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Early warning of fast landslides triggering based on instrumented slope data analysis

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Abstract: The results of laboratory infiltration experiments on instrumented small scale model slopes are presented. Loose granular pyroclastic soils from the mountainous area north-eastern of Napoli have been examined. The experiments aimed to reproduce the simple case of a homogeneous indefinite slope, for a better understanding of the hydraulic processes leading to slope failure. With this respect, useful information was provided by the results of coupled measurements of soil suction and volumetric water content, respectively carried out by minitensiometers and Time Domain Reflectometry. The obtained results indeed showed how soil wetting during rainfall infiltration took place under matric suction values around 5kPa smaller than what could be predicted by equilibrium water retention curves estimated in laboratory. Since steep slopes equilibrium is often guaranteed by cohesion increment due to suction under unsaturated conditions, the obtained result indicates that effective early warning of fast landslides should rely on direct monitoring of soil suction and water content in the field.

Keywords: Flowslides; Pyroclastic granular soils; Physical modelling; TDR; Early warning.

1. INTRODUCTION

Occurrence of fast landslides has become more and more dangerous during the last decades, due to the increased density of settlements, industrial plants and infrastructures. Such problem is particularly worrying in Campania (Southern Italy), where the fast population growth led a diffuse building activity without planning: indeed, recent flowslides caused hundreds of victims and heavy damages to buildings, roads and other infrastructures.

Large mountainous areas in Campania are mantled by loose pyroclastic granular soils up to a depth of a few meters from top soil surface. These soils have usually a grain size that falls in the domain of silty sands, including pumice interbeds (gravelly sands), with saturated hydraulic conductivities up to the order of 10^{-1} cm/min. Such deposits often cover steep slopes, which stability is guaranteed by the apparent cohesion due to suction under unsaturated conditions, that are the most common conditions for these slopes [Olivares and Picarelli, 2003]. Whereas rainfall infiltration causes soil to approach saturation, suction vanishes and slope failure may occur.

Besides soil physical properties, landslide triggering is influenced by several factors, such as rainfall intensity, soil initial moisture and suction, slope inclination, boundary conditions. Whereas slope failure occurs with soil close to being saturated, landslide may develop in form of fast and destructive flowslide.

Calibration of reliable mathematical models of such a complex phenomenon requires availability of experimental observations of the major variables of interest, such as soil

moisture and suction, soil deformation and displacements, pore water pressure, during the entire process of infiltration until slope failure. Due to the sudden trigger and extremely rapid propagation of such type of landslides, such data sets are rarely available for natural slopes where flowslides occurred. As a consequence landslide risk assessment and early warning in Campania rely on simple empirical models [Sirangelo et al., 2003] based on correlation between some features of rainfall records (cumulated height, duration, season etc.) and the correspondent observed landslides. Laboratory experiments on instrumented small scale slope models represent an effective way to provide such data sets [Olivares et al., 2008] useful for building up more complex models of landslide triggering prediction.

In this paper, a series of laboratory tests carried out on model slopes made by a single layer of granular pyroclastic soil taken in the mountainous area north-eastern of Napoli, are presented. Among the responses of the various sensors installed, coupled measurements of water content profiles by TDR and matric suction by tensiometers are presented. The obtained results show how instrumented model slope infiltration tests allow to estimate effective water retention curves experienced by the soil during infiltration.

2. MATERIALS AND METHODS

At the Geotechnical Laboratory of CIRIAM an instrumented flume to investigate on the mechanics of rainfall-induced landslides in initially unsaturated deposits of granular soils is available [Olivares et al. 2003a]. In the flume, a homogeneous model slope is reconstituted by a moist-tamping technique: with the flume in horizontal position, the soil is laid in thin layers having a thickness around 0.5cm in order to get a uniform distribution of porosity. After 48 hours, before inclining the flume at the desired angle, soil is gently wet with an artificial rainfall of weak intensity for few minutes, in order to prevent detachment of small aggregates from soil surface. All the tests have been carried out with uniform and constant rainfall until slope failure. Rain intensity, variable between 10mm/h and 110mm/h, is reproduced by an artificial system, through several spray nozzles installed above the lateral sides of the flume. In order to prevent erosion of the soil surface, the adopted nozzles produce nebulized water particles 0.1mm in diameter. During the infiltration process, slope behaviour is observed. In particular, matric suction at different positions and depths is measured by insertion of mini-tensiometers within the slope, while positive pore pressure is monitored by miniature transducers installed at the base of the model. Soil water content profiles are measured by Time Domain Reflectometry (TDR) metallic probes [Topp et al., 1980]. At the ground surface, the displacement field is observed through laser sensors, installed in different zones of the slope with the optical axis perpendicular to the soil surface in order to monitor settlements, and high definition video-cameras to obtain, through a Particle Image Velocimetry technique (PIV), the overall horizontal displacement field. Rainfall intensity and air temperature are measured respectively by a rain gauge located at the foot of the slope and a standard thermocouple. A sketch of the flume is given in figure 1; more details about all the devices installed are reported in Olivares et al. [2008].

For the presented applications in granular soils conventional jet-fill type tensiometers (Soil-Moisture Equipment), equipped with a porous ceramic cup with a nominal bubble pressure of 100kPa and a standard Bourdon-type vacuum gauge, have been used. The range of operation of the unit is 0-85kPa, sufficient for laboratory testing in sandy soils, with a sensitivity of about 1kPa. The response of the devices has been experimentally tested, resulting fast enough to follow the expected changes in suction during infiltration in the model slope [Olivares et al., 2008]. Prior to installation, all tensiometers are filled and tested with de-aired water to ensure that the ceramic tips are free from cracks and all connections are properly sealed.

Soil water content measurements have been carried out with a recently proposed method allowing to retrieve moisture distribution along a TDR metallic probe buried into the soil [Greco, 2006; Greco and Guida, 2008]. Soil moisture measurements by TDR rely on the relationship between bulk soil dielectric permittivity, ϵ_r , and its volumetric water content, θ

[Topp et al., 1980]. TDR experimental apparatus consists of a Tektronix 1502C cable tester connected to a three rods metallic probe installed in the slope orthogonal to soil surface, as shown in figure 1.

In all the presented tests the infinite slope scheme (ratio thickness/length smaller than 1/10) has been investigated, since it represents the most frequent case in the concerned area. The experiments have been conducted on air-fall unsaturated cohesionless pyroclastic soils involved in catastrophic flowslides, taken at the experimental fields of Cervinara [Olivares et al., 2003b] and Monteforte Irpino [Nicotera and Papa, 2007], North-East of Napoli. Figure 2 reports grain size curves of the investigated materials: in all cases, the soil is a silty sand with a high sandy component but also a significant amount of non-plastic silt.

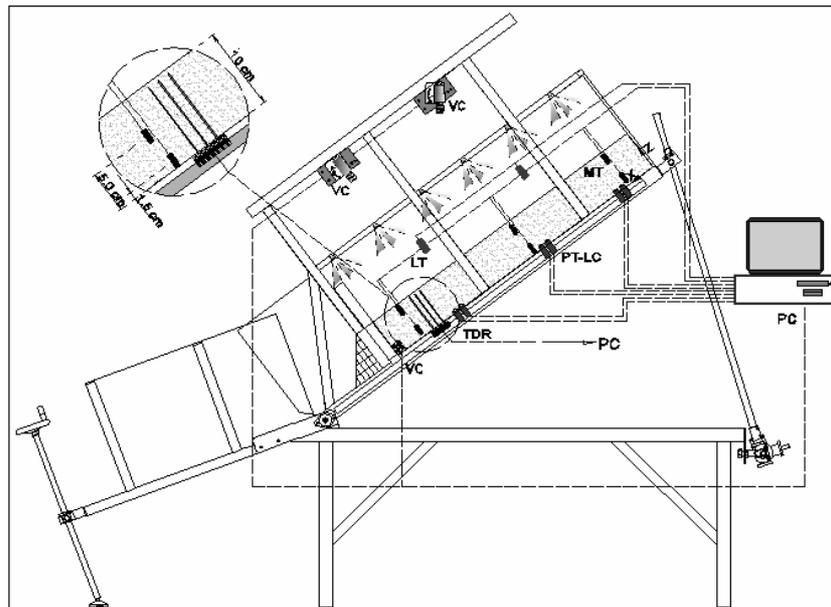


Figure 1. Sketch of the instrumented flume: LT = laser transducer; MT = minitensiometer; PT = pressure transducer; LC = load cell; TDR = TDR probe; VC = digital video-camera.

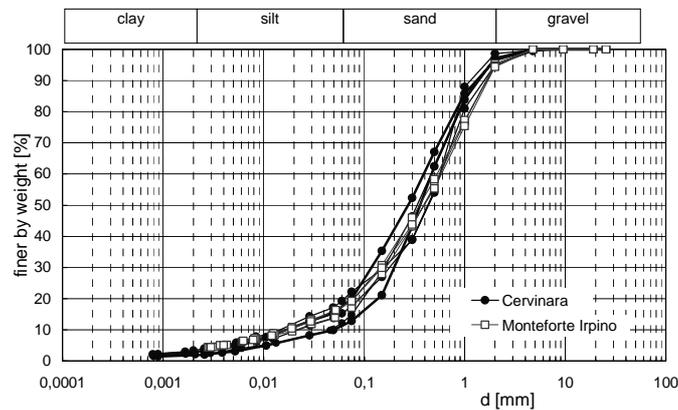


Figure 2. Grain size distributions of volcanic ashes.

Mechanical and hydraulic characterization has been carried out on undisturbed specimens recovered from pits dug along the slopes: Olivares and Picarelli [2003] and Nicotera and Papa [2007] respectively investigated the main soil properties of Cervinara and Monteforte Irpino ashes, which are summarized in Table 1. The volcanic ashes show quite similar properties: the specific weight is about 25kN/m^3 ; the porosity is quite high, ranging between 68% and 74%; the saturation degree, depending on environmental conditions, varies within a wide range but is generally much less than one; the saturated hydraulic conductivity of natural samples, measured by constant head tests, ranges between $1.0\text{E-}07$ and $7.0\text{E-}07\text{m/s}$; the saturated shear strength, measured through both CID and CIU triaxial

tests on saturated natural samples, is characterised by a friction angle of about 37° and a nil value of cohesion.

Since the unsaturated condition is the most frequent condition for the examined soils, their unsaturated properties have been investigated too. The water retention curves, shown in figure 3, have been evaluated through conventional laboratory tests: evaporation tests (using minitensiometer to explore suction between 0 and 80kPa and pressure plate for higher values of suction) on Monteforte Irpino ash [Nicotera and Papa, 2007]; evaporation and infiltration tests by use of minitensiometer and tests in suction controlled triaxial apparatus on natural and remoulded specimens of Cervinara ash [Olivares et al., 2003b]. The experimental results have been fitted through the expression proposed by van Genuchten [1980]: the correspondent values of parameters are reported in Table 1. A comparison between the retention curves of both soils seems to highlight that, in the range of suction of interest (0÷80kPa), the slope of the curve related to Cervinara ash is higher than the others obtained for Monteforte Irpino ash.

Table 1. Physical, mechanical and hydraulic properties of investigated soils.

Parameters	Cervinara	Monteforte Irpino
Specific weight (kN m ⁻³)	25.4÷25.9	25.2
Porosity	0.71÷0.74	0.71
Degree of saturation	0.48÷0.71	0.71
Saturated hydraulic conductivity k_{sat} (m s ⁻¹)	1·10 ⁻⁷ ÷ 5·10 ⁻⁷	7·10 ⁻⁷
Effective friction angle ϕ' (°)	38	37
Cohesion c' (kPa)	0	0
Residual volumetric water content θ_r	0.25	0.16
Saturated volumetric water content θ_{sat}	0.69	0.66
α (m ⁻¹) van Genuchten	1.8	1.2
n van Genuchten	7.1	1.5
m van Genuchten	0.15	0.33

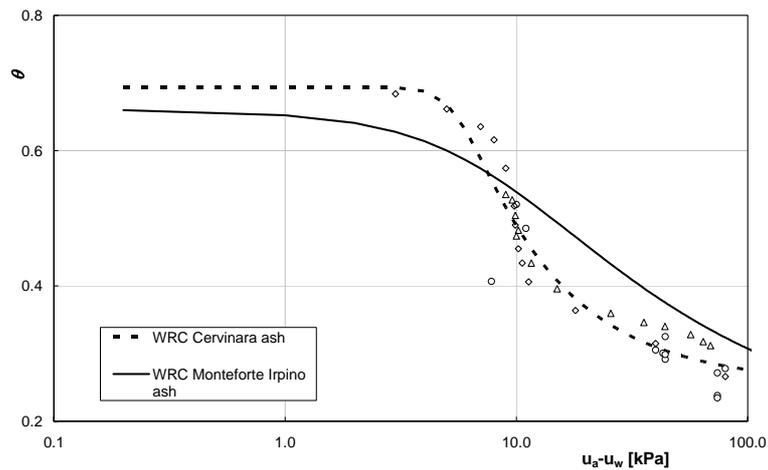


Figure 3. Water retention curves of volcanic ash from Monteforte Irpino [Nicotera and Papa, 2007] and Cervinara.

The unsaturated shear strength of Cervinara ashes has been measured by means of suction controlled triaxial tests using a mean net stress ($p-u_a$) between 20 and 70kPa and a suction (u_a-u_w) between 10 and 80kPa which are quite consistent with those existing in site [Olivares e Picarelli, 2003]. Such data show the significant role of suction, even for small values of (u_a-u_w): in particular, for a suction of 4-8kPa, the cohesion is 2-6kPa. Similar

results have been obtained by Nicotera and Papa [2007] for Monteforte Irpino ash.

For the application of TDR technique, the $\theta(\varepsilon_r)$ relationship has been experimentally determined for Cervinara soil over reconstituted samples. The obtained experimental points, plotted in figure 4, fall very close to $\theta(\varepsilon_r)$ relationships for low density volcanic soils available in literature [Tomer et al., 1999; Regalado et al., 2003], while application of the so-called ‘universal calibration relationship’ by Topp et al. [1980] would lead to soil water content underestimation.

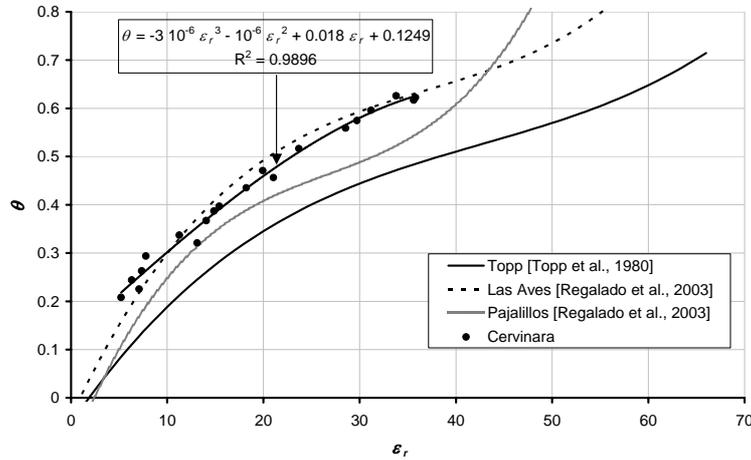


Figure 4. Dielectric permittivity vs. water content relationship for Cervinara ash compared with TDR ‘universal calibration relationship’ and specific relationship available in literature for volcanic ashes.

Table 2. Main characteristics of the tests

Test	D3	D4	D7
Investigated soil	Cervinara ash	Cervinara ash	Monteforte Irpino ash
Rainfall intensity (mm/h)	55	56	54
Duration of test (min)	36	30	95
Initial porosity n_0	0.75	0.75	0.69

The experiments have been carried out on 10cm thick, 50cm wide and 1.10m long slopes, with inclination of 40°. The bottom of the flume was impervious, while at the toe of the slope a geotextile drain was placed. A 9.5cm long TDR probe was placed at the bottom of the flume. Minitensiometers were installed at various positions within the slope. In particular two of them were placed nearby the TDR probe, respectively 1.5cm and 5cm above the bottom of the flume. The characteristics of each tests discussed in the following are given in Table 2.

3. RESULTS AND DISCUSSION

All the infiltration experiments lasted until slope failure was observed. Although the applied rainfall intensity was in all cases much higher than soil saturated hydraulic conductivity, no significant surface runoff was observed during the experiments, denoting that soil potential infiltration was never exceeded.

The response of the minitensiometers placed at various positions within the slope indicates that the infinite slope conditions were satisfactorily reproduced in all the tests: differences in suction values measured at the same depth inside the soil layer were always smaller than 1.5kPa. This result allows to consider water content distribution measured by the single TDR probe installed as representative of the entire slope behaviour.

Figure 5, in which z - axis is orthogonal to soil surface and directed from flume bottom ($z=0$) towards soil surface, shows some of the retrieved volumetric water content profiles at various times during experiment D3. The shape of the profiles is consistent with the expected infiltration process, while the time growth of cumulated infiltration height, h , estimated by integrating the retrieved profiles, is in good agreement with the applied artificial rainfall intensity, as it is showed in figure 6. In fact, the slope of $h(t)$ relationship results 44.0mm/h, roughly equal to the projection of the applied rainfall intensity along the inclined slope, until 18min after the beginning of the test. The following slope increase was due to the reduction of soil layer thickness, witnessed by observed surface settlement, w , also given in figure 6.

The last retrieved profile shown in figure 5 was acquired few seconds before slope failure, when soil saturation was reached. The departure of saturated water content from soil initial porosity value increases with depth. This result indicates that wet soil experiences volumetric collapse due to overburden load.

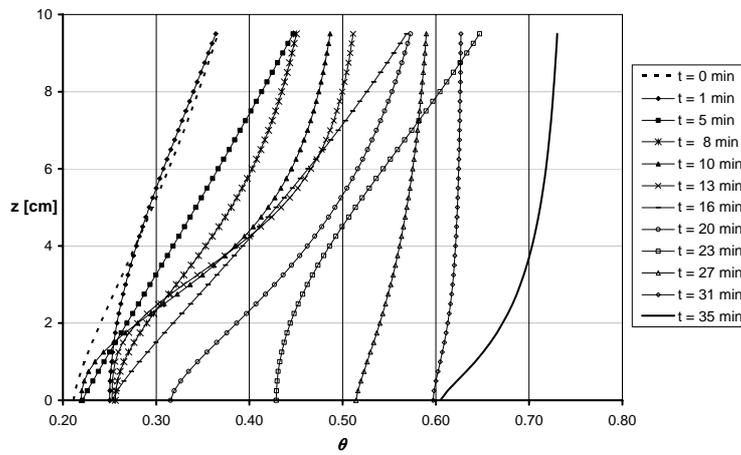


Figure 5. Volumetric water content profiles retrieved by TDR during experiment D3.

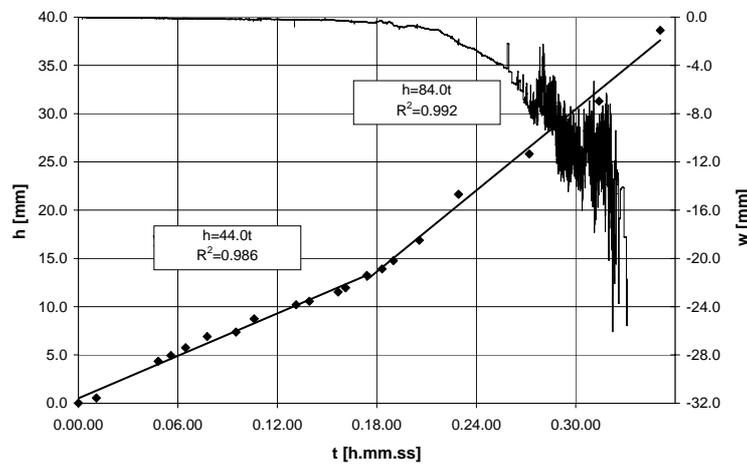


Figure 6. Cumulated infiltration height, h , and mean soil surface settlement, w , measured in experiment D3.

Figure 7 shows the time history of suction measured during experiments D4 and D7 by two minitensiometers buried at 1.5cm and 5.0cm above flume bottom, compared with the temporal evolution of volumetric water content at the same depths as given by water content profiles retrieved by TDR. It is worth to note that neither matric suction nor water content at 1.5cm changed before 30min after the start of experiment D7. A quite different response was observed at the same depth in experiment D4, during which the observed variables at the same depth started changing only 12min after the beginning of the test, although nearly the same artificial rainfall intensity was applied. Such result denotes that in

experiment D7 the component of water flow parallel to slope was much larger than during test D4.

The $(\theta, u_a - u_w)$ points obtained by coupling suction values measured by minitensiometers at 1.5cm and 5cm above flume bottom, with soil water contents read at the same depths along the profiles retrieved by TDR, are given in Figure 8. Although some dispersion is present, nearly all the experimental points fall below water retention curve estimated in laboratory, especially when soil saturation is approached. This result indicates that during the infiltration process reproduced in the model slope, soil experienced matric suction around 5kPa smaller than what could be expected from estimated water retention curve. As a consequence, soil suction contribution to slope stability resulted significantly smaller than expected. Since infiltration rate and boundary conditions applied to the slope during flume experiments resemble real slope conditions, it is expected that this result would be qualitatively confirmed also by field observations.

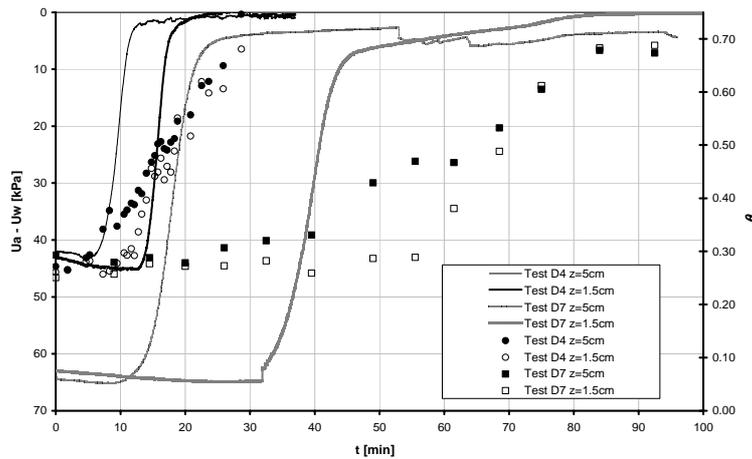


Figure 7. Matric suction (continuous and dashed lines) and volumetric water content (dots) time histories during experiments D4 and D7.

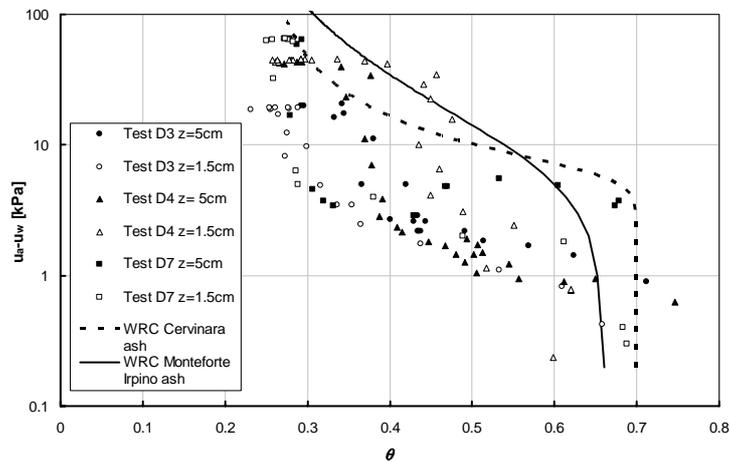


Figure 8. $(\theta, u_a - u_w)$ points measured during experiments D2, D4 and D7 compared with water retention curves estimated in laboratory for Cervinara and Monteforte Irpino ashes.

4. CONCLUSIONS

The results of infiltration tests in loose granular pyroclastic soil carried out on model slopes reproduced in an experimental flume in laboratory are presented. The measurement instruments installed in the flume allowed to monitor the entire phenomenon from the beginning of infiltration until slope failure. In particular, very useful information is

provided by the coupled measurements of soil matric suction and volumetric water content at various depths, acquired, respectively, with minitensiometers and a TDR metallic probe. The observed (θ , u_a-u_w) points, in fact, show that during an infiltration process in a steep slope, with inclination angle comparable with soil internal friction angle, soil wetting process takes place under smaller suction than what could be predicted by soil water retention curves estimated in laboratory. Slope equilibrium conditions may therefore be significantly affected by such behaviour, especially for the case of very steep slopes, with inclination larger than internal friction angle, where equilibrium is mainly guaranteed by cohesion component due to suction. The obtained results indicate that field measurements of soil water content by TDR can fruitfully supplement suction measurements for the implementation of effective early warning systems.

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