Analysis of spatial sensor network observations during landslide simulation experiments

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A spatial sensor network was tested during five experiments on a landslide simulation platform. Here, a landslide was triggered by means of simulated rainfall. The sensor network currently incorporates in situ sensors and two stereo imaging systems. In future, these sensors will be installed on a real-scene slope in Sichuan Province (South-West China). The paper focuses on the results of two latest landslide simulation experiments. While one experiment ended with a partial failure, the second one showed a complete slope collapse. In the first part of the study, the full data series are investigated to perform correlations and common pattern analysis, as well as to link them to the physical processes. In the second part, four subsets of sensors located in neighbouring positions are analysed. Although the small scale of the simulated experiment probably influenced the results, these experiments allowed ascertaining which sensors could be more suitable to be deployed on the real-scene landslide sites.

Keywords: engineering geology; landslides; monitoring; photogrammetry; simulations; spatial sensor network

1. Introduction

Laboratory testing and simulation are important tools for supporting researchers in investigating cause–effect mechanisms of landslides. Indeed, in most geological disasters, no countermeasures can be undertaken to control natural processes, because of the huge forces involved. Forecasting is the only way to save people and reduce damages to properties and human activities. A twofold approach can be followed for landslide simulation. The first is based on numerical modelling, which relies on the application of geotechnical models supported by monitoring observations (Nuhn, Kropat, Reinhardt, & Pickl, 2012). The second approach concerns the reconstruction of a scaled-down model of the landslide site, with similar topography, geomorphology and soil composition (a review of the literature on this field is given in subsection 2.1). The supposed triggering factors are then reproduced. Usually, these include the simulation of rainfall on the model as well as ground waterflow. Also, other instability sources can be introduced, such as earthquakes. Landslide simulation platforms are useful tools for understanding the landslide dynamic and for evaluating which kind of observations should be made for
monitoring purpose. On the other hand, the up-scaling and simplification from the real slope to the model may lead to a biased reconstruction of the geomorphological processes. To mitigate this problem, a thorough knowledge of the properties of the landslide to investigate is quite important. It should also be noted that this problem may concern both flume testing and numerical modelling.

An efficient monitoring solution should be able to collect as much information as possible, either in terms of spatial coverage and observation of multiple processes (Scaioni, Alba, Roncoroni, & Giussani, 2010). This requirement leads to the adoption of spatial sensor networks (SSN), intended as the whole set of coordinated different measurement systems aiming at collecting data on a landslide site. Sensors on surface, in the ground, and from aircrafts and space can be used (see e.g. Angeli, Pasuto, & Silvano, 2000; Blikra, 2008; Froese & Moreno, 2011; Gao, Wang, Li, Zhang, & Yang, 2009).

This paper is focusing on a landslide simulation platform that has been designed, set up and adopted to run experiments at the Centre for Spatial Information Science and Sustainable Development Applications of Tongji University (Shanghai, P.R. China). Here, the technical description of the whole system is only briefly addressed; more in-depth information is reported in other related papers (see Feng, Liu, Scaioni, Lin, & Li, 2012; Scaioni et al., 2012). Conversely, here the data analysis related to a pair of simulation experiments is focused on. Special emphasis is given to the comparison among different sensors. The scaled-down model has been derived from the typical geomorphology of unstable slopes located in Hongkou mountain area (Sichuan province, P.R. China), where the severe Wenchuan Earthquake took place on 12 May 2008. The simulation platform is expected to contribute to the development of a landslide monitoring system for the real scene. This paper features a prevalent experimental character. The authors want to show the whole information that has been possible to gather by means of the SSN installed on the simulation platform. The integration of observations into numerical models will be accomplished at a later stage.

In Section 2, a description of the simulation platform is reported. In Section 3, the experiments that have been carried out are presented. Section 4 is the main part of the paper, containing the description of the collected data with their analysis and discussion. Eventually, Section 5 draws some final considerations and suggestions for future work.

2. Landslide simulation platforms

2.1. Background and state-of-the-art

The realistic simulation of landslides based on scaled-down models has been accomplished following two different approaches. The first is based on the reconstruction of a model in a completely controlled environment. The second relies on the use of a real slope. The literature reports about some experiences focusing on rainfall-triggered landslides on soil or sand terrain. Tests on rock slopes are much more difficult to perform, requiring much longer activation time and the precise reconstruction of external and internal rock structure (Longoni et al., 2012).

Most works related to simulation platforms have been carried out to analyse flowslides and soil liquefaction in sand and clay terrains (Acharya, Cochrane, Davies, & Bowman, 2009; Eckersley, 1990; Greco, Guida, Damiano, & Olivares, 2010; Hird & Hassona, 1990; Jia, Zhan, Chen, & Fredlund, 2009; Moriwaki et al., 2004; Olivares...
et al., 2009; Prochaska, Santi, Higgins, & Cannon, 2008; Sharma & Nakagawa, 2010; Spence & Guymer, 1997; Wang & Sassa, 2001). The latter problem is particularly important in the case of earthquakes on sand soils close to saturation (Wang & Sassa, 2009). In Okura, Kitahara, Ochiai, Sammori and Kawanami (2002), an example of such kind of experiment is reported. Both the movement and the pore water pressure of the sand layers were monitored throughout the experiment, from the start of rainfall to the occurrence of landslide. Wang and Sassa (2003) and Ching-Chuan, Yih-Jang, Lih-Kang and Jin-Long (2009) carried out an in-depth investigation on the pore water pressure behaviour inside the soil and its relationship with the slope failure. Fang, Cui, Pei and Zhou (2012) reported about simulation experiments on a flume for studying soil in the region of Wenchuan Earthquake. Roncella, Scaioni and Forlani (2004) focused their work on the set-up of a high-speed camera system to track the surface displacements on a down-scaled model. The results of the analyses on data obtained from this system are reported in Montrasio and Valentino (2007). Uchimura and Towhata (2010) adopted a down-scale model of a sand slope to test a low-cost and simple monitoring method for early warning of landslides. This platform incorporated both micro-electro-mechanical systems (MEMSs) inclinometers and water content sensors. The reported results showed that rotation data responded 30 min before failures, information which could be used as a pre-alerting signal for early-warning purpose. Katz and Aharonov (2006) set up some experiments in a vibrating sand box to investigate the triggering mechanism of earthquake-induced landslides. Truong et al. (2008) also discussed ultrasonic monitoring of laboratory simulation of underwater landslides.

Ochiai et al. (2004) described a simulated rainfall-induced test conducted on a real slope (Mt. Kaba-san, Tsukuba, Japan). The observation of gradual and accelerating displacements on the slope surface before failure, compared to the water content of soil, was proved to be useful for early warning of landslides (Crosta & Agliardi, 2003). Although a major fidelity to the natural conditions, this approach suffers from the greater organisational problem due to the higher complexity, and from the reduced chance to change the experiment set-up. Travelletti, Oppikofer, Delacourt, Malet and Jaboyedoff (2008) presented the results of a similar experiment where a terrestrial laser scanning was used for the measurement of displacements on the surface. Here, some processing techniques were applied to point clouds gathered along time to detect deformations. These were then compared to observations coming from other contact sensors.

2.2. The landslide simulation platform at Tongji University

The simulation platform developed at Tongji University was designed to achieve some improvements with respect to the state-of-the-art reported above. First of all, a wide range of sensors were deployed, including contact instruments and remote sensors (low- and high-speed digital cameras). The integration of several kinds of sensors is widely recognised to give an important contribution in engineering geology investigations (Arosio et al., 2009). Second, the platform has been designed to test the prototype of SSN that will be adopted later in a real-scene environment.

At the moment, a variety of sensors was installed on the platform and used to record observations during experiments. These consist in triggering a landslide thanks to a rainfall simulation system. The model (see Figures 1 and 2) was designed to reproduce similar characteristics (inclination, soil layers and composition) of a ground slope in Hongkou area. In particular, a landslide triggered after the Wenchuan Earthquake
was considered near the village of Taziping. The Taziping landslide is located in the north valley of Baisha River, in the middle of two gullies of Shenxigou and Gangou. The landslide is about 20 km distant to the epicentre of the Wenchuan Earthquake and 4 km to the Yinxiu fault. The landslide is about 530 m long and 145 m wide. The relative elevation difference is about 363 m, ranging from 1007 m a.s.l. at the toe to 1370 m a.s.l. in the crest. The slope of the Taziping landslide is between 25° and 40°, with a relative steep source area detached from the bedrock and a relatively flat toe area accumulating the debris and gravels downward. The major deposit of the landslide is weathered andesite with a depth of about 20–40 m. This forms a slip surface of weathered rock detached from the intact bedrock layer. After the Wenchuan Earthquake, with the loose debris accumulation and fragile soil characteristics, the landslide was accelerated significantly after intensive rainfall and water infiltration. How much rainfall is necessary to trigger landslides in this area has not been investigated in-depth by previous studies. Tang, Zhu, Qi and Ding (2011) reported an accumulative rainfall of approx. 330 mm in 40 h (23–24 September 2008) which induced 969 new landslides in this area. These landslides may turn into debris flows with intensive surface water
adjunction and debris accumulation. The slope stability can be further decreased with the intensive human activities in this area such as road building, forest cutting and fruit cultivation.

Investigations and monitoring of this site are important because of the risk involved in a possible run-out (Uchimura, Wang, Qiao and Towhata, 2011), due to the presence of an inhabited area and a river close to the slope-toe. To emulate the real slope, the model was divided into three sectors (namely ‘1’, ‘2’ and ‘3’ in Figure 1) having each a different inclination (5°, 15° and 30°). Two soil layers were laid down. The lower with a depth of 50 cm was composed of a mixture of gravel, clay and sand in proportion 1:1:5. The upper with a depth of 30 cm was composed of clay and sand in proportion 1:3. Obviously, this structure was only approximately close to the typical one in Taziping. On the other hand, here the aim was only the one of recreating realistic conditions, yet suffering from scale problems. Consequently, the experiments described in next section were not focused to derive geological analyses but to accomplish the technical set-up of the SSN and to assess their sensibility and operational reliability.

The sensors used in the simulation platform were representative of the more extensive equipment to be adopted for real landslide observation. A first group of sensors was used to detect soil properties, especially in relation with the water content. Indeed, this was expected to be the factor inducing ground failure during experiments. This group encompassed soil, borehole, and osmotic pressure gauges, as well as piezometers. A second group was made up of accelerometers, which were used to record sudden ground displacements. Unlike all the other sensors, whose data acquisition rate was quite low (1/5–1/60 Hz), accelerometers had a high-dynamic rate in the order of 60–90 Hz. The third group consisted of cameras able to capture images at different speed and resolution. The sensor network entailed a pair of synchronised high-speed mono-chromatic cameras DALSA Falcon 4M60 (maximum frequency 62 Hz, sensor size 2352 × 1728 pixels, pixel size 7.4 μm and focal lens 24 mm) to gather stereo-images for three-dimensional (3D) digital reconstruction of the slope surface during experiments and surface displacement tracking (for more details see Feng et al., 2012). In addition, a couple of low-speed SLR (single-lens reflex) colour cameras Nikon D200 cameras (maximum frequency 5 Hz, sensor size 2896 × 1944 pixels, pixel size 8.1 μm and focal length 35 mm) was included. Indeed, the high-speed camera system might acquire a huge amount of data owing to the high frequency and the quite large image size, with consequent dramatic problems on data transmission from the sensors to the control unit. For this reason, the maximum acquisition rate of the high-speed cameras was not fully exploited, but a lower frequency of 20 Hz was set up. A video-surveillance camera was also included for real-time inspection of the slope. Eventually, a rain gauge and a weather station were used to record environmental parameters such as rainfall intensity, air temperature and humidity. The list and main properties of all adopted sensors are shown in Table 1. The rightmost column also reports the sensors which can output real-time data and those which require post-processing.

All sensors installed on the simulation platform were connected to a data acquisition unit, which could synchronise data gathering and dealt with broadcasting to a server station located in the university offices at about 800 m away. Here, a database had been designed and implemented to store all recorded signals. Data retrieving could be performed in real time for visualisation purpose.
3. Analysis of experiments

3.1. Experiment description

A total number of five experiments were carried out on the simulation platform. Tests from 1 to 3 were used to set up the whole system and are not discussed here.

3.1.1. Experiment 4

Experiment 4 was carried out on 6 March 2012 from 11:00 to 14:40 (total elapsed time 3:40). The imaging conditions were appropriate. Air temperature ranged from 10.1 to 13.1 °C, while relative humidity from 51–61%. These parameters did not affect the failure process of the model slope that was only influenced by rainfall applied at an average rate of 110 mm/h, for a total amount of 340 mm. Unlike successive Experiment 5, this was interrupted because of lacking water in the reservoir due to a technical problem. However, the achieved results were considered sufficient for further analyses. Five main events can be recognised in Experiment 4 (see corresponding photos in Figure 3). At the beginning, the lower part of Sector 1 started sliding after 48 min (Event 1). The superficial soil layer collapsed after a relative time of 2:19 (Event 2). Hereafter, soil failure continued. Some multiple small creeping occurred in Sector 2 (Event 3). Also in this case, only the superficial soil layer was interested (5 cm depth). This led to the failure of a large portion of Sector 2, resulting in a transversal discontinuity across the flume (Event 4). After 3:40, the run-out of the entire superficial layer of Sectors 1 and 2 was observed.

3.1.2. Experiment 5

Experiment 5 was run on 27 March 2012 from 11:20 to 15:00 (total elapsed time 3:40). The condition was less appropriate for capturing images from the cameras because of the sharp increase of sunshine. Air temperature ranged from 19.2 to 27.8 °C, while relative humidity from 21 to 45%. However, neither in this case they significantly

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### Table 1. Number and characteristics of operational sensors in the landslide simulation platform.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Number of sensors (depth in ground-cm)</th>
<th>Actual acquisition rate (Hz)</th>
<th>Precision</th>
<th>Real time/Post-processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. 4</td>
<td>Exp. 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezometers</td>
<td>5 (80)</td>
<td>1/5</td>
<td>.1 kPa</td>
<td>RT</td>
</tr>
<tr>
<td>Dual-axial inclinometer</td>
<td>1 (80)</td>
<td>1/5</td>
<td>.01 deg</td>
<td>RT</td>
</tr>
<tr>
<td>Mono-axial inclinometer</td>
<td>1 (10)</td>
<td>1/5</td>
<td>.01 deg</td>
<td>RT</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>5 (15)</td>
<td>100</td>
<td>.01 g</td>
<td>RT</td>
</tr>
<tr>
<td>Soil pressure gauge</td>
<td>1 (50)</td>
<td>1/5</td>
<td>.1 kPa</td>
<td>RT</td>
</tr>
<tr>
<td>Osmometer</td>
<td>1 (80)</td>
<td>1/5</td>
<td>.1 kPa</td>
<td>RT</td>
</tr>
<tr>
<td>Borehole pressure</td>
<td>1 (70)</td>
<td>1/5</td>
<td>.1 kPa</td>
<td>RT</td>
</tr>
<tr>
<td>Raingauge</td>
<td>1</td>
<td>1/5</td>
<td>.1 mm</td>
<td>RT</td>
</tr>
<tr>
<td>Weather station</td>
<td>1</td>
<td>1/5</td>
<td>N/A</td>
<td>RT</td>
</tr>
<tr>
<td>Low-speed stereo-camera system(^a)</td>
<td>1</td>
<td>1/10</td>
<td>4–17 mm</td>
<td>PP</td>
</tr>
<tr>
<td>High-speed stereo-camera system(^a)</td>
<td>0</td>
<td>20</td>
<td>2–6 mm</td>
<td>PP</td>
</tr>
<tr>
<td>Video-surveillance camera</td>
<td>1</td>
<td>50</td>
<td>–</td>
<td>RT</td>
</tr>
</tbody>
</table>

\(^a\) The estimated precision of information extracted from images gathered by both stereo-camera systems is not the same on the whole slope but depends on position.
influenced the experiment. Rainfall was simulated at 142 mm/h, for a total amount of 520 mm (Figure 4). Some photos describing the six main events recognised in Experiment 5 can be found in Figure 3. During the initial period, a progressive creeping of the upper soil layer in Sector 1 was observed. This led to the appearance of the first diagonal creeping on the slope surface (Event 1) after 1:05 elapsed time from the beginning of the experiment. After 1:41, the superficial layer of Sector 1 slid down. Then, soil creeping extended to Sector 2 with formation of a wedge fracture (Event 3). The top of the wedge was in correspondence of the point where a sensor’s cable entered.
into ground. In the sequel, the superficial layer of Sector 2 started to slide. In a first stage, the process occurred only at the bottom (Event 4). Then, this extended to the whole lower half of this sector (Event 5). After 3:27 from the beginning, a multiple rotational landslide happened involving the entire slope (Event 6). In this case, also the inferior soil layers slid down.

The analysis of the gathered data has been organised in different steps. First of all, the change of the water table level is described in subsection 3.3. Secondly, the analysis of correlations between different sensors is presented in subsection 3.4. Third, a comparison between sensors located in close positions is carried out (subsection 3.5). Eventually, results from imaging sensors are described in subsection 3.6.

3.2. Spatial location of sensors

The spatial location of sensors adopted in both experiments is described in the next paragraphs. Figure 5 shows their positions.

Figure 4. Plot of rainfall gauge during Experiment 5. Arrows show the times of the events described in Figure 3.

Figure 5. Location of deployed sensors on the landslide simulation platform for Experiments 4 and 5.
3.2.1. Sensor related to water content

Five piezometers were aligned along the intermediate longitudinal section of the slope. No significant difference in piezometer deployments could be noticed between Experiments 4 and 5, except labels. A soil pressure gauge was located in the transversal section at the interface between Sector 1 (5° inclination) and 2 (15°) of the flume. A borehole pressure gauge was installed in the intermediate section of Sector 2. Depth was 70 cm, i.e. less than piezometer 502 that was located nearby. An osmometer was positioned between Sectors 2 (15°) and 3 (30°).

3.2.2. Inclinometers

Two different kinds of inclinometers were adopted. The single-axis inclinometer 1, which rendered better precision, was placed in the highest part of the slope (Sector 3).

![Graphs showing pressure and inclinometer data](image)

Figure 6. Plots of observations from piezometer 502, borehole pressure gauge and dual-axes inclinometer 1 during Experiment 4.
It was aligned to detect inclinations in the up-to-down slope direction. The dual-axes inclinometer 2 was located in the middle of Sector 2. Its axes were aligned to detect rotations along and across the slope direction. Data acquired by inclinometer 2 during Experiment 4 are displayed in Figure 6. Figures 7 and 8 show observations from inclinometers 2 and 1 during Experiment 5.

3.2.3. Acceleration sensors

Five accelerometers were installed during Experiment 5. Many data communication problems were encountered during Experiments from 1 to 4. Although during Experiment 5 the most problems had been fixed, Sensor 4 still recorded noisy observations. Data observed by accelerometers 1 and 6 are shown in Figure 9, while data from accelerometer 5 are reported in Figure 8. Accelerometer measurements are related to three axes (x, y, z) which are approximately aligned the same way for each sensor. The x-axis is oriented upwards along the local plumb line and recorded mainly the gravity acceleration component (in plots, this component was subtracted from the raw data). Other two axes lie in a roughly horizontal plane: z-axis is directed along the slope direction downwards; and y-axis is in the across-slope direction to complete a right-hand cartesian tern.

3.2.4. Imaging sensors

In Experiment 5, both low-speed camera and high-speed camera systems were used to collect the images of the slope during the movement. The frequency of low-speed

![Figure 7](image-url)  
**Figure 7.** Plots of observations from piezometer 502, borehole pressure gauge and dual-axes inclinometer 2 during Experiment 5.
cameras was set to six frames per minute (fpm). The final part of the experiment when the landslide accelerated was captured by the high-speed camera at a frequency of 20 frames per second (fps).

In order to recognise the status of the landslide body according to these image sequences, the feature points on the landslide surface were analysed based on the feature point tracking method (Feng et al., 2012). First of all, SIFT algorithm (Lowe, 2004) was applied to extract feature points from all images of both sequences. Second, the feature points extracted from each pair of two consecutive images along the same sequence (left or right camera) were matched based on the comparison between SIFT descriptors. Third, the RANSAC (Fischler & Bolles, 1981) algorithm was used to remove wrong point pairs by exploiting the relative orientation between cameras. Finally, the instantaneous velocity of the landslide was calculated on the basis of the valid matched feature points that were also tracked between two consecutive image pairs.

Figure 8. Plots of observations from piezometer 506, inclinometer 1 and accelerometer 5 during Experiment 5.
3.3. Analysis of the water table

3.3.1. Experiment 4

As can be seen in Figure 10, piezometers recorded no variations in the water table until 13:34 (absolute time). This means that water did not accumulate in the slope at the beginning of the experiment, but flowed down on the slope surface. On the other hand, after artificial rainfall stopped, the subsequent rain had resulted in a sharp increase of the water table level. Only exception was the upper part of slope, where piezometer 506 did not record significant changes. The multiple failures in Event 3 occurred when the water table dramatically increased. In the plot of Sensor 501, that is located just in the area interested by failure (lower Sector 2), the event time can be easily detected at 13:50. Similar outcomes can be observed in the case of Event 4, when the three piezometers 501, 502, and 503 showed a sudden lowering of the water table. The final
run-out of the superficial layer of both Sectors 1 and 2 (Event 5) occurred during a further deep increase of the water table level.

3.3.2. Experiment 5

All piezometers recorded a similar trend, except the lower one (501) which showed a different behaviour (Figure 10). A sharp increase of the water table can be observed after start of rainfall (Figure 4). As expected, the water table level decreased from the lower to the upper part of slope. Only one exception is given by Sensors 503 and 504, where water level had inversion. All piezometers observed a quite stable behaviour until 13:30, i.e. approximately one hour before the final collapse (Event 6). Then, the water level started to rise throughout the entire slope in a similar way. Small deviations from this trend can be noticed. These are probably due to temporary breaks of rainfall, as can be deduced by comparing Figures 4 and 10. On the other hand, it was not possible to correlate the small variations in the signal trends to any event on the ground surface. The slope failure was recorded by all sensors. On the other hand, the failure time is difficult to predict from piezometers’ observations only.

3.4. Correlations between sensors

In this subsection, the correlations between sensors, diverse components of the same sensor, and rainfall are analysed. Correlations are really important for cross-validation
of measurements and for the correct application of mechanical or empirical models. As a measure of the correlation degree, the linear correlation coefficient ($\rho_{ij}$) between synchronous observations in two generic data-sets $i$ and $j$ has been adopted. Although this parameter gives information on direct and inverse linear dependency only, it is generally used as a good indicator of correlation. Data-sets $i$ and $j$ are considered as elements of a two-dimensional (2-D) random variable. Each of them has expectation and standard deviation ($\mu_i$ and $\sigma_i$, and $\mu_j$ and $\sigma_j$) for data-sets $i$ and $j$, respectively. Given the covariance $\sigma_{ij}$ between both data-sets, the linear correlation coefficient ($\rho_{ij}$) can be evaluated as follows:

$$\rho_{ij} = \frac{\sigma_{ij}}{\sigma_i \cdot \sigma_j}$$

In the sequel, absolute computed values of correlation are classified according to this empirical rule: (1) high correlation when $0.8 < |\rho| < 1$; (2) medium correlation when $0.6 < |\rho| < 0.8$; (3) medium-low correlation when $0.4 < |\rho| < 0.6$; and low correlation when $|\rho| < 0.4$. Results are graphically illustrated in Figure 11. As can be seen in Table 1, the most sensors collected data in synchronous way, except accelerometers. Subsampling of accelerometer observations was carried out to make them comparable with other data.

### 3.4.1. Inclinometers

As can be seen in Figure 11, all inclinometer observations were well correlated to rainfall gauge, especially during Experiment 4 ($|\rho| > 0.8$). Lower absolute values were found during Experiment 5 ($|\rho| > 0.71$), while the cross-slope component of the dual-axes inclinometer 2 also showed poor correlation with rainfall. These results were confirmed by looking at the intrinsic correlation between different kinds of inclinometer observations, which showed a strong linear dependency ($|\rho| \approx 1$).

<table>
<thead>
<tr>
<th>Exp 5 -&gt;</th>
<th>rain</th>
<th>inclinometers</th>
<th>piezometers</th>
<th>pressure sensors</th>
<th>Exp 5</th>
</tr>
</thead>
<tbody>
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<td>Exp 4</td>
<td>rain</td>
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<td>2-sl</td>
<td>2-cr</td>
<td>S01</td>
</tr>
<tr>
<td>in</td>
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<td>0.71</td>
<td>0.52</td>
<td>0.78</td>
<td>0.59</td>
</tr>
<tr>
<td>2-sl</td>
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<td>0.91</td>
<td>0.84</td>
<td>0.71</td>
<td>-0.09</td>
</tr>
<tr>
<td>2-cr</td>
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<td>0.99</td>
<td>0.98</td>
<td>0.55</td>
<td>0.03</td>
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<tr>
<td>S01</td>
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<td>0.93</td>
<td>0.89</td>
<td>0.88</td>
<td>-0.38</td>
</tr>
<tr>
<td>S02</td>
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<td>0.95</td>
<td>0.92</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>S03</td>
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<td>0.91</td>
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<tr>
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<td>0.55</td>
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<tr>
<td></td>
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<td>0.33</td>
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</tbody>
</table>

Figure 11. Overview of linear correlations between observations from different sensors during Experiments 4 (in the lower triangle) and 5 (in the upper triangle). Acronyms are used for the pressure sensors (OS: osmometer; BH: borehole pressure gauge; and SP: soil pressure gauge) and for the components of the dual-axes inclinometer 2 along ‘slope’ (SL) and ‘cross-slope’ (CR) directions. Accelerometers will be separately analysed in Tables 3 and 4. Colours give a quick outlook of the results. Green cells represent high correlations ($0.8 < |\rho| < 1$); blue cells medium correlations ($0.6 < |\rho| < 0.8$); orange cells medium-low correlations ($0.4 < |\rho| < 0.6$); and white cells low correlations $|\rho| < 0.4$. 

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3.4.2. Sensors related to the water content

Figure 11 shows that rainfall is highly correlated with piezometers in Experiment 4, except in the upper part (Sensor 506). In Experiment 5, correlations decrease from the bottom (Sensor 501, $\rho = .78$) to the top of the slope (Sensor 504, $\rho = .38$). Correlations between piezometers were higher for sensors located in Sectors 1–2 (501, 502, 503 and 504) during Experiment 4, while they showed lower values with Sensor 506. Rainfall was strongly linearly dependent with soil pressure gauge observations in Experiment 4 ($\rho = .96$). Here, the osmometer showed medium-high correlation with rainfall ($\rho = -.77$), while borehole pressure gauge was uncorrelated. During Experiment 5, low-medium correlations were found with rainfall ($\rho = .68$). Looking at the relationships between different kinds of pressure sensors, osmotic pressure gauge had medium-size correlation with borehole pressure gauge. Piezometers and pressure sensors were highly correlated in Experiment 4 with both osmotic and borehole pressure gauges. The only exceptions were piezometers 502 and 506 with soil pressure sensor, probably due to the locations in different parts of the slope. In Experiment 5, low correlations were found when comparing piezometers and other pressure sensors, except piezometer 506 and osmometer ($\rho = -.96$). Generally, in both experiments, low correlations were found between any sensor and soil pressure gauge ($|\rho| \leq .53$).

In Experiment 4, medium and high correlations were found between inclinometers and piezometers ($0.72 \leq |\rho| \leq .96$). The result is quite different for Experiment 5, where only Sensors 501 and 506 showed medium-level correlations with inclinometers, despite the fact they were not located in close positions. The comparison between inclinometers and pressure sensors resulted in similar correlations for both experiments. Highest correlations were found for the osmometer, medium size for borehole pressure gauge, very poor values in the case of soil pressure gauge.

3.4.3. Accelerometers

As can be seen in Table 2, components $x$ and $z$ of the accelerometers always resulted in medium-high negative values for linear correlations (from $-.99$ to $-.69$). The minus sign refers to the fact the displacements along $x$-axis were negative, while the ones along $z$-axis positive. All accelerometers located on the right side of the slope (No. 1, 3 and 5) showed a medium-high value for both $\rho_{xy}$ and $\rho_{xz}$ correlations. Lower values were determined for Sensor 6 on the left side, showing a different behaviour between both sides of the slope. This result was confirmed by the analysis of video sequences, as reported in subsection 3.6. Table 2 also reports about correlations between accelerations and rainfall. Generally, these values were quite low, as a consequence of the fact that rainfall and accelerations were not linearly correlated. When looking at correlations

<table>
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<tr>
<th>Sensor</th>
<th>$\rho_{xy}$</th>
<th>$\rho_{xz}$</th>
<th>$\rho_{yz}$</th>
<th>$\rho_{xy}$</th>
<th>$\rho_{xz}$</th>
<th>$\rho_{yz}$</th>
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<tbody>
<tr>
<td>1</td>
<td>$-.61$</td>
<td>$-.80$</td>
<td>$.95$</td>
<td>$-.37$</td>
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<td>$.66$</td>
<td>$-.36$</td>
<td>$.42$</td>
<td>$.73$</td>
</tr>
<tr>
<td>5</td>
<td>$-.77$</td>
<td>$-.97$</td>
<td>$.65$</td>
<td>$.19$</td>
<td>$-.52$</td>
<td>$-.04$</td>
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<tr>
<td>6</td>
<td>$-.36$</td>
<td>$.99$</td>
<td>$-.40$</td>
<td>$.20$</td>
<td>$-.82$</td>
<td>$.23$</td>
</tr>
</tbody>
</table>
between diverse accelerometers, the first relevant outcome was a significant linear dependency between components of Sensors 1 and 3, both located on the right side of Sector 2 ($0.6 \leq |\rho| \leq 0.98$). This confirmed the presence of a mechanism linking the deformations in this sector. The second concerned Sensors 5 and 6 that generally featured strong linear dependency ($0.65 \leq |\rho| \leq 0.99$). The results of this analysis showed that accelerations had a quite complex behaviour on the slope. However, they highlighted short-term response before the events, while rainfall directly had more influence on other long-term cumulative signals.

### 3.5. Correlations between sensors in neighbouring locations

In the last part of the analysis of correlations, the attention was focused on comparing diverse sensors located in close positions. This is likely to enhance similarity or disparity in the observations, useful for the optimisation of the future SSN design. Four groups of sensors were analysed per experiment, each of them incorporating from two to four sensors as described in Table 3 that also shows where they are located.

#### 3.5.1. Experiment 4

Subset 1 was not involved in the final failure (Event 5) that affected only the upper layer of soil (unlike in Experiment 5), while the sensors were buried in the inferior layers. This did not result in a clear recognition of single events.

Subset 2 was mainly involved in the Event 4. Figure 11 shows medium-high correlations between these sensors, with the exception of the borehole pressure gauge. Event 3 can be seen only in piezometer 502 (Figure 6), not by the dual-axes inclinometer. On the other hand, Event 4 was detected by all instruments. Whilst piezometer 502 and borehole pressure gauge did not give a significant premonitory signal, inclinometers started to record rotations a few minutes before this local failure. The final failure (Event 5) was observed only by both components of inclinometer 2, particularly along the ‘slope’ direction as shown in Figure 6.

Subset 3 was directly involved in both Events 4 and 5. As can be seen in Figure 11, correlations between both sensors’ observations were high in absolute value. During the

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Subset</th>
<th>Position</th>
<th>No. of sensors</th>
<th>Sensors involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>Lower Sector 2</td>
<td>2</td>
<td>Piezometer 501, oil pressure gauge</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Middle Sector 2</td>
<td>4</td>
<td>Piezometer 502, dual-axes inclinometer 2, borehole pressure gauge</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Upper Sector 2</td>
<td>2</td>
<td>Piezometer 503, osmometer</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Sector 3</td>
<td>2</td>
<td>Piezometer 506, single-axis inclinometer 1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Lower Sector 2</td>
<td>3</td>
<td>Piezometer 501, oil pressure gauge, accelerometer 3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Middle Sector 2</td>
<td>4</td>
<td>Piezometer 502, dual-axes inclinometer 2, borehole pressure gauge</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Upper Sector 2</td>
<td>4</td>
<td>Piezometer 504, osmometer, accelerometers 1 and 6</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Sector 3</td>
<td>3</td>
<td>Piezometer 506, single-axis inclinometer 1, accelerometer 5</td>
</tr>
</tbody>
</table>
first part of experiment (Figure 12), both sensors recorded a quite flat trend. After restarting of rainfall at 13:05, both series had a sudden rise. Osmotic pressure had a delay of 24 min, but after that followed the piezometer 503. The first event detected in both data-sets was Event 4 but, unfortunately, the final failure was not observed in any of them. This means it affected only the superior part of the soil and could not be recognised by these two sensors which were buried in deeper locations.

Subset 4 was partly involved in Event 4 and more in Event 5. Only the single-axis inclinometer was correlated with rainfall gauge, while piezometer 506 did not show a significant linear dependency on rainfall (see Figure 11). This was motivated by the limited area that collected water in the upper part of the slope. Correlation between both sensors was at average level. The general trend of observations agrees with results already shown for other subsets. A quite flat trend corresponding to the small amount of accumulated water at the beginning of the Experiment 4 can be noticed and then a sudden rise occurs. According to the previous outcomes, both signals featured a significant change. This happened when rain started again after a break at 13:05. Event 4 can be clearly seen in the inclinometer observations, where it corresponds to the abrupt rise of measured rotation. On the contrary, this event could not be identified by piezometer 506. The same occurred for the final failure, which can be noticed in the inclinometer measurements only.

3.5.2. Experiment 5

In subset 1, both piezometer 501 and soil pressure gauge were correlated with rainfall, while only the component z of the accelerometer was correlated with it (Table 2). Events 4 and 5 can be recognised in both piezometer and soil pressure data. All components of accelerometer 3 showed an abrupt increase at 14:15. This did not correspond to any specific failure, but a pre-alerting signal of the final failure (Event 6). All sensors detected the slope run-out, although piezometer and soil pressure gauge did not give any useful early-warning information.

Subset 2 was mainly involved in Event 5 and in the final run-out. Unlike Experiment 4, here correlations between all sensors and rainfall were low, except for the component of the dual-axes inclinometer 2 aligned to the slope direction (Figure 7). Also, linear correlations between different sensors resulted lower than in Experiment 4. Obviously, the two components of the inclinometer 2 were strongly linearly dependent. The sensors directly depending on the water content did not give useful information.
here, especially the borehole pressure gauge (see Figure 7). This result confirmed what had been found in Experiment 4 about the poor information content conveyed by this kind of sensor (at least in this implementation). Piezometer readings started rising 32 min before the final run-out (Event 6). This sudden growth can be interpreted as pre-alerting signal for failure. Most relevant were information achieved from both inclinometers, and especially from the one in the slope direction. Here, a premonitory signal can be read about 30 min before run-out.

From the analysis of correlations computed on the whole data-sets from subset 3, only some components of accelerometers 1 and 6 (located at the right and left sides of the slope, respectively) were highly correlated with rainfall (see Figure 11). Table 4 shows how correlations between different kinds of sensors were generally low, with an exception of osmometer and accelerometer 6 that were on the same side of the slope. The main conclusion from the plots reported in Figure 11 is that this region suffered from instability in the lower part. This can be demonstrated by the increase of some horizontal acceleration in correspondence of the failure in Sector 1 (Event 1). Another important remark is given by the sudden increase that the most accelerometers’ components and piezometer 503 featured 15 min before the final run-out (Event 6).

As already observed in Experiment 4, in subset 4 only the observations from single-axis inclinometer 1 were correlated with rainfall (Figure 11). This motivated by the limited area that collected water in the upper part of the slope. Very low correlations between sensors were found, except when looking at x-y-z components of accelerometer 5. When comparing observations to the event chronicle described in Section 3.1.2, the

<table>
<thead>
<tr>
<th>Osmotic pressure</th>
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<th>Accelerometer 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>Piezometer 503</td>
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<td>-.60</td>
</tr>
<tr>
<td>Osmotic pressure</td>
<td></td>
<td>.00</td>
</tr>
<tr>
<td>Accelerometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>-.61</td>
</tr>
<tr>
<td></td>
<td>z</td>
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</tr>
<tr>
<td>Accelerometer</td>
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</tr>
<tr>
<td>6</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>y</td>
<td></td>
</tr>
</tbody>
</table>

Figure 13. Results for point tracking on a pair of consecutive images just before the final run-out of Experiment 5.
Figure 14. Instantaneous velocity field at intervals of .5 s during slope failure in Experiment 5 (Event 6).
First remark is the change in both inclinations and accelerations (see Figure 8). This was already found in the analysis of subset 3 and corresponded to the Events 1 and 2. On the other hand, Event 3 on Sector 2 was slightly reflected only in the signal from piezometer 506. Event 5 (and partially Event 4) had effect on all sensor measurements. In particular, this was the moment when all observations started a sharp rise-up leading to the final run-out in short time (30 min later). Accelerometer response was briefly delayed (15 min) as already noticed from other subset observations. Eventually, the final failure was recorded by all sensors. Only inclinometer 1 and accelerometer 5, however, would allow a prediction.

3.6. Preliminary results from imaging sensors

In the present paper, only some preliminary results from processing the image sequence recorded during Experiment 5 are reported. This subsection highlights the potential of such techniques to be integrated in the SSN for landslide monitoring. Furthermore, some similarities with respect to results obtained from contact sensors are shown.

Results at different steps of point matching and tracking for two image pairs (termed as ‘left’ and ‘right’ image) corresponding to the time just before the final run-out (Event 6) are depicted in Figure 13(a). Images were recorded by using the high-speed camera system working at 20 Hz frequency. Both cameras had been previously calibrated for removing image distortion and computing inner orientation parameters (Luhmann, Robson, Kyle, & Harley, 2011). The relative orientation between the ‘left’ and ‘right’ images was computed by exploiting some coded targets put on the flume framework (see Feng et al., 2012 for details). Some minor changes occurred on the landslide surface during an interval of .5 s corresponding which separated the acquisition of images 1 and 2. The feature point extraction by using SIFT algorithm first extracted corresponding points between each pair of synchronous images. This task resulted for instance in 22023 points on the ‘left’ image and 21961 on the ‘right’ image at time $t_1$ (Figure 13(b)). After matching between images at time $t_1$, about 5% of point pairs were rejected by RANSAC. At last, 13660 point pairs were preserved as the match results. By comparing the positions of matched point tracked along two consecutive image pairs (at times $t_1$ and $t_2$), the instantaneous velocities were computed. The instantaneous velocity vectors (Figure 13(c)) show that most of displacements were concentrated in the bottom right side of slope. This confirmed the asymmetric behaviour of the slope failure that was already found from contact-based sensors analysis. In the same way, in order to recognise the landslide run-out dynamic, the instantaneous velocity field was calculated at intervals of .5 s (see Figure 14).

4. Conclusions

In the paper, two experiments on the scaled-down landslide simulation platform established at Tongji University have been presented and discussed. In both, a rainfall-induced landslide was simulated. The main aim of the experiments was to assess the spatial sensor network (SSN) installed on the platform from both technical and scientific sides. In particular, the analysis of single sensors and groups of them allowed detecting which was likely to be applied in a real landslide with similar characteristics located in Taziping (Sichuan province, P.R. China).

First of all, outcomes from experiments demonstrated the need of multiple sensors in the SSN, because none of them was able to recognise all the premonitory signals.
This was due to either the spatial coverage and the diversity of the processes detectable by different kinds of sensors. In particular, information on the water content seems to be sufficiently provided by a line of piezometers deployed along the slope. Other pressure-related sensors like soil pressure gauge, osmometer and borehole pressure gauge did not output significant additional information. This was due to the position of the sensors and the slope characteristics influencing the mass movement. However, this cannot be assumed as a general conclusion. The same sensors could give better results in different conditions. Indeed, the scale difference between model and real slopes is expected to influence these kinds of sensors more than the one measuring deformation and displacements (Jia et al., 2009). This limitation is going to be further investigated in future experiments.

Inclinometers gave very good results, as largely proved in the literature. A denser network of such sensors should provide useful information for prediction purpose, especially in the case of a complicated landslide with unknown mechanism. Due to the high correlation, dual-axes inclinometers did not provide much more results than single-axis instruments, taking into account the increase in the amount of data to handle.

Accelerometers did not provide a significant added value if compared to inclinometers. Although in other typologies of slopes (e.g. in rock slopes) measurements of vibrations are also important, here they did not demonstrate to be quite significant from the analysis of correlations. In addition, they produce a huge amount of data which would require a broader band for data communication.

Some important outcomes are expected from processing of video sequences gathered by the stereo-camera systems installed on the landslide simulation platform. The initial results obtained from Experiment 5 showed how image sequences can be processed to track points describing the velocity field on the slope surface. In addition, images could be also used to compute landslide volume on the basis of dense image matching techniques (Grün, 2012). Also, the high-speed cameras allow one to capture high-resolution videos of slope failure, which can be useful for the analysis of landslide collapse dynamic. In the future, the application of time-of-flight cameras (Piatti & Rinaudo, 2012) and gaming 3D imaging sensors (Menna, Remondino, Battisti and Nocerino, 2011) could be successfully used for directly gathering 3D data during landslide simulation experiments. Moreover, the high frequency of these sensors would also allow one to deal with high-dynamic tests.

A critical point for applying SSN in landslide early-warning systems is to define the alarm threshold of sensors (Uchimura et al., 2010). Landslide experiments can help set up values for threshold at a small-scale platform. On the other hand, judgements based on threshold must be checked to avoid false alarms. In order to improve the accuracy of landslide prediction and the reliability of SSN, assimilation of spatial data observations into geotechnical/mechanical models is the new edge of research, leading to the improvement of the modelling process (Gigli, Fanti, Canuti, and Casagli, 2011). Eventually, a better knowledge of the soil strength and properties may help obtain more realistic results from flume simulations.

One of the aspect that is expected to give some major concerns when moving from the simulation platform to the real environment is data communication from the landslide place to the control room located at a distance of some tens or some hundred kilometres far away. Such real applications would call for more involved and reliable media than those used in the simulation platform (see Scaioni et al., 2012), due to the much longer distance and the harsh conditions in the mountain environment. A more efficient solution may be based on a local server to be allocated in a safe place near the
landslide. The local server has the functions of data pre-processing, data storage, sensor check-up and retransmission of selected information to a remote station. While the monitoring network from in situ sensors collects very detailed information of a landslide at local scale, the applications of remote sensing techniques have greater potential in providing more comprehensive spatial information at regional scale. For wide-area deformation monitoring and geomorphological analyses, several remote sensing platforms are planned to be integrated with the in situ sensors for the Taziping landslide, like a ground-based InSAR, a very long-range terrestrial laser scanning, and the acquisition of images and laser data from UAV, aircrafts and satellites. Moreover, the integration of other kinds of additional local sensors into the SSN should allow us to measure absolute and relative displacements between points in the real environment (e.g. GNSS sensors, crackmeters, distometres and robotic total station measurements).

Acknowledgements
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