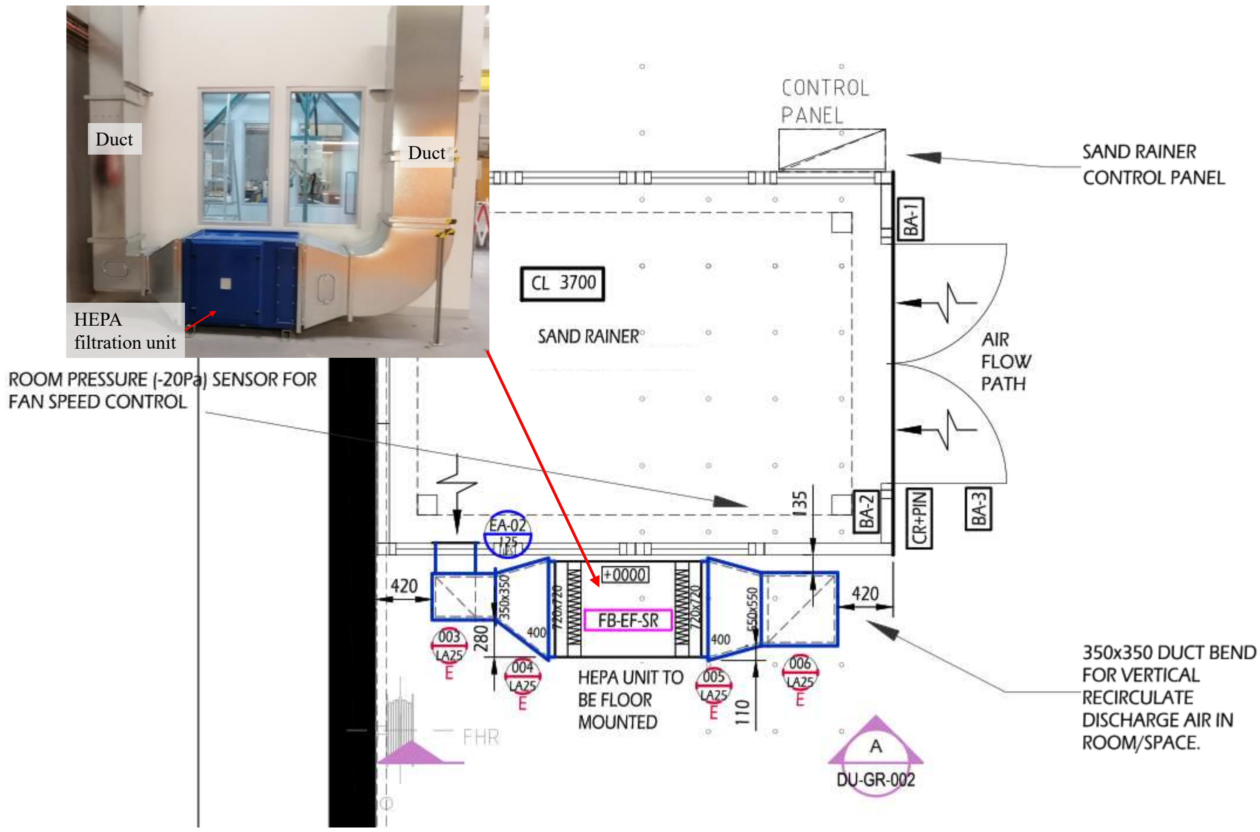

Figure 3. Ductwork layout of the mechanical extraction and HEPA filtration system serving the enclosure.

4.4 Automated hopper actuation

To reduce operator proximity during periods of elevated dust generation, the sand rainer hopper was fitted with a pneumatically actuated door that can be operated remotely from outside the enclosure. This allows sand flow to be initiated and terminated without personnel entering the enclosed space. Pneumatic actuation was selected for its robustness and suitability for fail-safe operation, with loss of electrical control signal resulting in automatic hopper closure. The actuator and associated pneumatic components were integrated into the existing sand rainer with minimal modification.

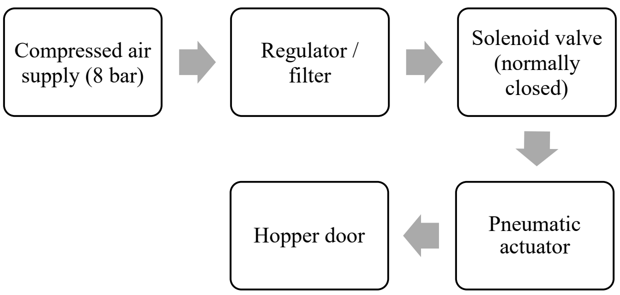

Figure 4. Conceptual pneumatic layout of the automated hopper door actuation system.

As shown schematically in Figure 4, compressed air from the laboratory supply is routed through an external regulator and filter assembly before passing through an electrically actuated solenoid valve to a pneumatic actuator directly connected to the hopper door. The solenoid valve remains closed in the absence of an active control signal, ensuring that sand flow cannot occur unless the system is intentionally enabled and operating under safe conditions.

4.5 Electrical interlocks and fail-safe control

Electrical interlocking was implemented to ensure that hopper door actuation is only possible when the experimental enclosure is in a safe state. Hopper actuation is initiated via an independent physical control switch located externally on the sand rainer control panel.

Figure 5 shows the electrical interlock and fail-safe control logic for automated hopper door actuation. A normally open safety relay interfaces the enclosure door safety system with the hopper actuation circuit. When the enclosure doors are fully closed, the enclosure safety system energises the relay, permitting power to be supplied to the solenoid valve controlling the hopper door. Manual actuation is therefore only possible when enclosure integrity is confirmed.

The interlock is designed to be fail-safe: loss of electrical power, loss of the enclosure door safety signal, or opening of the enclosure doors causes immediate de-energisation of the relay, removal of power from the solenoid valve, and automatic closure of the hopper door. This configuration prevents sand release under unsafe conditions and removes reliance on operator intervention for dust exposure control.

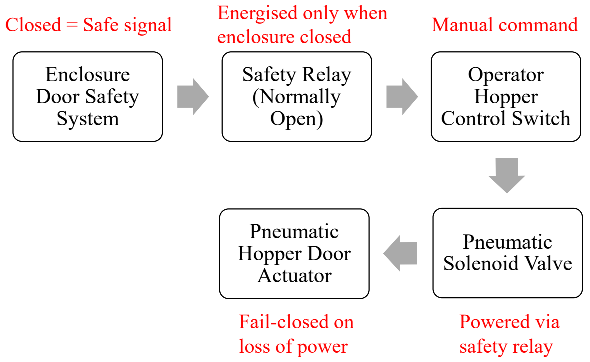

Figure 5. Conceptual electrical interlock and fail-safe control logic governing pneumatic hopper door actuation.

5 CONCLUSIONS

This paper describes the safety-in-design development of an enclosed and automated sand rainer system to reduce operator exposure to RCS during sand raining operations. Early hazard identification, informed by material safety data, observed operating practices, and tightening regulatory limits, indicated that procedural controls alone were insufficient to manage exposure risks.

The adopted engineering solution integrates a purpose-built enclosure, remote pneumatic hopper actuation, electrical interlocks with fail-safe logic, and a negative-pressure HEPA-filtered extraction system. These measures collectively address key exposure pathways by containing dust at source, maintaining inward airflow at enclosure boundaries, and eliminating the need for operator presence during high-dust tasks. The enclosure was designed around a pre-assembled commercial sand rainer and integrated into an existing laboratory without modification to the core equipment.

Operational use shows a clear qualitative reduction in visible airborne dust and improved containment of sand within the raining zone, alongside safer and more controlled operation. The work demonstrates how engineering controls can be effectively retrofitted to specialised laboratory equipment to meet increasingly stringent silica exposure requirements, with direct relevance to physical modelling laboratories handling granular materials.

While operational experience demonstrates a clear qualitative reduction in visible dust and improved containment, future work will include quantitative airborne particulate monitoring to verify compliance with relevant exposure standards and further validate system performance.

REFERENCES

Butterfield, R. and Andrawes, K. Z. (1970). An air activated sand spreader for forming uniform sand beds. *Géotechnique*, 20 (1): 97-100. https://doi.org/10.1680/geot.1970.20.1.97

Choi, S.-K., Lee, M.-J., Choo, H., Tumay, M. T. and Lee, W. (2010). Preparation of a large size granular specimen using a rainer system with a porous plate. *Geotechnical Testing Journal*, 33 (1): 45-54. https://doi.org/10.1520/GTJ101634

Cresswell, A., Barton, M. E. and Brown, R. (1999). Determining the maximum density of sands by pluviation. *Geotechnical Testing Journal*, 22(4): 324-328. https://doi.org/10.1520/GTJ11245J

Garnier, J. and Cottineau, L. M. (1988). La centrifugeuse du LCPC: Moyens de préparation des modèles et instrumentation. *Proceedings of Centrifuge 88*, Corte (ed.), Taylor & Francis, London, UK, pp. 83-90.

Safe Work Australia (2023). *Silica*. https://www.safeworkaustralia.gov.au/safety-topic/hazards/silica

Stuit, H. G. (1995). *Sand in the geotechnical centrifuge*. PhD thesis, TU Delft, Delft, Netherlands.

Tabaroei, A., Abrishami, S. and Hosseininia, E. S. (2017). Comparison between two different pluviation setups of sand specimens. *Journal of Materials in Civil Engineering*, 29 (10): 04017157. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001985

WorkSafe Victoria (2024). *Crystalline silica*. https://www.worksafe.vic.gov.au/crystalline-silica

Zhao, Y., Gafar, K., Elshafie, M.Z.E.B., Deeks, A.D., Knappett, J.A. and Madabhushi, S.P.G. (2006). Calibration and use of a new automatic sand pourer. *Proceedings of the 6th International Conference on Physical Modelling in Geotechnics*, Ng, Zhang and Wang (eds.), Taylor & Francis, London, UK, pp. 265-270.