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From Laboratory to Territory: Comparative Analysis of Displacement Monitoring Technologies for Landslides Using a Laminar Shear Box

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ABSTRACT: Monitoring ground displacement in unstable soil masses is a key component of Medellín's landslide monitoring program managed by the Disaster Risk Management Agency (DAGRD). Ensuring reliable and operationally effective monitoring requires assessing the performance and limitations of displacement measurement technologies under controlled conditions prior to field deployment.This paper presents the design and construction of a 3 m-high large-scale laminar shear box developed to provide a controlled physical modelling environment for testing subsurface displacement monitoring devices. The system enables the imposition of prescribed displacement profiles using hydraulic actuators acting against a reaction wall, allowing the simulation of deformation patterns representative of slope instabilities.Four displacement monitoring technologies were experimentally evaluated: (i) a conventional inclinometer, (ii) a commercial remote-monitoring inclinometer, (iii) an in-house developed remote-monitoring inclinometer, and (iv) Time Domain Reflectometry (TDR) devices. The comparison focused on displacement profile consistency, deformation range, spatial resolution, acquisition frequency, telemetry capability, and data interpretation. Results show that all inclinometer-based systems capture similar displacement trends at low to moderate deformation levels, while differences become more pronounced under large semi-cyclic loading. The in-house system better preserves curvature changes with depth, improving the identification of localized deformation zones. TDR performance was limited under distributed deformation. Overall, the study shows how large-scale physical modelling can support the selection and validation of displacement monitoring technologies for landslide early warning systems.

1 INTRODUCTION

Landslide risk is a persistent concern in Medellín and the Aburrá Valley, where unstable urban hillslopes interact with intense development and recurrent triggering conditions (Gómez and Villarraga, 2013; Nieto, Aristizábal and Ozturk, 2025). In this context, the Administrative Department for Disaster Risk Management of Medellín (DAGRD) leads the city's disaster risk management actions, including the implementation of monitoring systems and early warning mechanisms as preventive strategies and to support timely, evidence-based decisions to reduce fatalities and economical losses.

Among several strategies, DAGRD has implemented SIMER, a Risk Scenario Monitoring System that operates across multiple instrumented sites representing landslide risk scenarios, and can therefore be interpreted as a set of local landslide early warning systems (Lo-LEWS) following the definitions proposed by Calvello (2017), Guzzetti et al. (2020), and Pecoraro et al. (2019). These scenarios are typically localized instabilities where ground displacement is a primary variable used to guide actions such as field inspections, prioritization of interventions, and evacuation decisions. When mitigation measures have been implemented, monitoring is also used to verify performance and confirm whether displacement trends are stabilized.

Inclinometers are one of the main techniques for monitoring subsurface ground displacement. In the conventional approach, a technician uses a portable probe to measure borehole deformation by recording the inclination variations at predefined depths (Allasia *et al.*, 2020). Despite its advantages, this workflow has practical limitations, including the need to commute to the site, potential accessibility constraints, and a monitoring frequency that depends on the availability of the probe and trained personnel.

Timely detection of landslide initiation or significant acceleration is a key indicator of adequate LEWS performance (Pecoraro, Calvello and Piciullo, 2019). However, conventional inclinometer campaigns may not always provide the desired temporal resolution, particularly under operational constraints commonly encountered by DAGRD in Medellín. These limitations motivate the development of the complementary cost-effective technology named SMaRT-Node (Soil Monitoring and Response Technology Nodes), consisting of a set of devices or sensors capable of measuring several geotechnical variables of interest in the context of landslide monitoring, such as water content, water pressure, accumulated rainfall, and terrain displacements. As such, a SMaRT-Node may include an in-place inclinometer for remote monitoring of in-depth terrain displacements, based upon inertial sensors. The SMaRT-Nodes can increase acquisition frequency and enable telemetry, either as standalone solutions or as redundant instruments alongside conventional inclinometers.
Before the large-scale deployment of a network of SMaRT-Nodes, it is essential to assess the performance and limitations of the proposed instrument relative to established alternatives. To this end, a 3 m-high large-scale laminar shear box was designed and constructed for evaluating the in-depth performance of the SMaRT-Node's inclinometer by comparing its readings against established reference instruments, including a conventional case-probe inclinometer, an in-place commercial inclinometer, and a Time Domain Reflectometry (TDR) system. This paper presents the shear box setup, describes the monitoring technologies assessed, and reports the results of the experimental comparison.

2 LARGE-SCALE LAMINAR SHEAR BOX: DESIGN AND CONSTRUCTION

The design of the large-scale shear box in this study was inspired by previous designs built primarily for dynamic testing purposes along with shake tables (Jafarzadeh, 2004; Vivek and Raychowdhury, 2019; Castelli *et al.*, 2022).

The dimensions and a representative sketch of the large-scale laminar shear box are shown in Figure 1. The apparatus consists of 13 square laminar frames stacked vertically, resembling a set of drawers due to the imposed and constrained direction of movement of each frame relative to its neighbors.

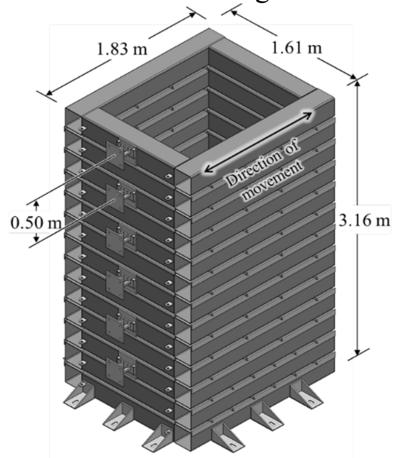

Figure 1. Rear isometric view of the laminar shear box.

As shown in Figure 2, each frame is constructed by welding 0.22 m × 0.22 m steel hollow square sections, forming a rigid perimeter. Frames are stacked and gravitationally supported one above the other, while allowing controlled relative displacements. To ensure safe, stable, and quasi-uniform inter-frame motion, a roller-guidance system is implemented along the two sides of each frame aligned with the direction of movement. This system comprises two sets of rollers, which reduces friction and limits rotations while maintaining alignment during operation. The bottom frame is anchored to the laboratory floor using structural steel angles, providing a fixed base boundary condition for the assembly.

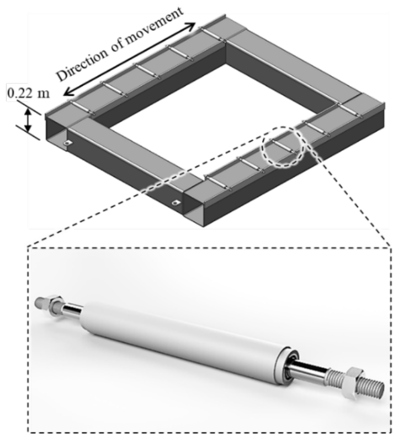

Figure 2. Detailed view of the roller mechanism enabling relative displacement between frames.

Because the inter-frame roller mechanism is a critical component transmitting the cumulative gravitational load of the upper frames while enabling low-resistance motion, its structural performance was verified before constructing the laminar shear box. First, a finite element model was developed to evaluate stresses and deformations under the expected roller loads. The numerical results indicated that even under twice the design load per roller, stresses remained within the elastic range and predicted deformations were negligible, with no expected impact on system performance. As a second verification step, a representative roller assembly was subjected to a uniaxial loading test up to the same load level used in the numerical assessment. The test yielded a maximum non-permanent displacement of 0.002 mm, confirming the numerical prediction and supporting the adequacy of the roller design for the intended loading regime.

Figure 3 shows the final constructed laminar shear box. The system was installed adjacent to the laboratory reaction wall, which provides the restraint and alignment required for controlled lateral loading. Hydraulic jacks acting against the reaction wall are used to impose prescribed horizontal displacements on individual frames with millimetric precision, enabling the generation of target displacement profiles along the height of the box. To increase flexibility in loading configuration, six jack-connection supports were incorporated, allowing actuation at different elevations and accommodating the geometric constraints and spacing imposed by the seismic laboratory reaction-wall setup; these supports were also mechanically tested in both compression and tension, showing satisfactory performance for the expected loading range.

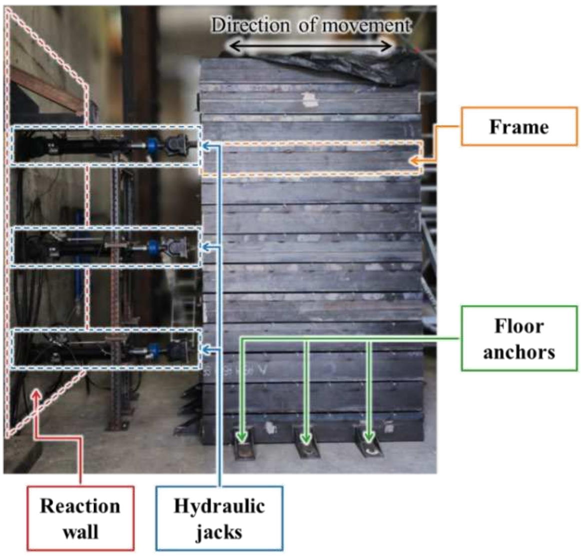

Figure 3. Lateral view of the constructed laminar shear box.

3 MONITORING TECHNOLOGIES ASSESSED

Figure 4 shows the layout of the four monitoring technologies installed in the laminar shear box. The test configuration includes: (i) a conventional inclinometer (manual surveying), (ii) a commercial remote-monitoring inclinometer, (iii) an in-house developed remote-monitoring inclinometer, and (iv) two Time Domain Reflectometry (TDR) cable arrays. The two remote-monitoring inclinometers are also known as in-place inclinometers (IPI), meaning that a set of sensors is permanently installed inside an inclinometer casing and measurements are acquired automatically at fixed depths. Depending on the architecture, data can be stored locally at the surface (e.g., in a data logger) and retrieved periodically, or transmitted remotely to a receiver (e.g., server/cloud storage) via available communication systems. The following subsections summarize the main features of each technology

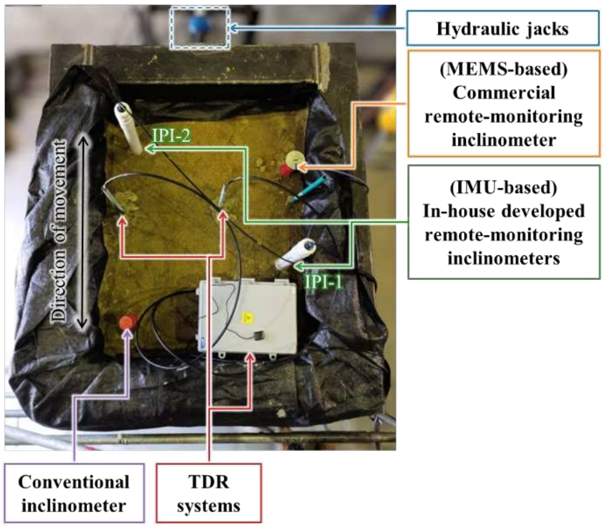

Figure 4. Plan view of the laminar shear box showing the location of the assessed monitoring technologies.

The monitoring systems were installed with sufficient lateral spacing to avoid measurement interference between instruments. Boundary effects were addressed through the test configuration: the analyzed displacement component coincides with the direction of hydraulic jack actuation, and the sensors were installed in paired positions along the box, with two instruments located near the hydraulic jacks, two TDR arrays in the central zone, and two instruments at the farthest end of the box. This arrangement enables comparison of the technologies under similar deformation conditions while capturing potential spatial variability. The imposed deformation is global to the soil mass and controlled by hydraulic actuation rather than induced by the sensors. Additionally, the laminar shear box incorporates a roller-guidance system that allows relative motion between frames and reduces shear transfer and boundary constraints within the assembly.

3.1 Conventional inclinometer

A conventional inclinometer survey is performed using a portable probe that is progressively positioned by an operator at predefined depth intervals (typically every 0.5 m) inside a grooved tube known as the inclinometer casing. The probe records changes in inclination with depth, which are subsequently integrated to obtain lateral displacement profiles. Modern probes commonly rely on MEMS (micro-electromechanical systems) accelerometers to measure tilt. Although conventional inclinometers can provide high-quality displacement profiles when surveys follow good field practice, their main limitation in operational monitoring is the dependence on site access and personnel availability. As a result, acquisition frequency is constrained by logistics, which can reduce temporal resolution during periods of rapid slope evolution (Dunnicliff, 1993; Bassett, 2011).

3.2 Commercial remote monitoring inclinometers

Commercial remote-monitoring inclinometers extend the conventional concept by installing an array of in-place sensors permanently inside the casing to record inclination at fixed depths. Sensors (uniaxial or biaxial MEMS) are typically connected to a surface data acquisition unit, which collects measurements at high frequency. Depending on the deployment, data may be stored locally for later retrieval or transmitted automatically via available telecommunication system. This approach addresses the main operational limitation of manual surveys by enabling automated acquisition and near-real-time access to measurements when telemetry is enabled (Dunnicliff, 1993; Bassett, 2011). This technology normally implies a higher cost compared to the conventional monitoring approach; however, to reduce it, sensor spacing is often increased, which lowers vertical resolution and may limit the ability to precisely localize the active shear zone unless prior information is available to guide sensor placement.

3.3 In-house developed remote monitoring inclinometer

In addition to the design and construction of the large-scale shear box, this study developed a cost-effective remote-monitoring inclinometer intended to complement existing displacement monitoring practice. The system uses inertial measurement units (IMUs) housed in capsule-like nodes that integrate accelerometers, gyroscopes, and, in some configurations, magnetometers. Changes in capsule orientation are interpreted as changes in ground inclination and then converted into displacement indicators. Similar to commercial IPIs, the in-house system enables automatic and remote monitoring, reducing dependence on field visits. A key motivation for this development is affordability: the lower unit cost allows denser sensor spacing, which increases the vertical spatial resolution of the monitored deformation profile and improves the characterization of distributed shear zones.

3.4 Time Domain Reflectometry (TDR) devices

TDR systems monitor subsurface deformation using coaxial cables grouted within boreholes. When shear deformation is sufficient to crack the grout and deform the cable (by pinching, stretching, or shearing), the cable impedance changes. A voltage pulse injected at one end produces reflections at impedance discontinuities, allowing the identification of depths where damage has occurred. Repeated measurements track the evolution of reflection signatures over time, which can also provide a qualitative indication of progressive deformation intensity, particularly where movement localizes into a shear band (Anderson and Welch, 2000; Dowding and O'Connor, 2000).

4 EXPERIMENTAL TESTING

The experimental program consisted of imposing a sequence of controlled lateral displacement profiles on the laminar shear box by pushing forward and backward selected frames against the reaction wall with hydraulic jacks, as illustrated in Figure 5.

Example of an imposed displacement profile

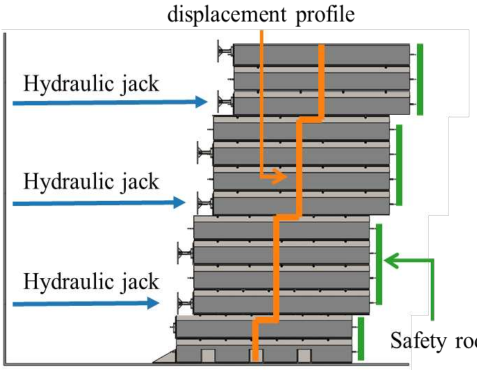

Figure 5. Example of an imposed displacement profile on the shear box.

By applying different target displacements at different elevations, the test produced multiple deformation patterns along the height of the box, from near-uniform translation along a single shear plane to stepped or distributed shear profiles. Each imposed profile was held long enough to acquire quasi-synchronous readings from all monitoring systems, enabling direct comparison of their displacement profiles.

Across the test sequence, all four systems capture the same overall kinematic progression: negligible deformation during the initial stages (first row of Figure 6) followed by progressively larger accumulated displacement profiles as the imposed deformation increases (second and third rows of Figure 6). For the low-displacement stages, the profiles are nearly coincident, indicating consistent baseline behavior and good short-term repeatability. The purpose of the experiment is to compare the kinematic deformation profiles measured by the different monitoring technologies rather than to reproduce the exact displacement pattern imposed by the hydraulic jacks. While the jacks prescribe displacements at discrete elevations, the soil mass undergoes internal deformation and strain redistribution, so the resulting displacement field differs from the actuation pattern. For this reason, the imposed profile is not shown in Figure 6, as it could be misleading; instead, the figure focuses on comparing the deformation profiles reconstructed by the different monitoring systems under the same controlled deformation field. As deformation increases, the profiles become increasingly non-linear with depth, with larger displacements developing in the upper portion of the column and smaller displacements at depth, consistent with a progressively distributed shear pattern rather than rigid translation along a single thin slip surface.

A clear spatial effect emerges when the instruments are compared according to their position relative to the hydraulic jacks. The two devices located furthest from the jacks (In-house IPI-1 and the conventional inclinometer) show the best agreement over most stages, reproducing similar profile shapes and comparable displacement magnitudes. In contrast, the instruments located closest to the jacks (In-house IPI-2 and the commercial IPI) exhibit a noticeable mismatch in the upper half of the profiles during the final stages, when the system crossed back through the zero baseline and continued into negative accumulated displacements. This divergence suggests that additional internal deformation modes were activated after the large, imposed deformation, which resulted in a maximum cumulative displacement path of approximately 30 cm over the forward–backward loading sequence.

The smoother displacement profiles obtained from the conventional inclinometer and the commercial IPI are consistent with the known influence of casing stiffness, which can redistribute localized deformation over a broader depth interval, whereas the in-house IPI preserves sharper curvature changes that may better reflect localized deformation gradients.

Several mechanisms could contribute to the observed discrepancies in the pull-back profiles, including progressive frame racking/rotation, frictional stick-slip or backlash in the roller-guidance system, localized torsion near the actuation points, and/or irreversible deformation of the tested medium and instrument-casing coupling. Consequently, the pull-back profiles reflect not only differences in sensor response, but also a more complex and non-uniform deformation state of the shear box assembly after the large semi-cyclic loading history.

An additional observation is that the commercial IPI and the conventional inclinometer tend to produce smoother displacement profiles than the two in-house IPIs. This behavior can be beneficial or misleading depending on its origin. In some systems, smoother profiles may result from profile reconstruction procedures such as interpolation between fixed sensor depths or internal filtering intended to improve stability. Conversely, the in-house IPIs display sharper curvature changes, which can indicate greater sensitivity to localized deformation gradients and may be advantageous for more precise identification of localized shear zones at depth (e.g., landslide slip surfaces). However, sharper profiles can also result from localized noise, sensor malfunction, or partial decoupling between the casing and the sensor capsules. For this reason, interpreting these features as “localized deformation detection” should be supported by repeatability across consecutive snapshots and consistency between simultaneous measurements. In the present tests, both in-house IPIs show repeatable profile features across adjacent stages and indicate a consistent depth at which the profile curvature sharpens (approximately 0.7 m), coincident with the elevation where the upper hydraulic jack applies actuation. Under these conditions, the higher spatial detail captured by the in-house IPIs can be interpreted as a practical advantage for constraining shear-plane depth in landslide monitoring applications.

TDR results are not shown in Figure 6 as they were not directly comparable with the inclinometer-derived displacement profiles under the present test configuration, and the recorded traces did not exhibit stable, trackable reflection features. A plausible explanation is that the imposed deformation produced a distributed or massive cracking and debonding between the cable arrays and the grouting, rather than localized damage zones comparable to shear planes. Such widespread grout damage can generate multiple impedance discontinuities along the cable, producing overlapping reflections and an apparent increase in signal noise, which prevents robust localization of deformation and reliable comparison with the displacement profiles.

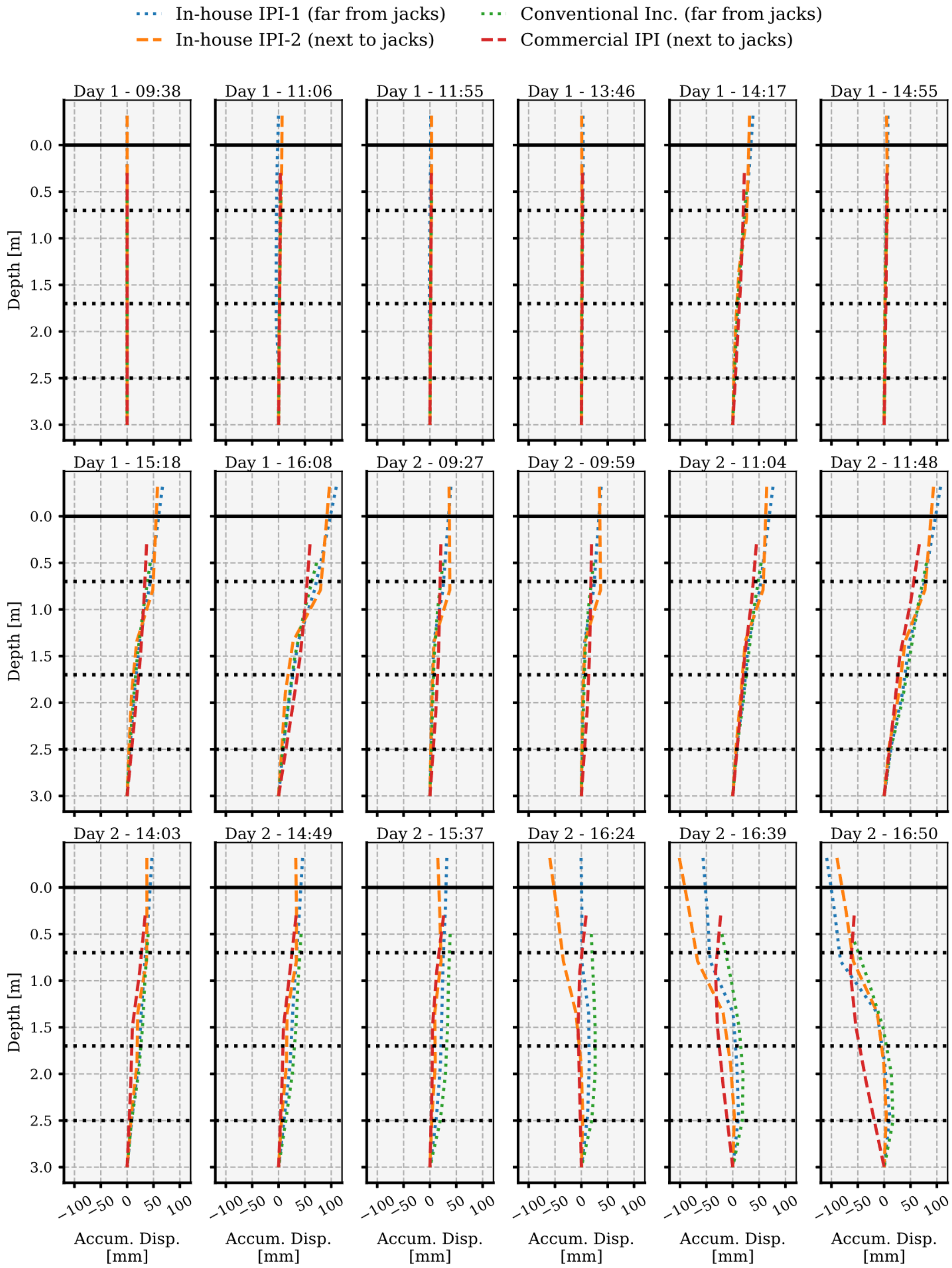

Figure 6. Comparison of the displacement profiles obtained from all the assessed technologies. Doted black lines correspond to the depths at which the hydraulic jacks act.

5 CONCLUSIONS

This study demonstrates how large-scale physical modelling can directly support everyday geotechnical monitoring decisions by providing a controlled environment where displacement sensors can be tested, compared, and verified before field deployment. The 3 m-high laminar shear box composed of stacked frames with a roller-guidance system and actuated by hydraulic jacks against a reaction wall, enabled the controlled imposition of displacement profiles suitable for multi-instrument comparisons.

One practical application of this type of laboratory setup is that results from these large-scale procedures allow disaster risk management agencies such as DAGRD in Medellín and similar agencies worldwide assess which displacement technology (and configuration) is most suitable for their Lo-LEWS before field deployment of a monitoring network.

The main goal of the experiment setup is to enable a controlled comparative evaluation of monitoring technologies, rather than to establish absolute calibration of displacement measurements. Overall, the four instruments produced comparable displacement profiles in terms of trend, magnitude, and general shape, particularly at low to moderate deformation levels, where the curves are closely aligned. Differences become more visible at the largest imposed semi-cyclic loading, but the global kinematic interpretation remains consistent across devices. A notable distinction is that the in-house IPIs tend to preserve sharper curvature changes with depth, which can be advantageous because it may capture more localized deformation gradients and thus help identify landslide failure surfaces.

Beyond landslide-instrument benchmarking, the large-scale laminar shear box can support other physical-modelling applications. With suitable boundary conditions and actuation, it could be adapted for 1D shear-wave propagation studies (e.g., mounting on a shaking table to investigate strain-compatible wave transmission, stiffness degradation, and sensor response under cyclic loading). It could also serve as a controlled platform for testing ground-improvement or reinforcement elements—for example, simplified micropile/anchor interaction under imposed lateral deformation, comparative testing of connection details, or validation of instrumentation strategies for reinforced slopes and retaining systems.

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