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Research article

Experimental and numerical studies of displacement fields and failure mechanisms in untreated and reinforced slopes using optical flow analysis

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Abstract: Slope failures have caused significant human casualties and economic losses worldwide, with impacts reaching billions of dollars annually. These failures underscore the critical need for effective slope stability analyses. In particular, the mining industry faces this risk due to the accumulation of waste in tailing dams, which have a history of catastrophic failures. This study introduces a novel approach to analyze slope displacement fields and failure surfaces using the Digital Image Displacement (DID) method for an optical flow analysis, combined with a MATLAB code for data correction, numerical verification through Finite Element Method (FEM), and Limit Equilibrium Method (LEM) analyses. This novel methodology in geotechnical applications provides high, pixel-level sensitivity, thus enabling the detection of small displacement fields over short time intervals and spatially localized motions necessary to track the initial development of progressive failure. Forty-one experiments were conducted on untreated and geosynthetic-reinforced sandy slopes, thereby using more than 700 high-resolution digital images to investigate failure shapes and displacement fields. The results revealed a logarithmic spiral failure shape for both untreated and reinforced slopes, with reinforced slopes exhibiting deeper and more pronounced rupture surfaces. Geosynthetic reinforcement significantly improved the slope stability, which resulted in the Factor of Safety (FS) increase for 30° slopes from 1.2 to over 3 and increasing load-bearing capacity (up to 1700N) while reducing displacements. Additionally, the study emphasized the critical influence of slope geometry and compaction on the overall stability, thereby identifying closer reinforcement spacing (e.g., within

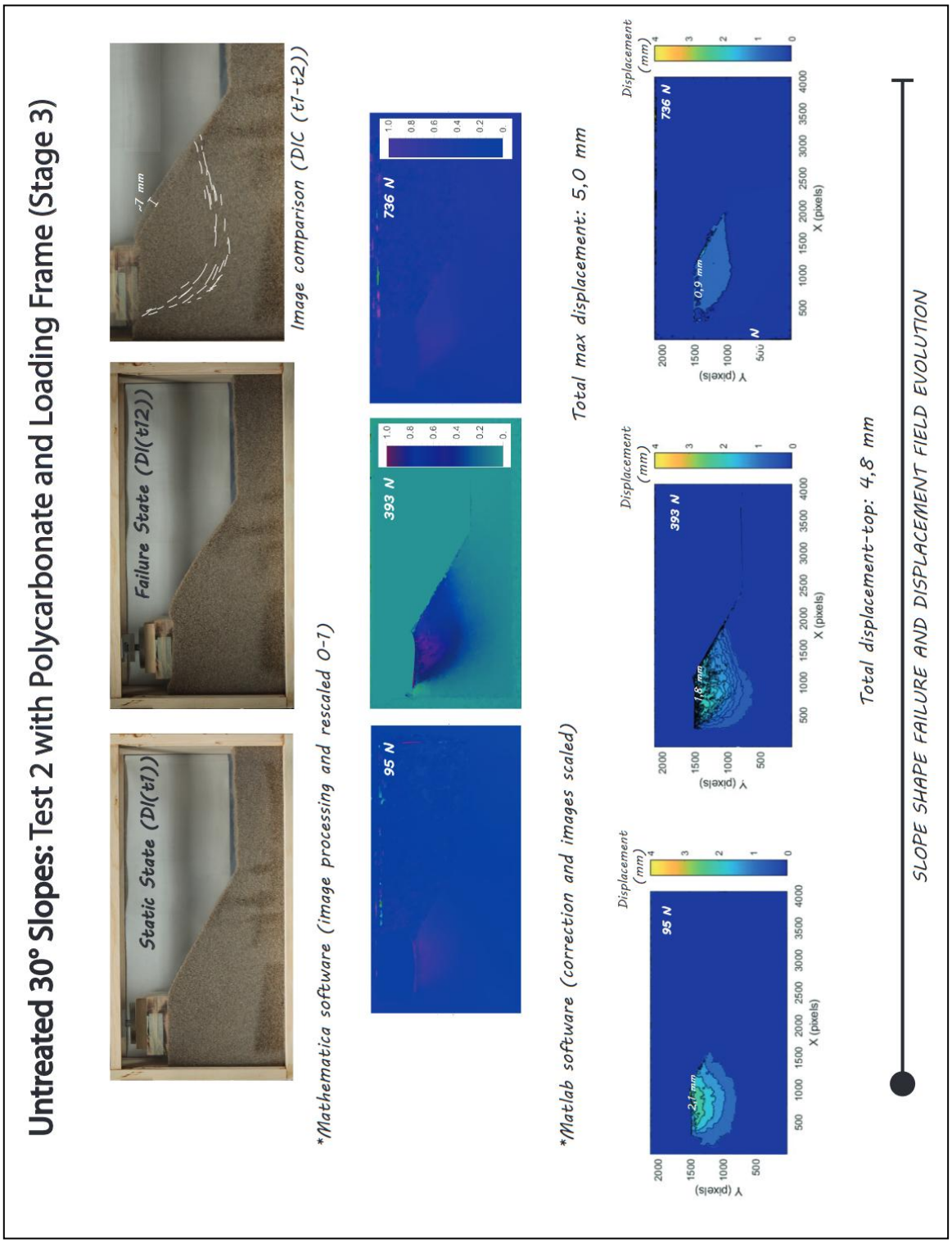
one-third slope height) as the most effective design configuration to maximize stabilization. These findings offer valuable insights into the slope behavior, improve the precision of displacement measurements, and advance geotechnical engineering practices for enhanced risk mitigation and slope stability analyses.

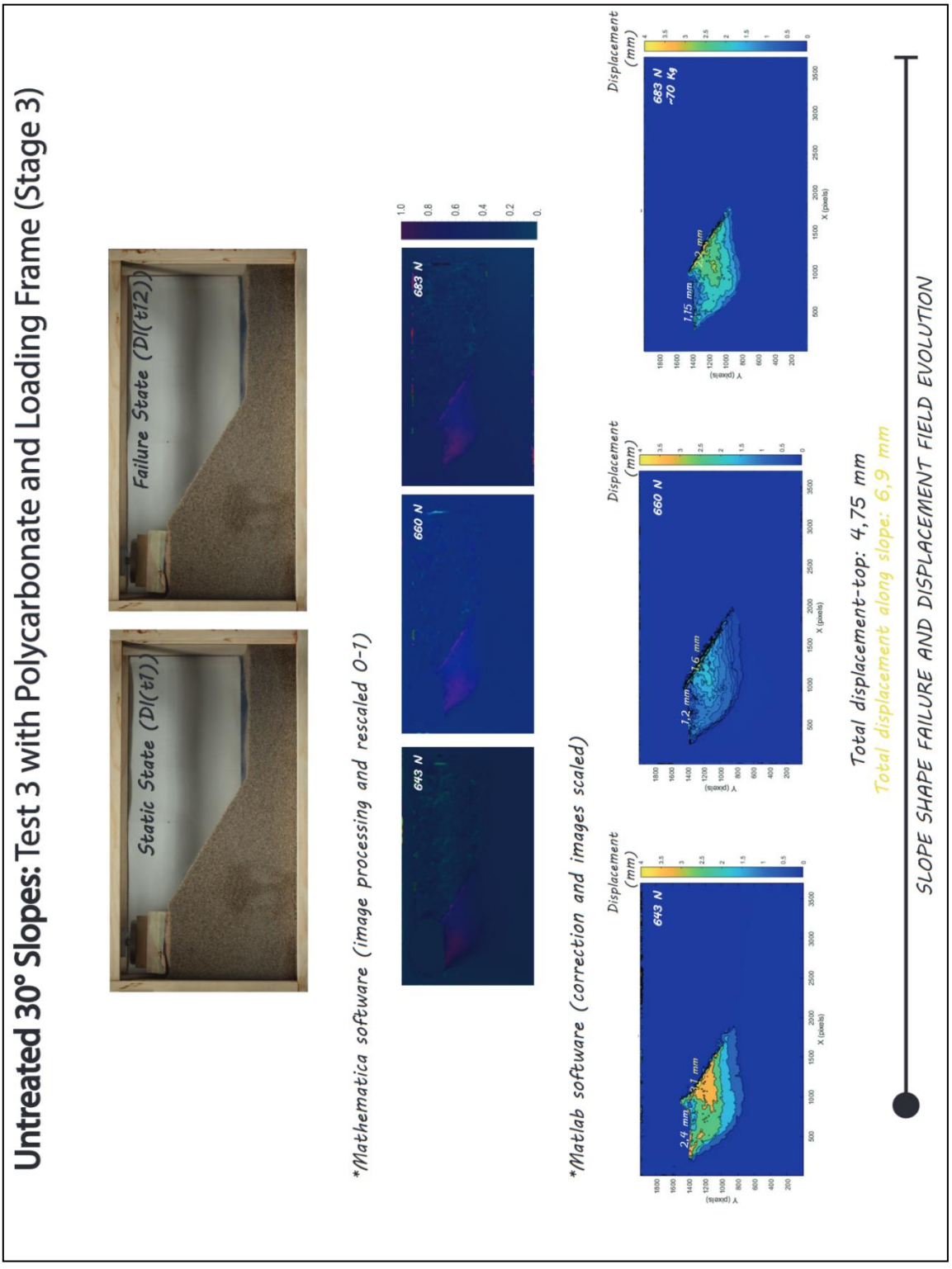
Keywords: slope failure; digital image displacement; geosynthetic reinforcement; logarithmic spiral

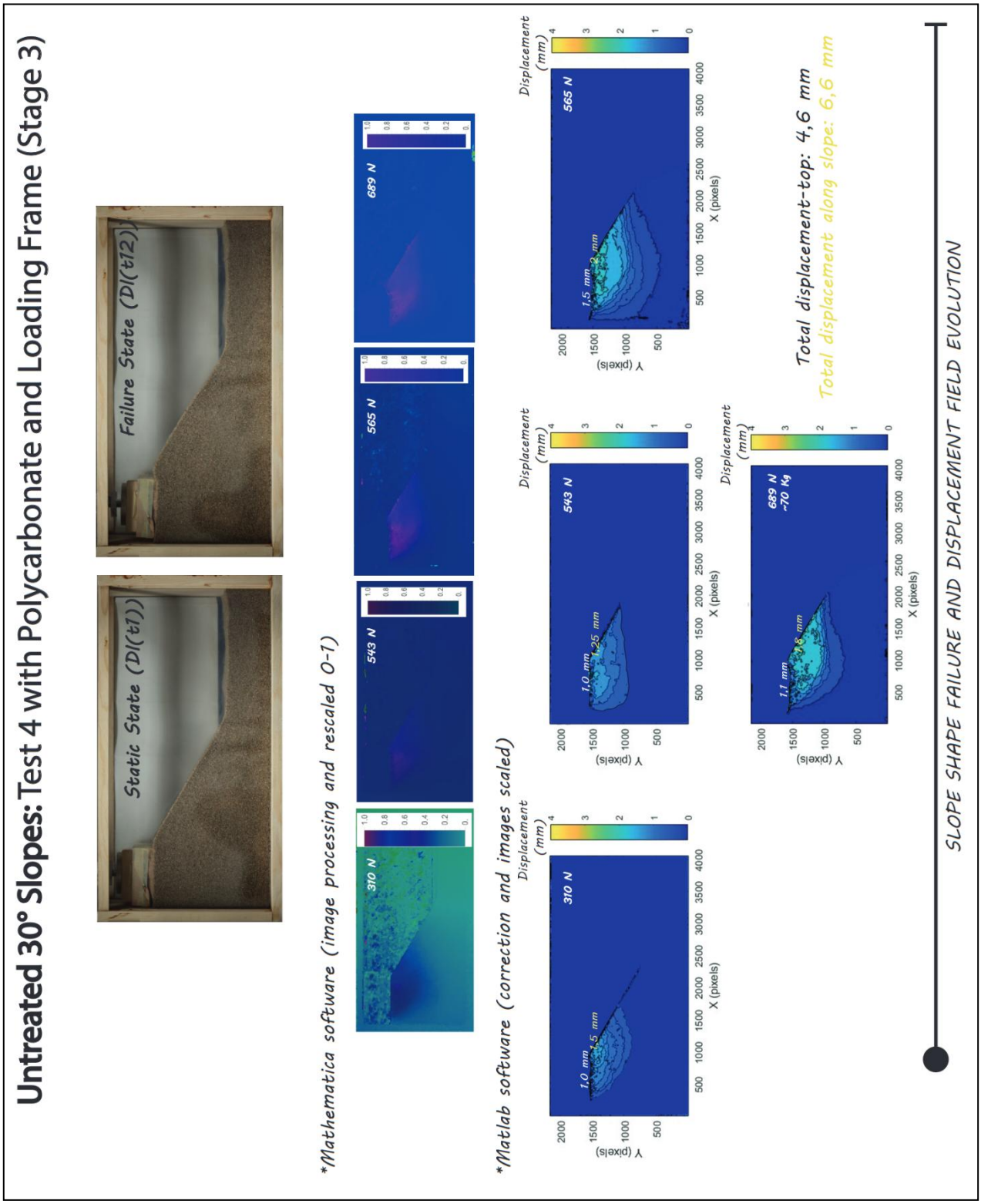
Supplementary

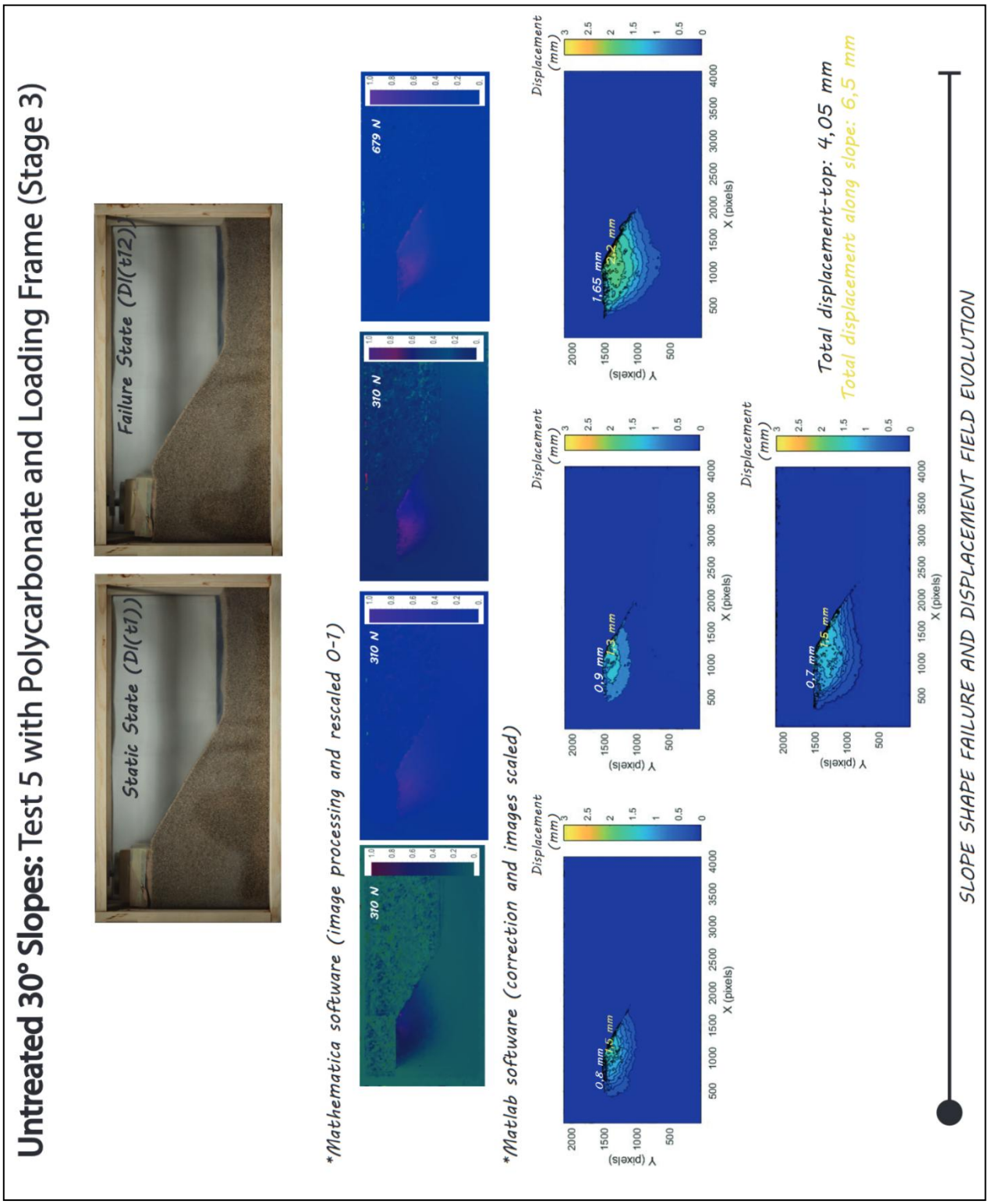
Appendix A

*Appendix A.1. U*ntreated 30° slopes failure shapes and displacement fields

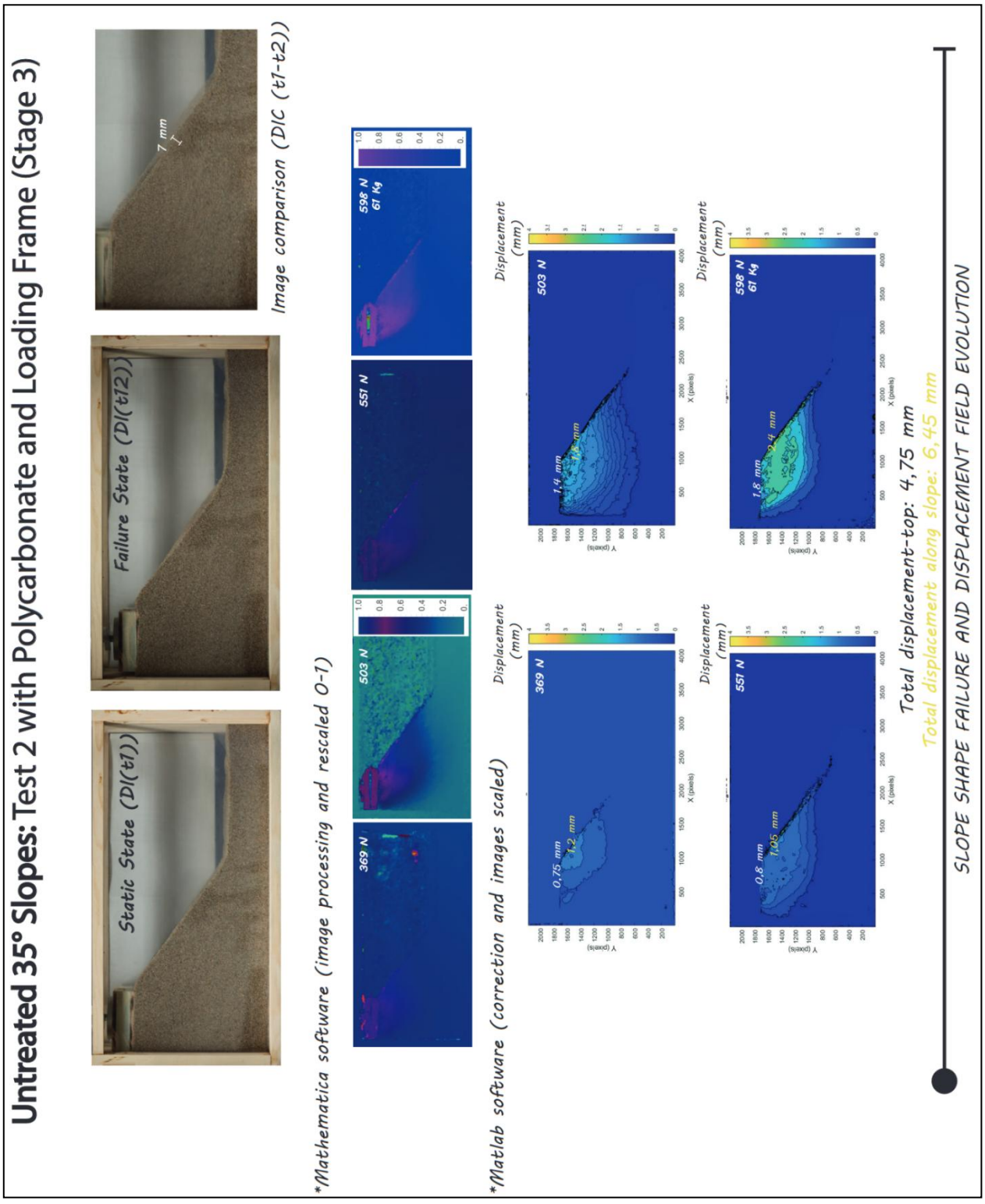


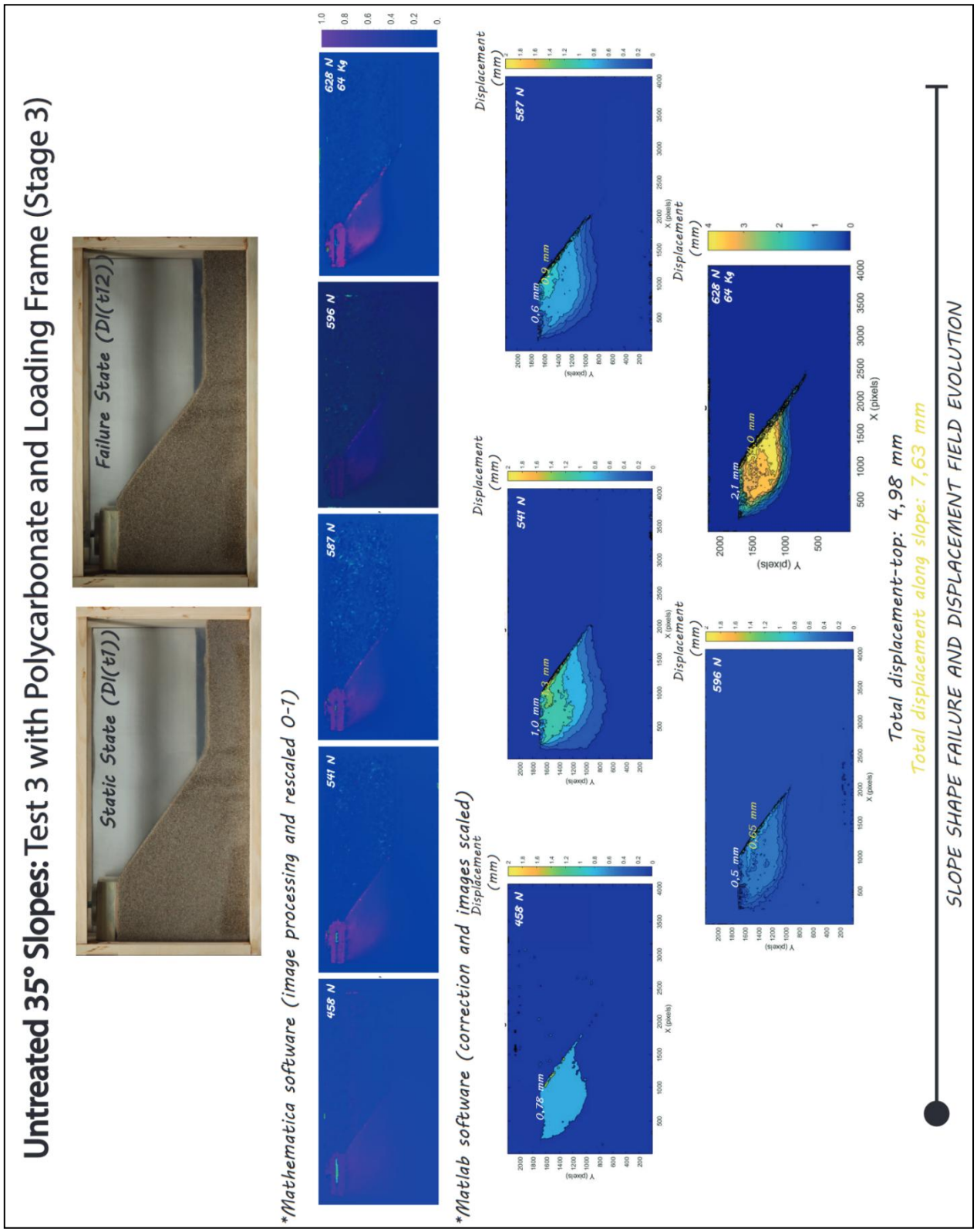

Untreated 30° Slopes: Test 3 with Polycarbonate and Loading Frame (Stage 3)
Static State (D(t1))
Failure State (D(t2))
*Mathematica software (image processing and rescaled 0-1)
643 N
660 N
683 N
1.0
0.8
0.6
0.4
0.2
0.
*Matlab software (correction and images scaled)
Displacement (mm)
643 N
2.4 mm
2.1 mm
660 N
1.2 mm
1.6 mm
683 N
~70 Kg
1.75 mm
2 mm
Y (pixels)
X (pixels)
Total displacement-top: 4,75 mm
Total displacement along slope: 6,9 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION


Untreated 30° Slopes: Test 4 with Polycarbonate and Loading Frame (Stage 3)
Static State (D(t1))
Failure State (D(t2))
*Mathematica software (image processing and rescaled 0-1)
310 N
543 N
565 N
689 N
*Matlab software (correction and images scaled)
Displacement (mm)
Y (pixels)
X (pixels)
1.0 mm
1.5 mm
1.25 mm
1.6 mm
1.1 mm
1.8 mm
689 N -70 Kg
Total displacement-top: 4,6 mm
Total displacement along slope: 6,6 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION


Untreated 30° Slopes: Test 5 with Polycarbonate and Loading Frame (Stage 3)
Static State (DI(t1))
Failure State (DI(t2))
*Mathematica software (image processing and rescaled 0-1)
310 N
310 N
679 N
*Matlab software (correction and images scaled)
Displacement (mm)
Y (pixels)
X (pixels)
0,8 mm
1,5 mm
0,9 mm
1,3 mm
0,7 mm
1,5 mm
1,65 mm
2,2 mm
Total displacement-top: 4,05 mm
Total displacement along slope: 6,5 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION

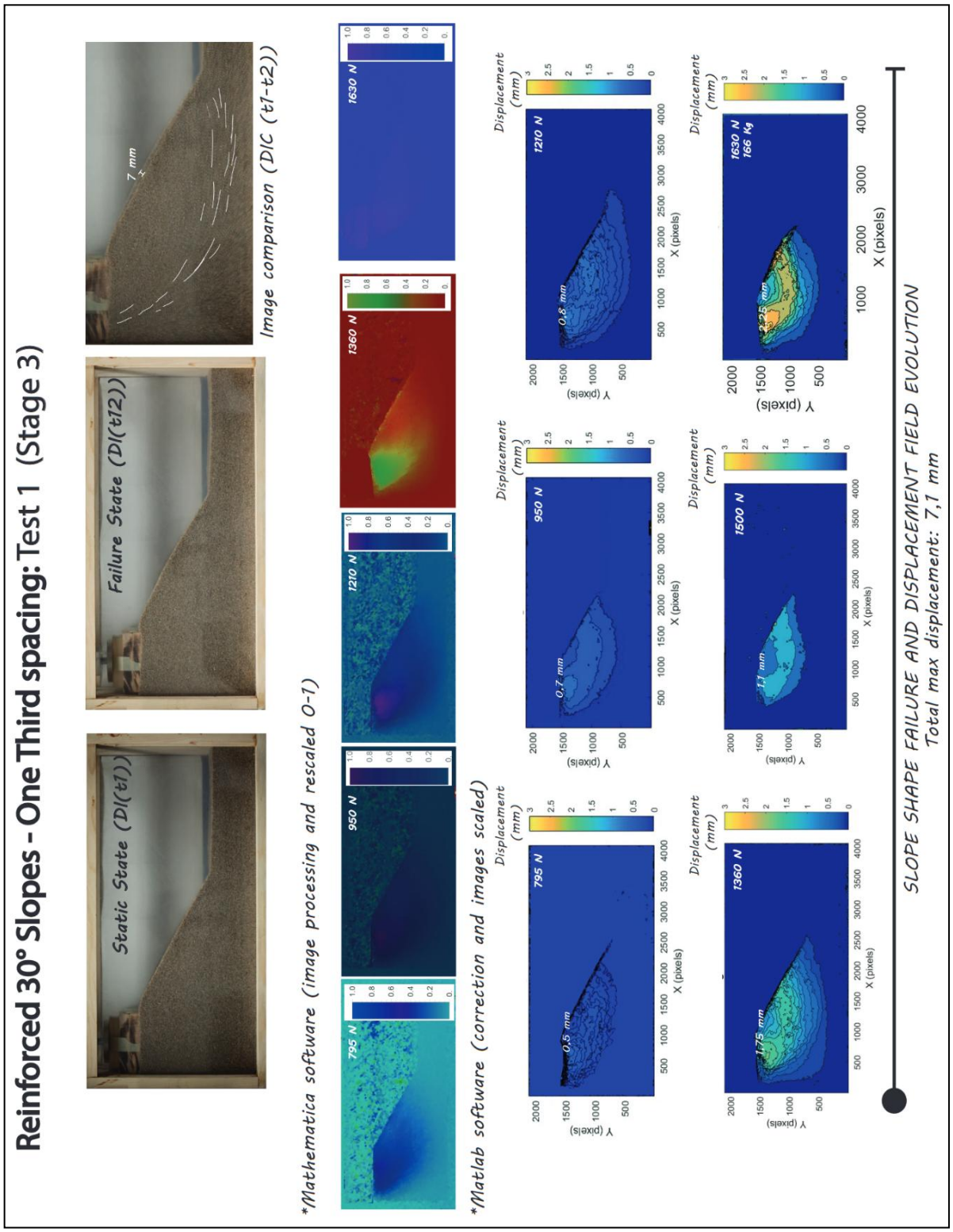
Appendix A.2. Untreated 35° slopes failure shapes and displacement fields

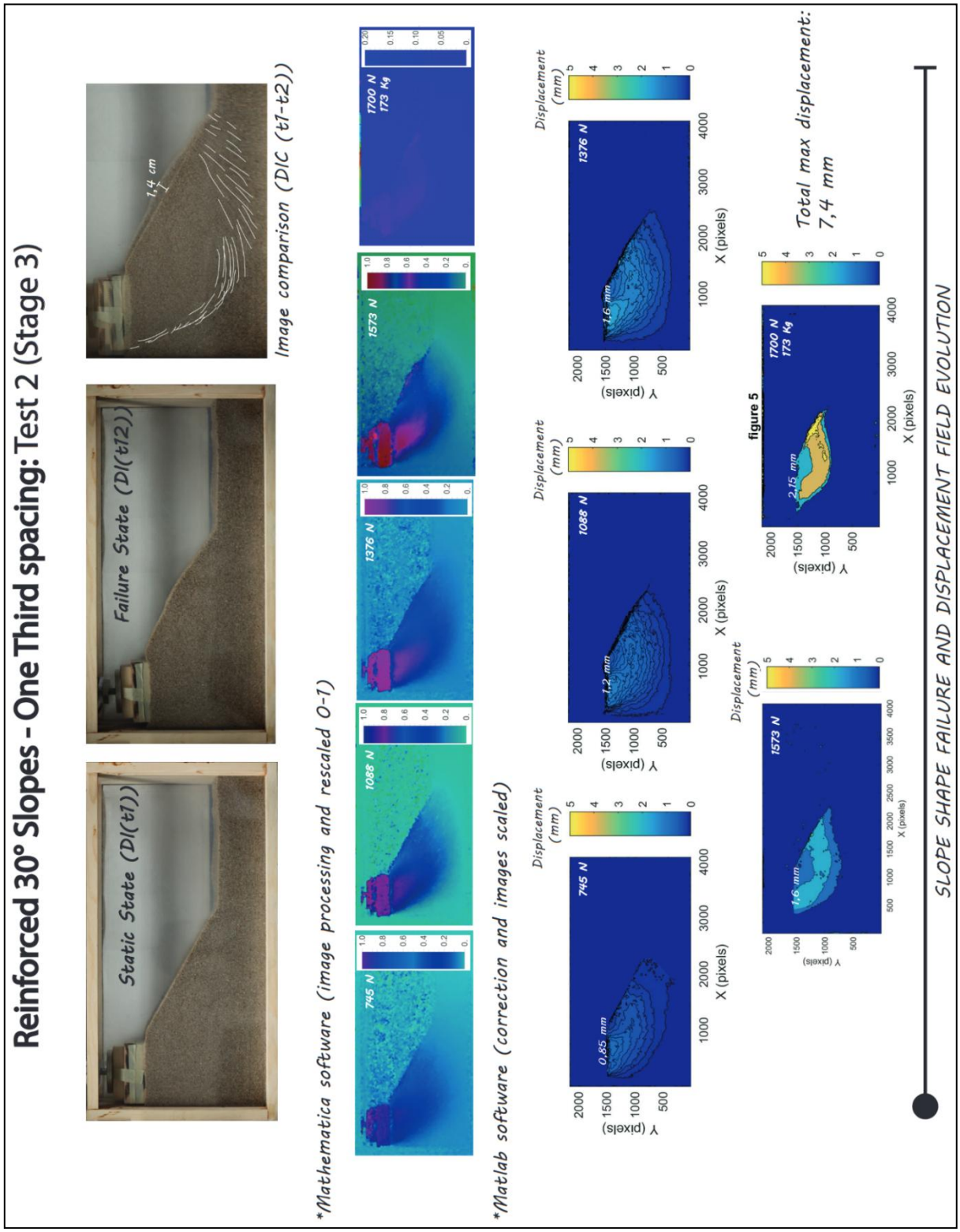


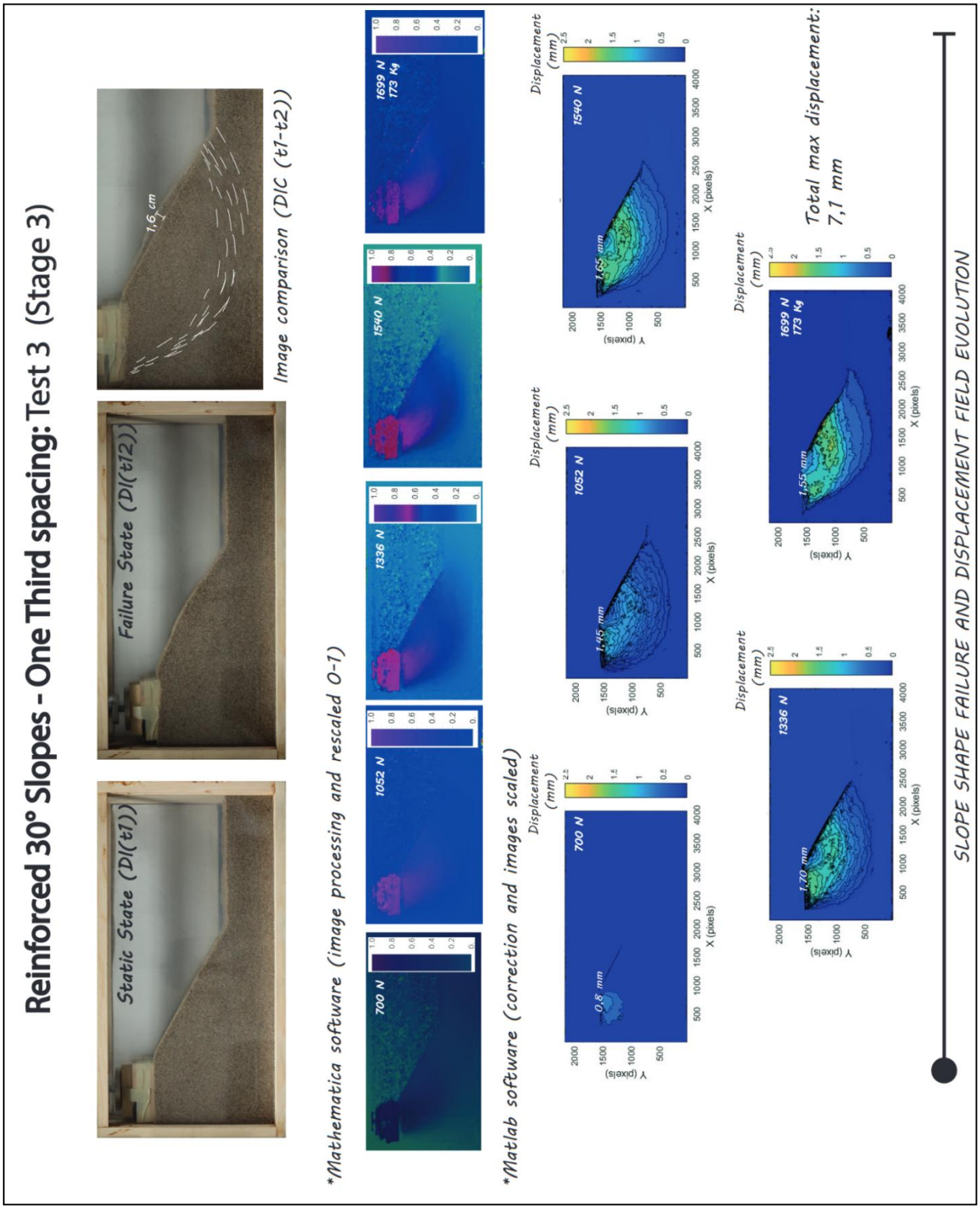

Untreated 35° Slopes: Test 3 with Polycarbonate and Loading Frame (Stage 3)
Static State (DI(t1))
Failure State (DI(t12))
*Mathematica software (image processing and rescaled 0-1)
458 N
541 N
587 N
596 N
628 N
64 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
0,78 mm
1,0 mm
0,6 mm
0,5 mm
0,65 mm
2,1 mm
Y (pixels)
X (pixels)
Total displacement-top: 4,98 mm
Total displacement along slope: 7,63 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION

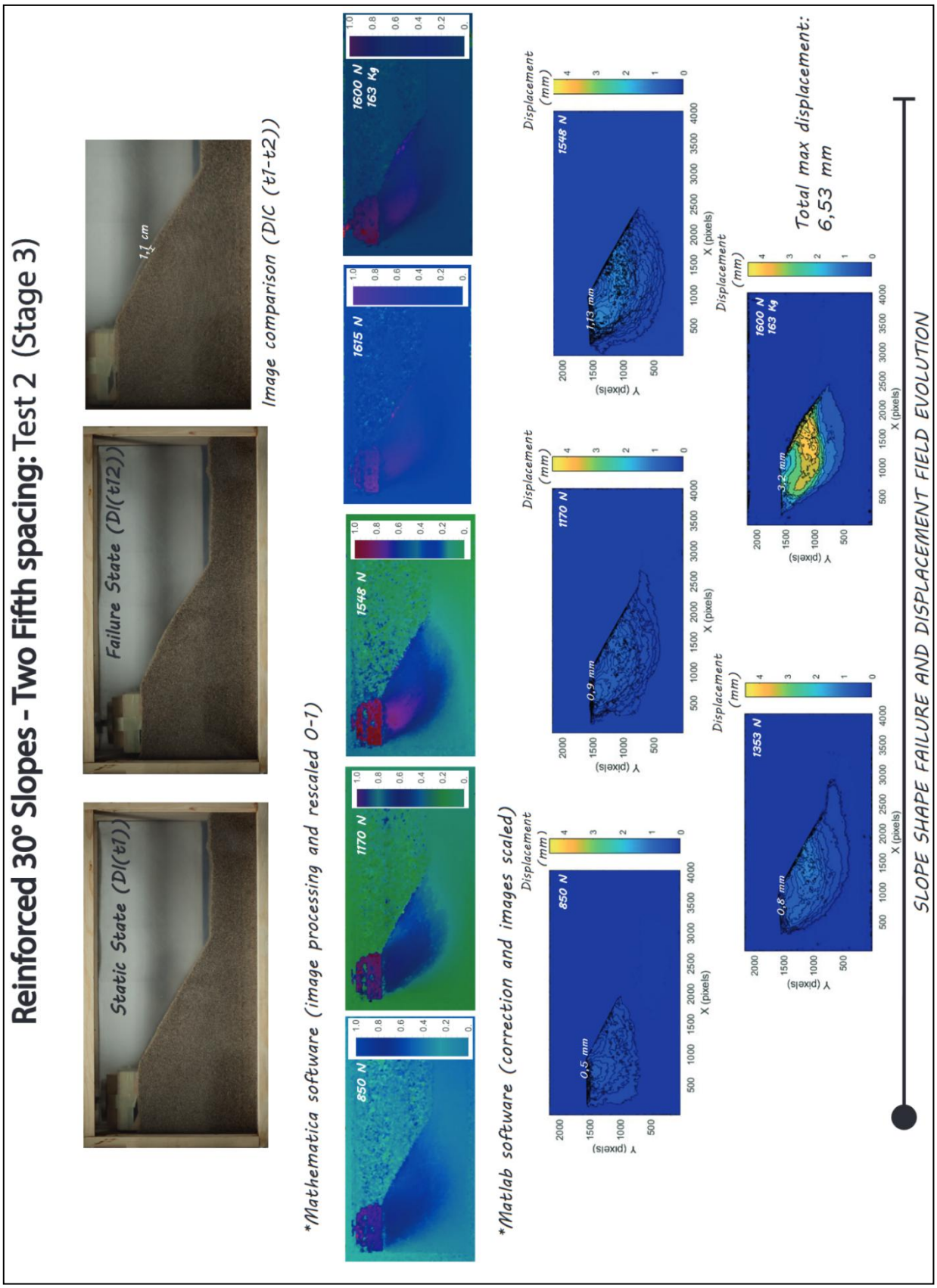
Appendix B

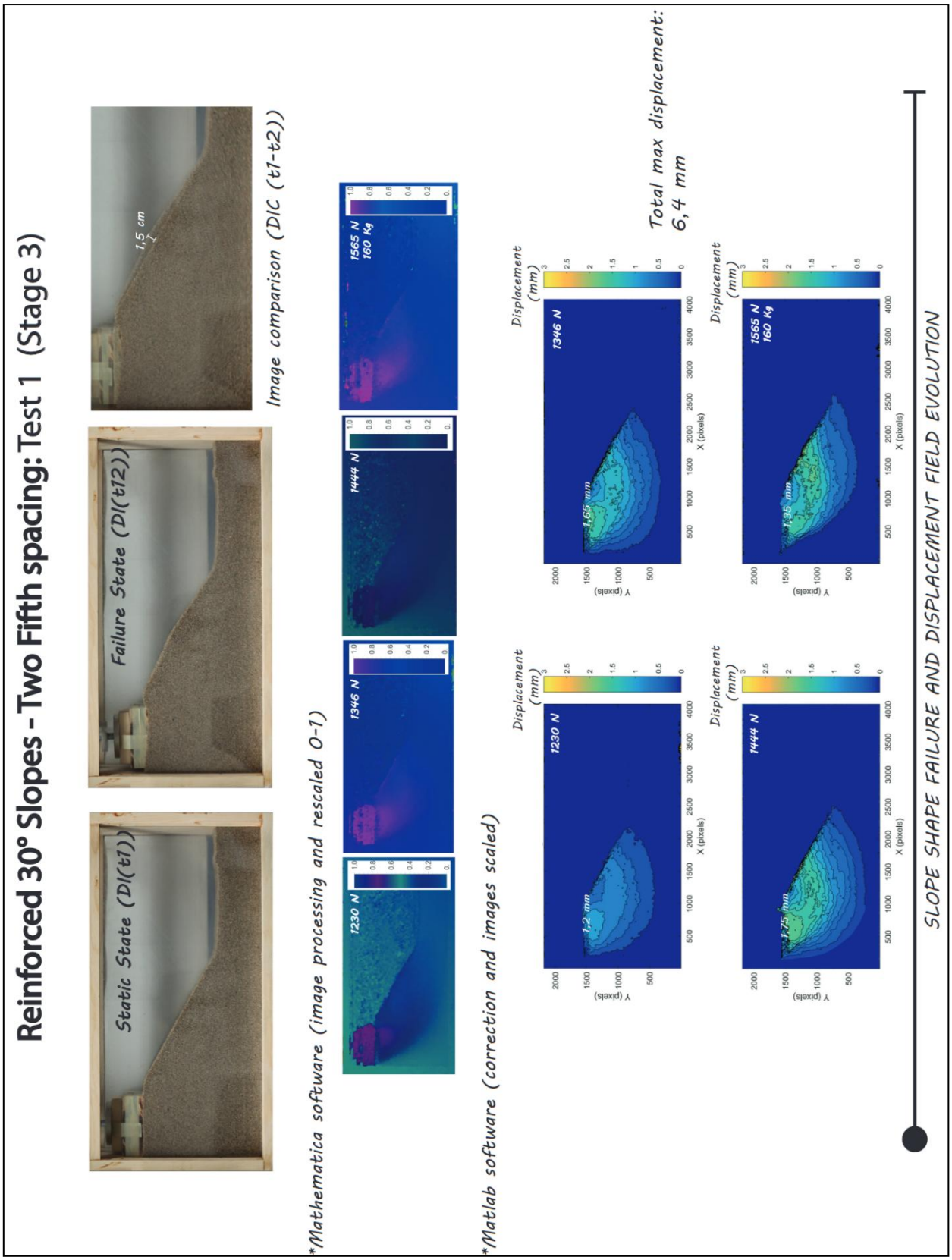
Appendix B.1. Reinforced 30° slopes failure shapes and displacement fields

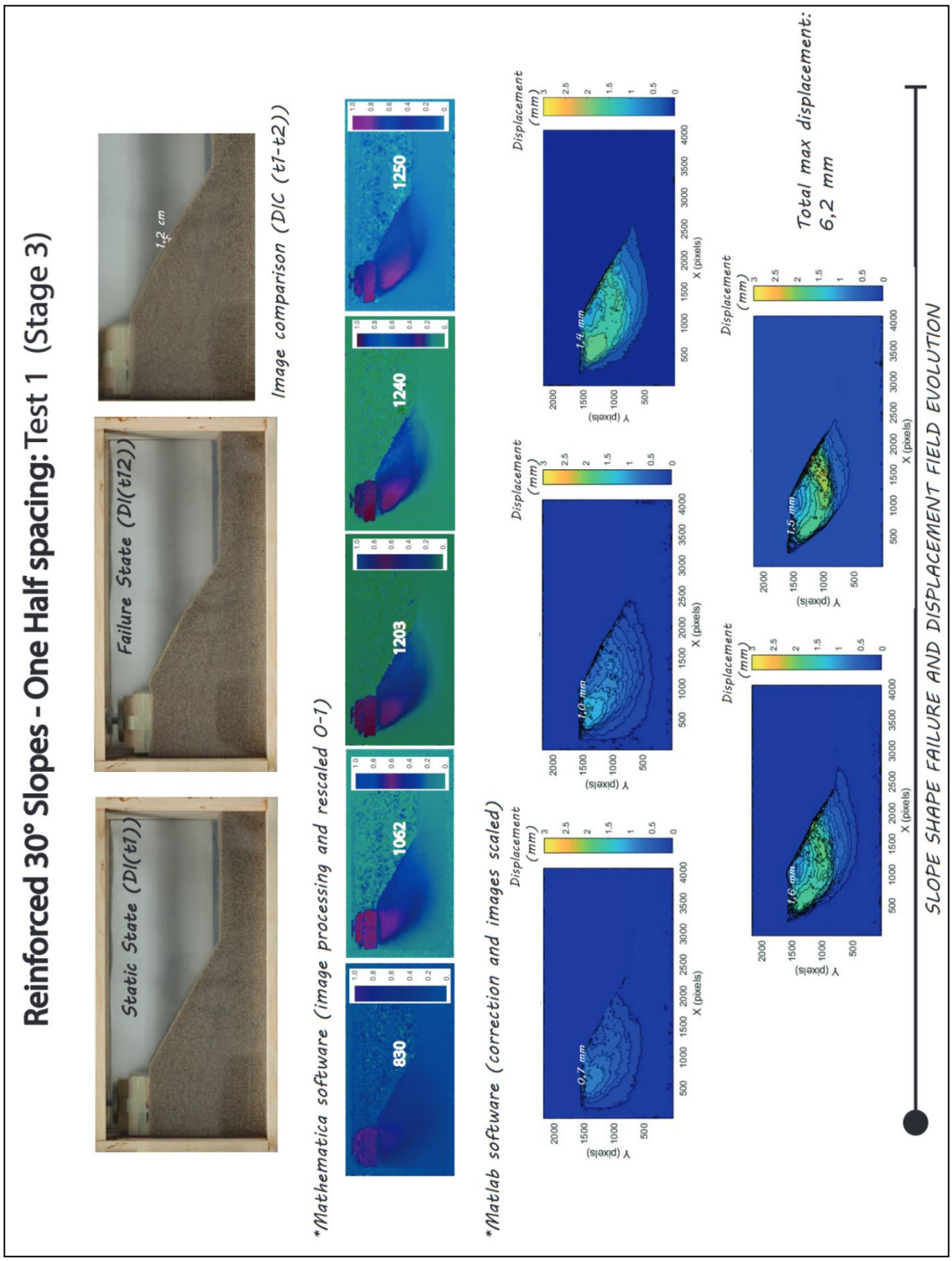



Reinforced 30° Slopes - One Third spacing: Test 2 (Stage 3)
Static State (DI(t1))
Failure State (DI(t12))
1,4 cm
Image comparison (DIC (t1-t2))
*Mathematica software (image processing and rescaled 0-1)
745 N
1088 N
1376 N
1573 N
1700 N
173 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
Y (pixels)
X (pixels)
0,85 mm
1,2 mm
1,6 mm
2,15 mm
figure 5
Total max displacement:
7,4 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION

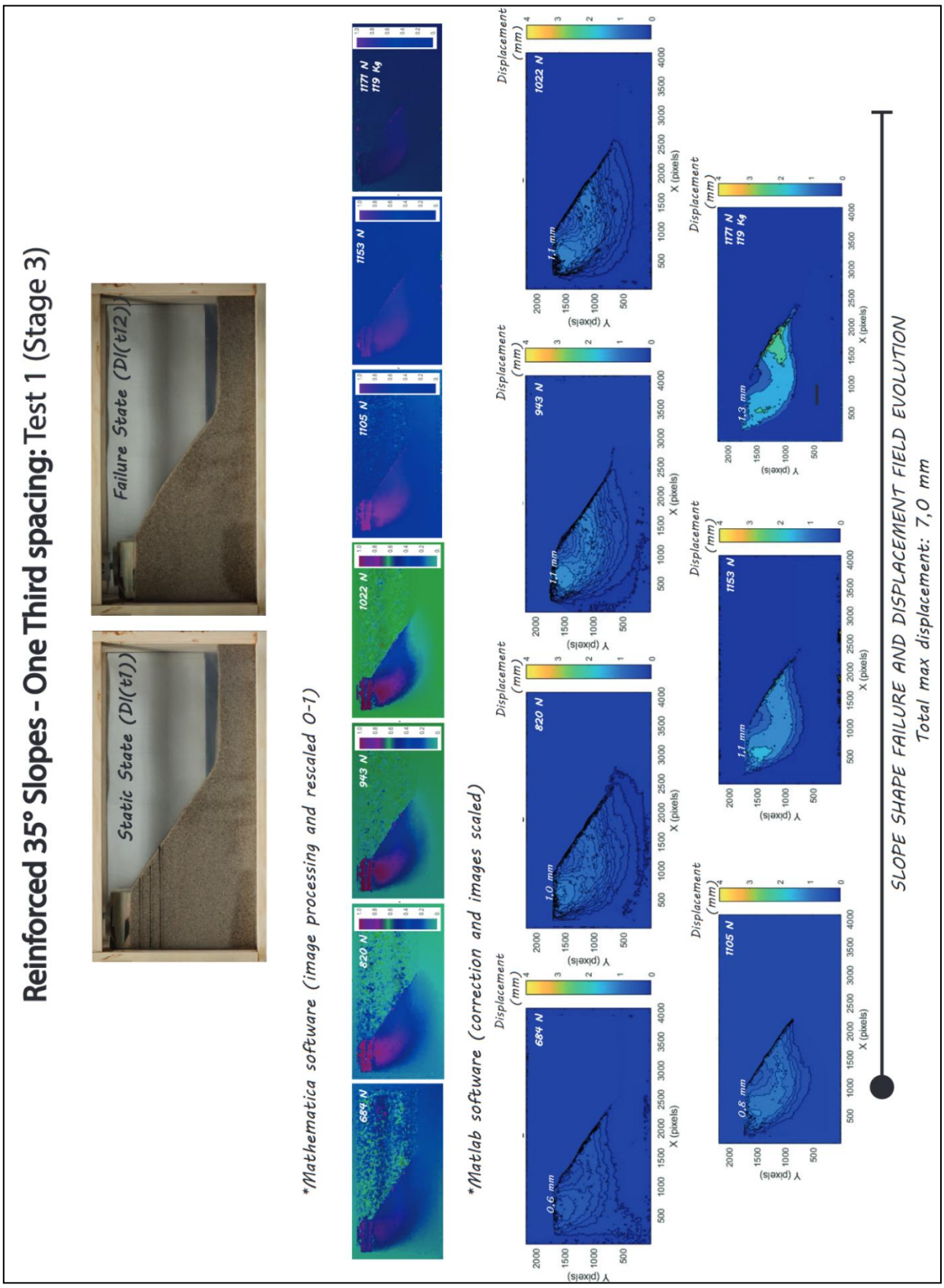

Reinforced 30° Slopes - One Third spacing: Test 3 (Stage 3)
Static State (D(t1))
Failure State (D(t2))
1,6 cm
Image comparison (D(C (t1-t2))
*Mathematica software (image processing and rescaled 0-1)
700 N
1052 N
1336 N
1540 N
1699 N
173 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
0,8 mm
1,45 mm
1,55 mm
1,65 mm
1,70 mm
Total max displacement:
7,1 mm
Y (pixels)
X (pixels)
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION

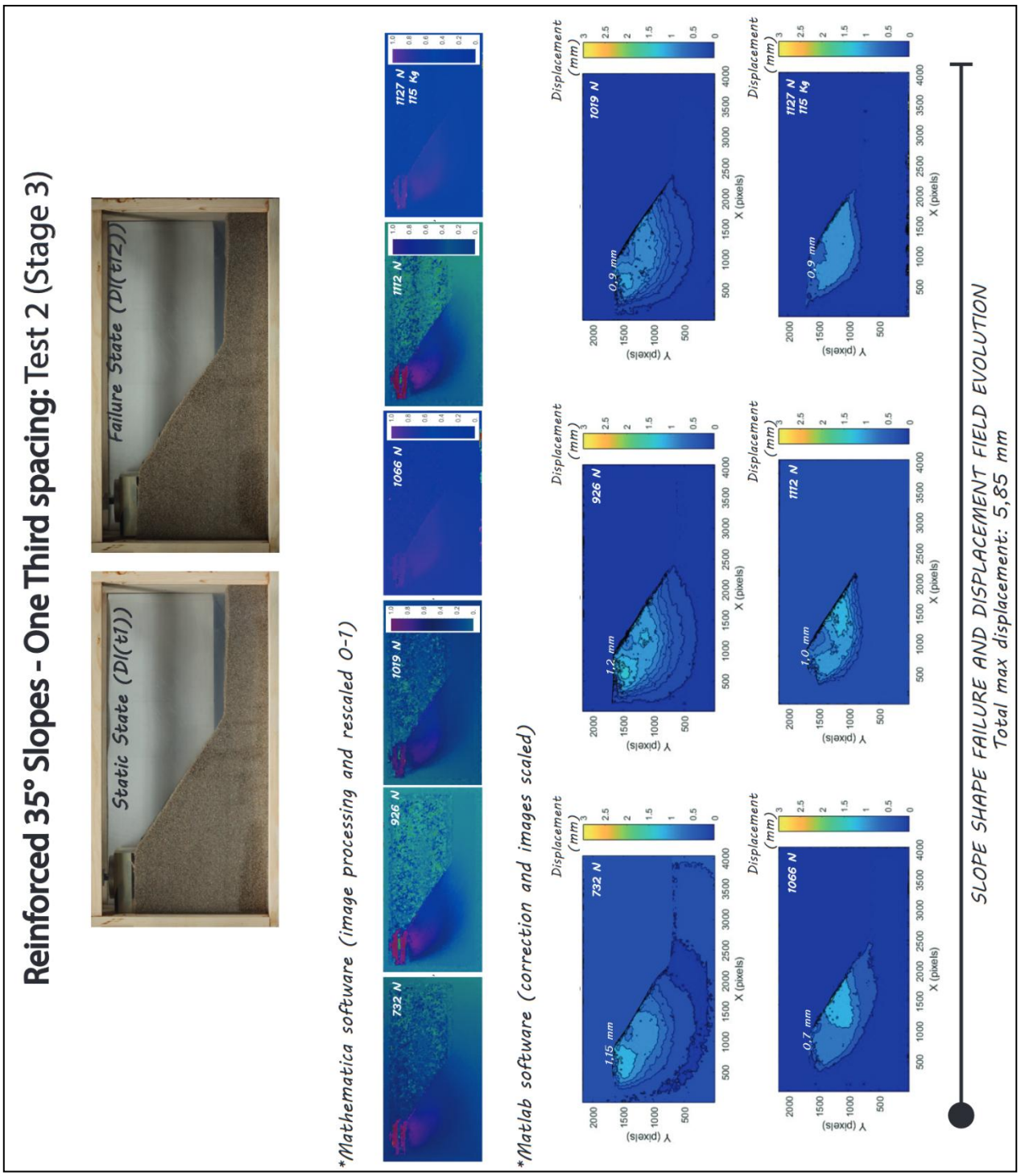

Reinforced 30° Slopes - Two Fifth spacing: Test 2 (Stage 3)
Static State (DI(t1))
Failure State (DI(t2))
1,1 cm
Image comparison (DIC (t1-t2))
*Mathematica software (image processing and rescaled 0-1)
850 N
1170 N
1548 N
1615 N
1600 N
163 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
0,5 mm
0,9 mm
1,13 mm
0,8 mm
3,2 mm
Total max displacement:
6,53 mm
X (pixels)
Y (pixels)
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION

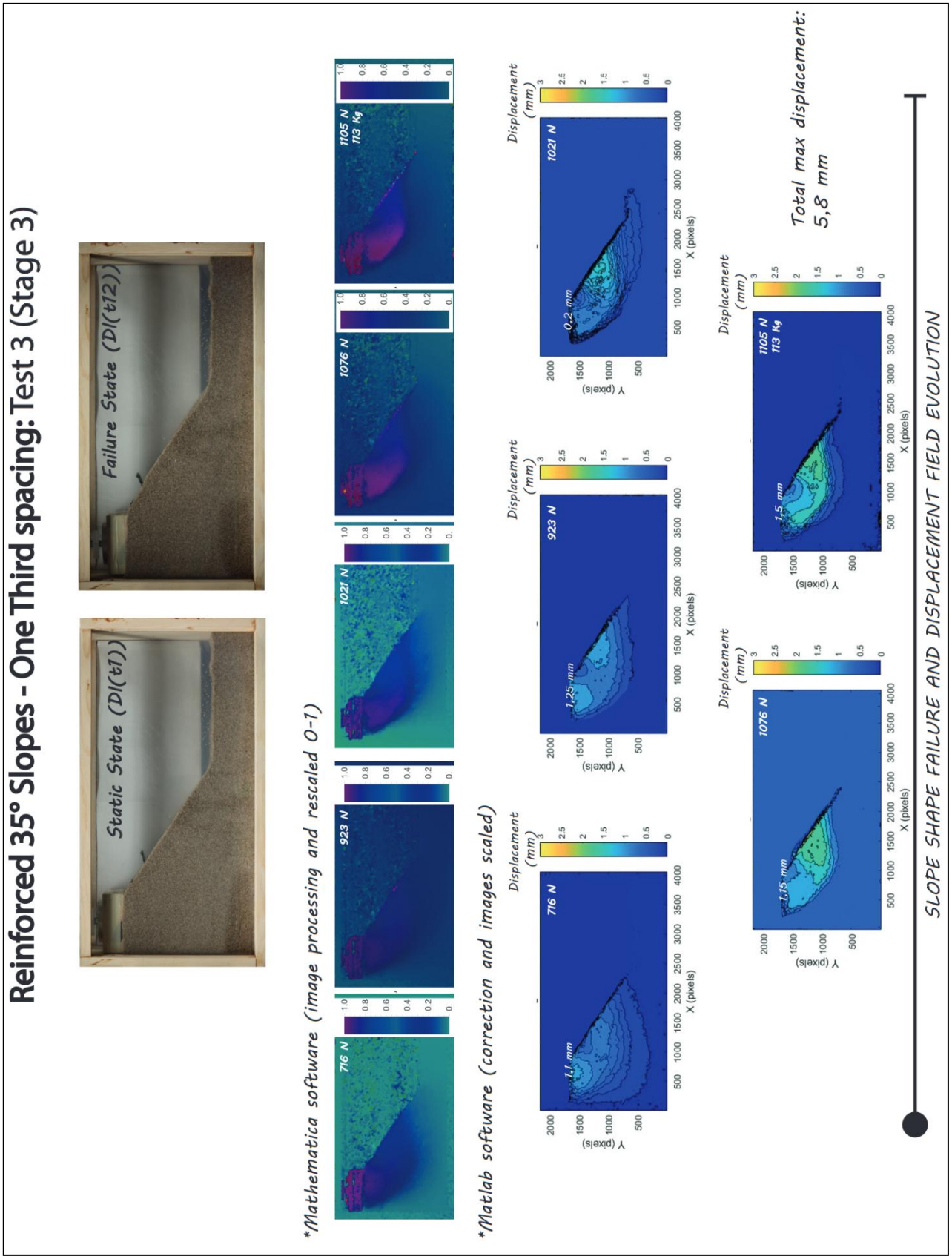

Reinforced 30° Slopes - Two Fifth spacing: Test 1 (Stage 3)
Static State (DI(t1))
Failure State (DI(t12))
1,5 cm
Image comparison (DIC (t1-t2))
*Mathematica software (image processing and rescaled 0-1)
1230 N
1346 N
1444 N
1565 N
160 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
1,2 mm
1,65 mm
1,75 mm
1,35 mm
Total max displacement:
6,4 mm
X (pixels)
Y (pixels)
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION

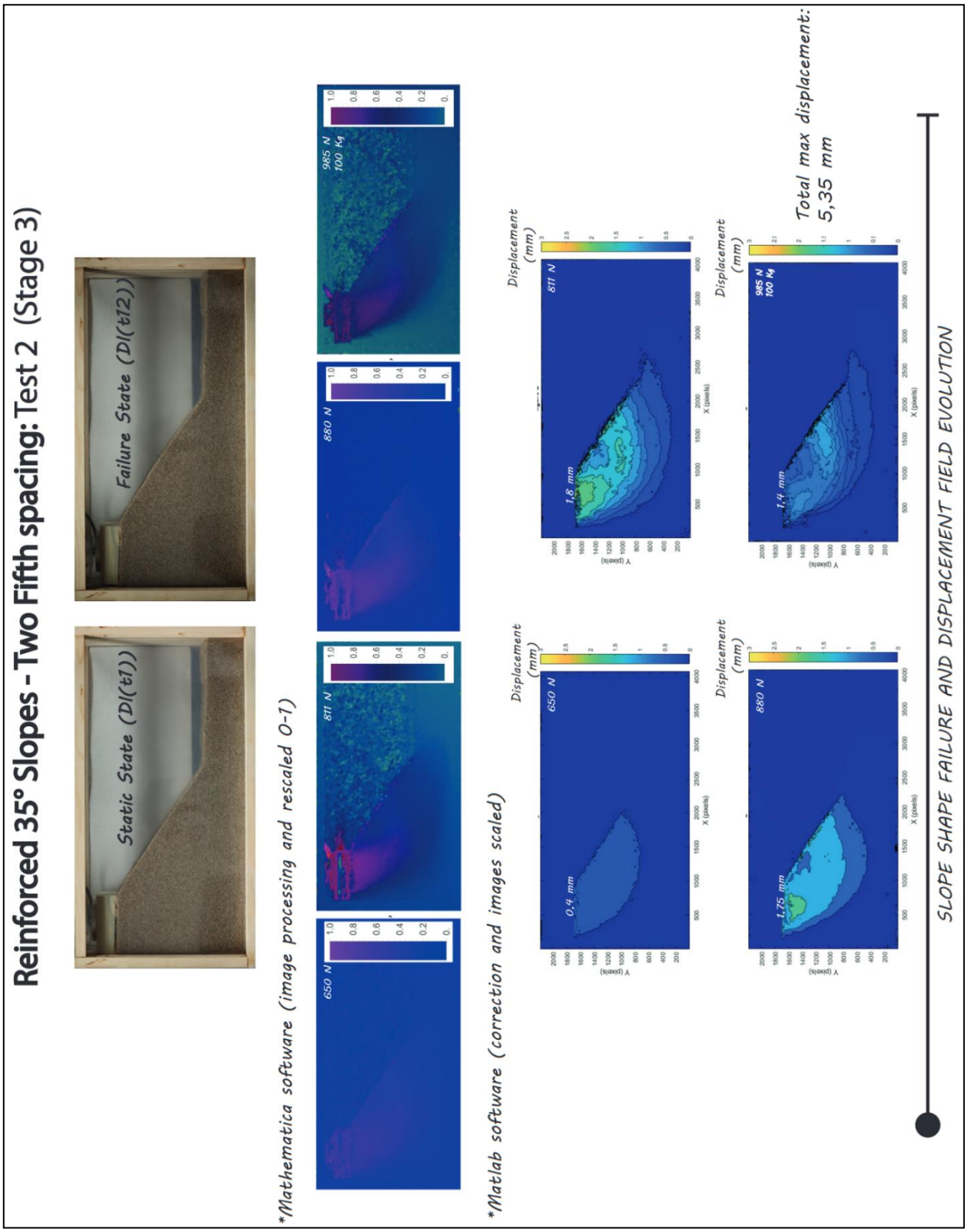

Reinforced 30° Slopes - One Half spacing: Test 1 (Stage 3)
Static State (DI(t1))
Failure State (DI(t12))
1,2 cm
Image comparison (DIC (t1-t2))
*Mathematica software (image processing and rescaled 0-1)
830
1062
1203
1240
1250
*Matlab software (correction and images scaled)
Displacement (mm)
0,7 mm
1,0 mm
1,4 mm
1,5 mm
1,6 mm
Total max displacement: 6,2 mm
X (pixels)
Y (pixels)
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION

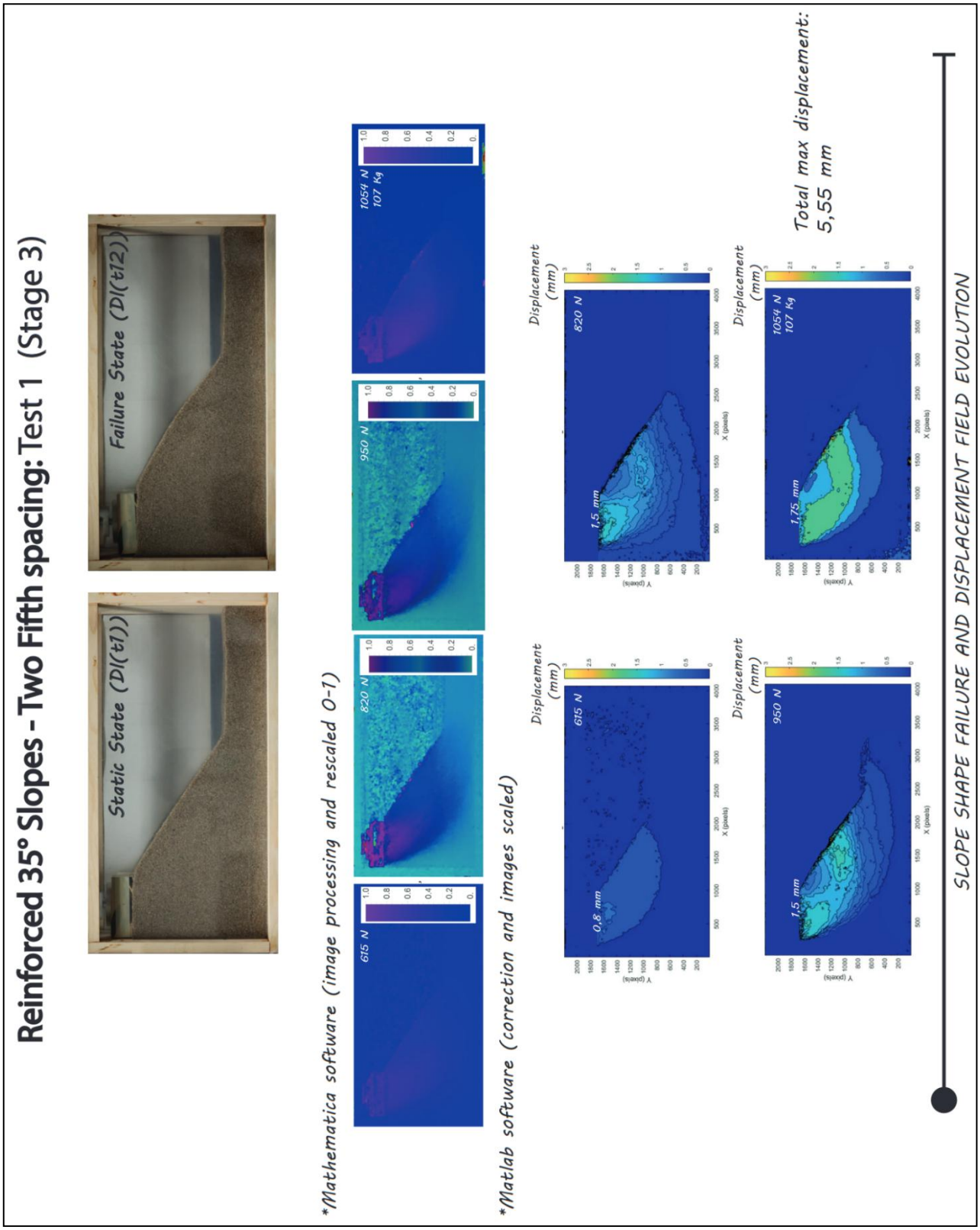
Appendix B.2. Reinforced 30° slopes failure shapes and displacement fields.

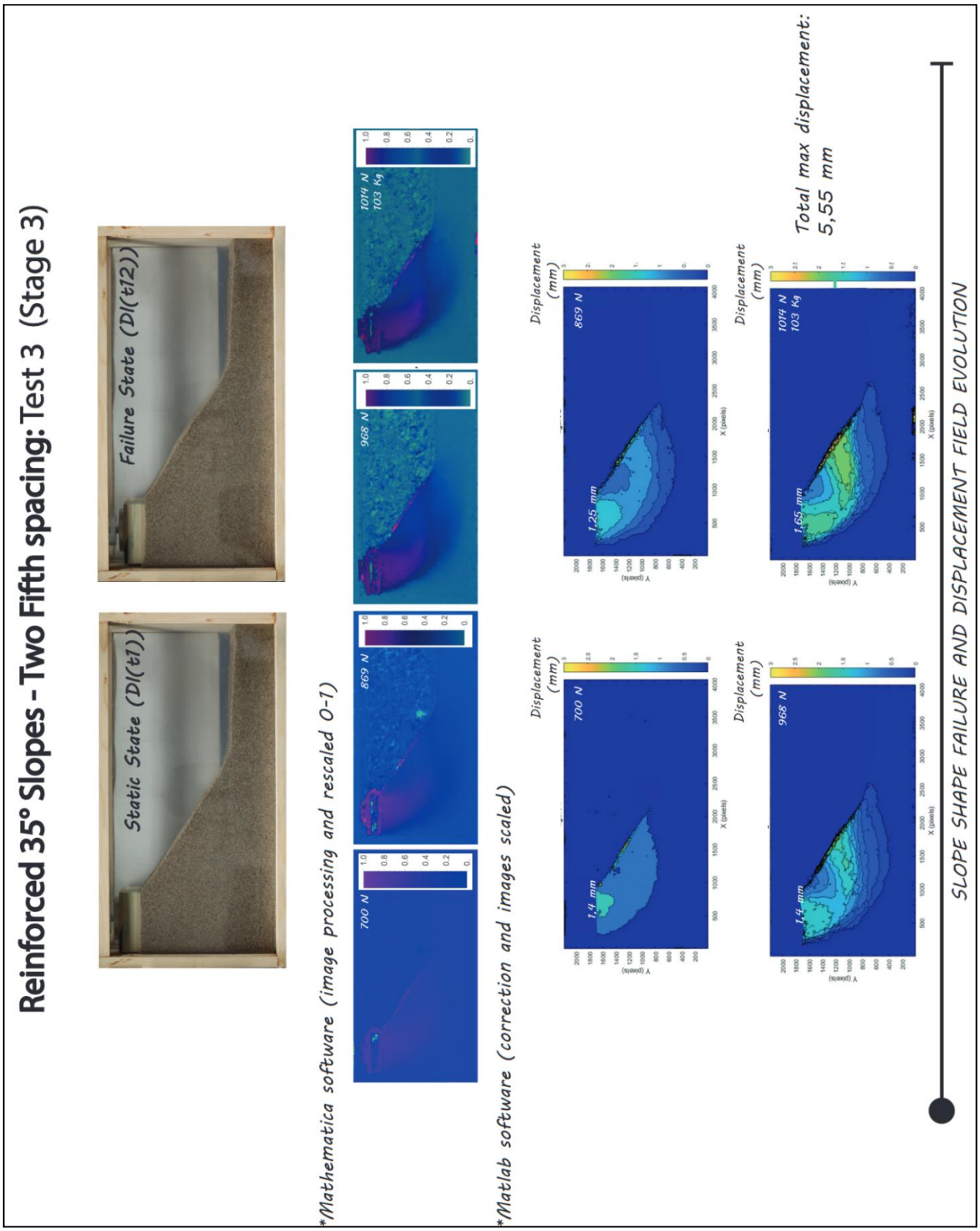


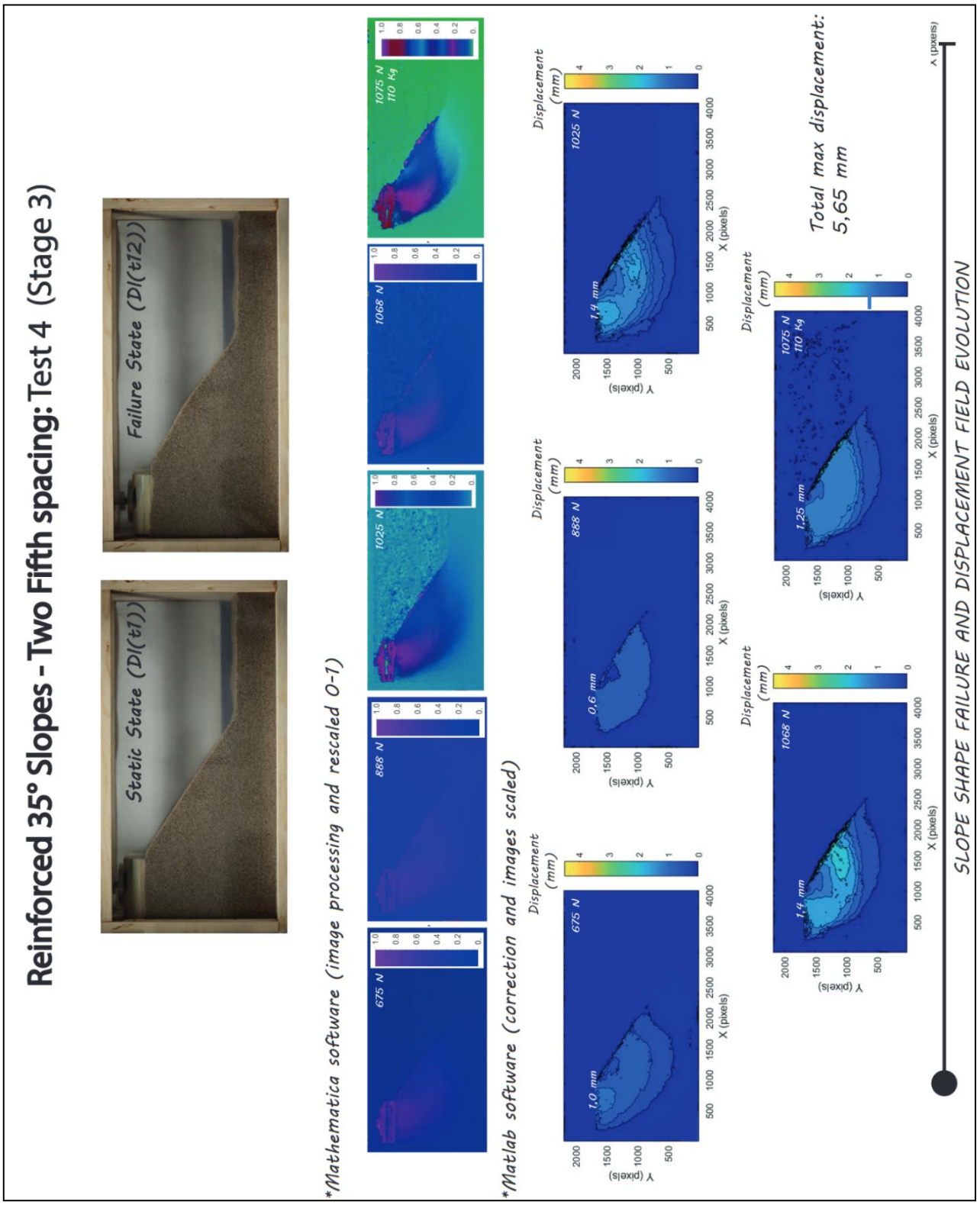

Reinforced 35° Slopes - One Third spacing: Test 2 (Stage 3)
Static State (DI(t1))
Failure State (DI(t2))
*Mathematica software (image processing and rescaled 0-1)
732 N
926 N
1019 N
1066 N
1112 N
1127 N
115 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
X (pixels)
Y (pixels)
1,15 mm
1,2 mm
1,0 mm
0,7 mm
0,9 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION
Total max displacement: 5,85 mm

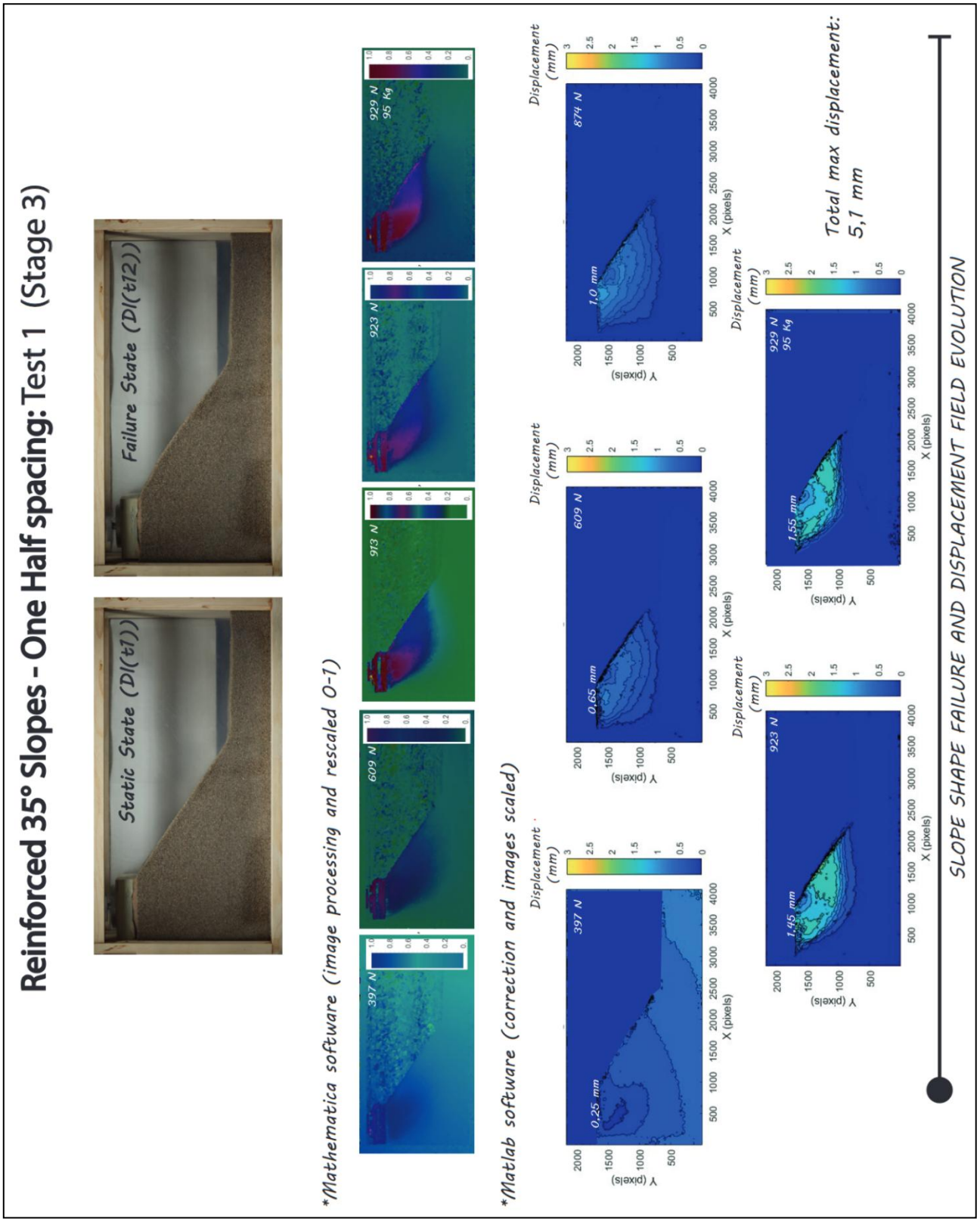

Reinforced 35° Slopes - One Third spacing: Test 3 (Stage 3)
Static State (DI(t1))
Failure State (DI(t2))
*Mathematica software (image processing and rescaled 0-1)
716 N
923 N
1021 N
1076 N
1105 N
113 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
1.1 mm
1.25 mm
0.2 mm
1.15 mm
1.5 mm
Y (pixels)
X (pixels)
Total max displacement:
5,8 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION


Reinforced 35° Slopes - Two Fifth spacing: Test 2 (Stage 3)
Static State (DI(t1))
Failure State (DI(t12))
*Mathematica software (image processing and rescaled 0-1)
650 N
811 N
880 N
985 N
100 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
650 N
0.4 mm
811 N
1.8 mm
880 N
1.75 mm
985 N
100 Kg
1.4 mm
Total max displacement:
5,35 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION


Reinforced 35° Slopes - Two Fifth spacing: Test 1 (Stage 3)
Static State (DI(t1))
Failure State (DI(t2))
*Mathematica software (image processing and rescaled 0-1)
615 N
820 N
950 N
1054 N
107 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
0,8 mm
1,5 mm
1,75 mm
Total max displacement:
5,55 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION


Reinforced 35° Slopes - Two Fifth spacing: Test 3 (Stage 3)
Static State (D(t1))
Failure State (D(t12))
*Mathematica software (image processing and rescaled 0-1)
700 N
869 N
968 N
1014 N
103 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
1,4 mm
1,25 mm
1,65 mm
Total max displacement:
5,55 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION


Reinforced 35° Slopes - Two Fifth spacing: Test 4 (Stage 3)
Static State (DI(t1))
Failure State (DI(t12))
*Mathematica software (image processing and rescaled 0-1)
675 N
888 N
1025 N
1068 N
1075 N
110 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
1,0 mm
0,6 mm
1,4 mm
1,25 mm
Y (pixels)
X (pixels)
Total max displacement:
5,65 mm
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION


Reinforced 35° Slopes - One Half spacing: Test 1 (Stage 3)
Static State (D(t1))
Failure State (D(t2))
*Mathematica software (image processing and rescaled 0-1)
397 N
609 N
973 N
923 N
929 N
95 Kg
*Matlab software (correction and images scaled)
Displacement (mm)
0,25 mm
397 N
0,65 mm
609 N
1,0 mm
874 N
1,45 mm
923 N
1,55 mm
929 N
95 Kg
Total max displacement:
5,1 mm
X (pixels)
Y (pixels)
SLOPE SHAPE FAILURE AND DISPLACEMENT FIELD EVOLUTION