Integration of field monitoring and mechanics based warning against rainfall induced landslide

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Rainfall Induced Landslide

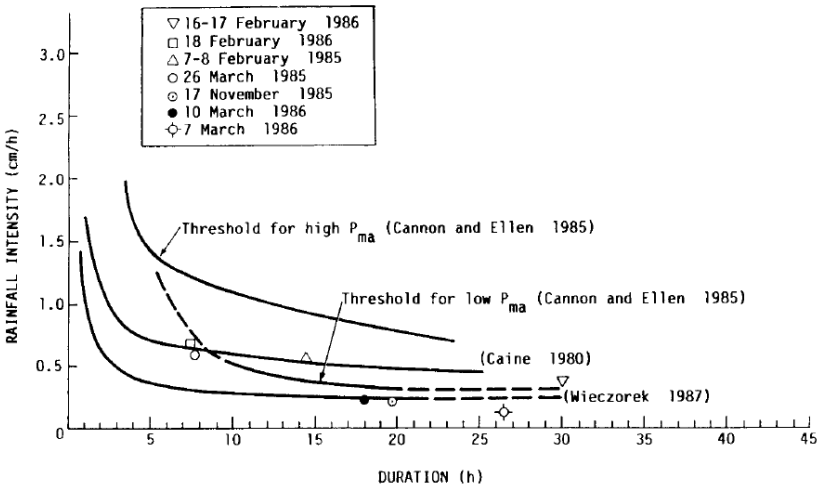
Warning of an imminent slope failure....

Shiao-Lin Village Landslide, 2009

Warning of rainfall induced landslide
– Existing methods –

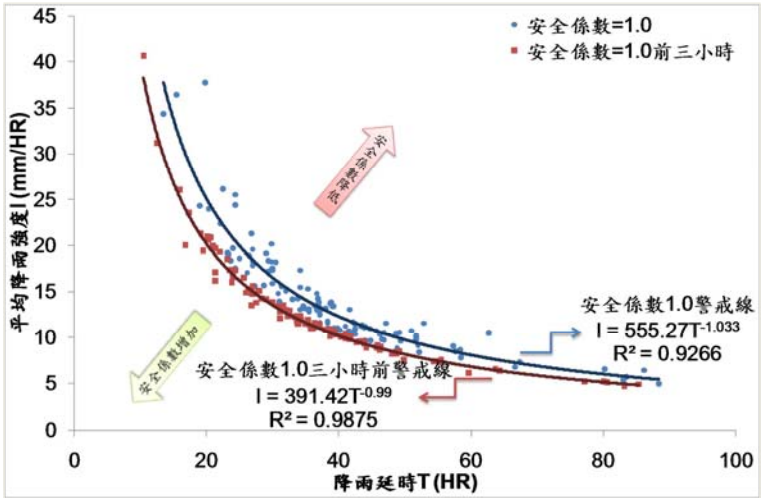
- Rainfall based empirical procedure
- Ground displacement based empirical procedure
- Numerical simulation based semi-empirical procedure w/ considerations of rainfall and ground water conditions

Rainfall based empirical procedure



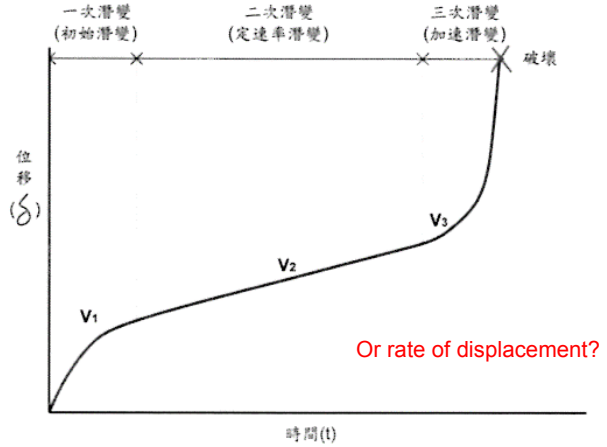
(Keefer et al., 1987)

Threshold curves used in Taiwan



(SWCB, 2010)

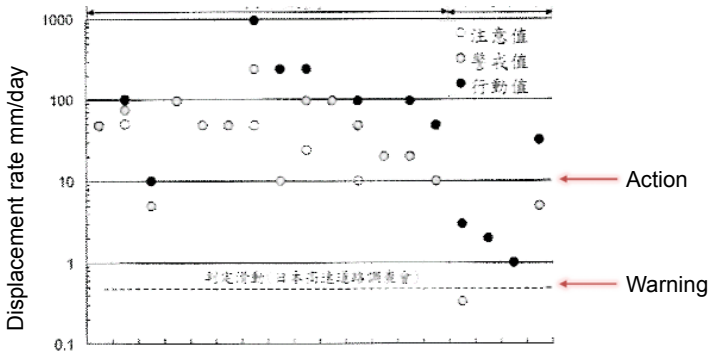
Displacement based empirical procedure



Or rate of displacement?

(Liao et al., 2013)

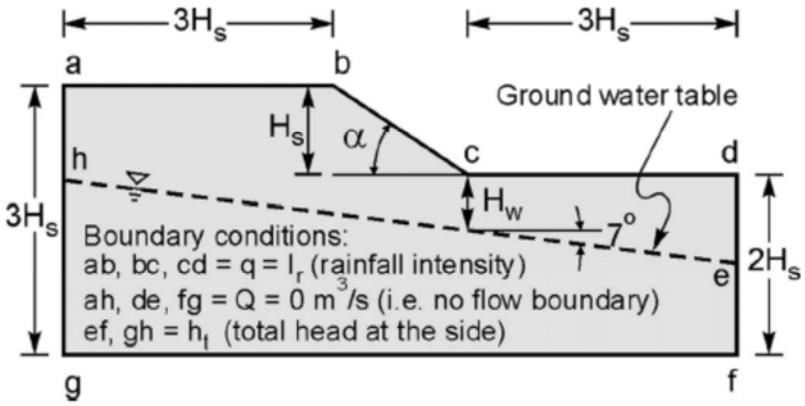
Displacement based empirical procedure



Meaningful only with automated readings.
Taking derivative of field data?

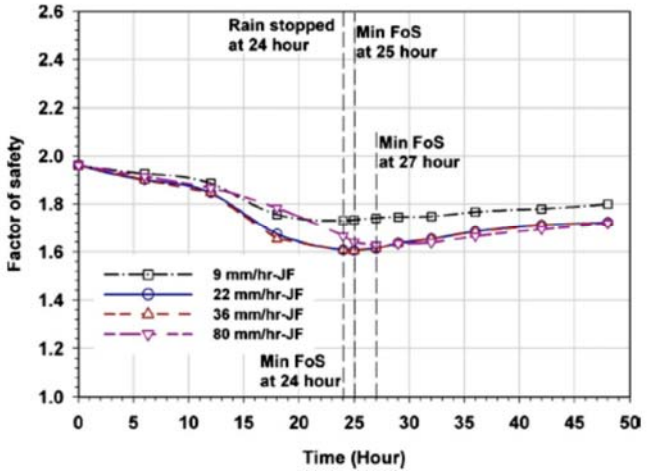
(Liao et al., 2013)

Numerical simulation based



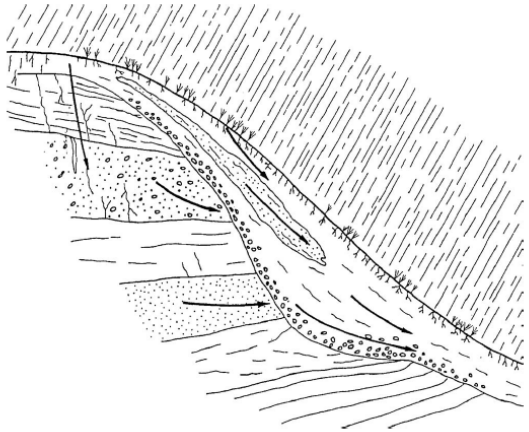
(Rahardjo et al., 2007)

Numerical simulation based



(Rahardjo et al., 2010)

Possible infiltration & seepage in ground during intense rainfall



(Johnson & Sitar, 1990)

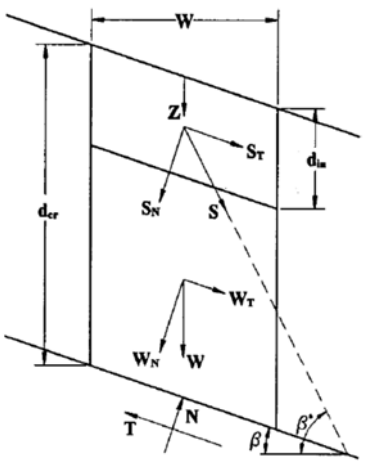
Drawbacks

- Empirical in nature – limited to local conditions
- Need of antecedent soil moisture conditions
- Good chance for false alarms?

Potential for warning of rainfall induced landslide Based on stress conditions (failure mechanics)

- 1-D infiltration in an infinitely long slope with a planar shear surface
- Field stress path approach

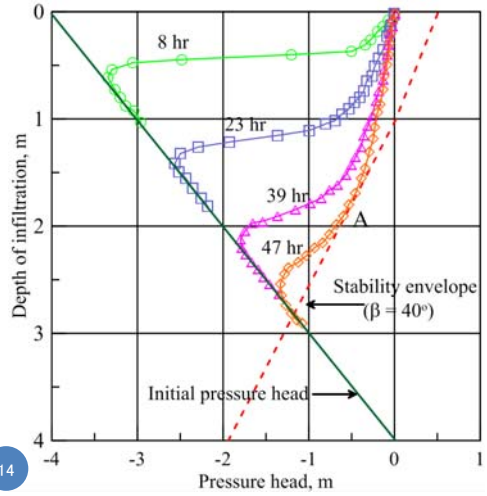
Infinite slope slice w/ planar shear surface



(Collins and Znidarcic, 2004)

$$d_{cr} = \frac{c' + \gamma_w \cdot h_c \cdot \tan\phi^b - \gamma_w \cdot h_p \cdot \tan\phi'}{\gamma \cdot \cos^2\beta \cdot (\tan\beta - \tan\phi')}$$

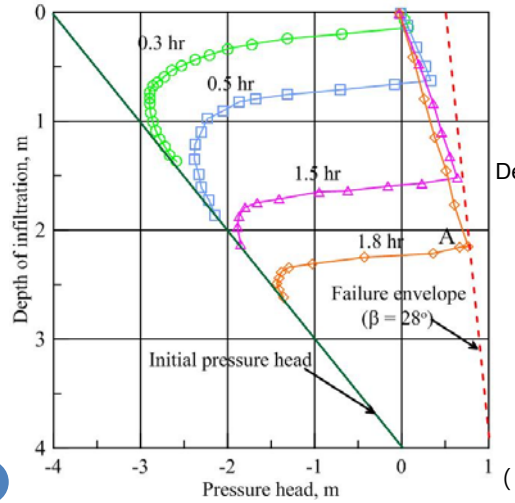
Slope failure under negative PWP & 1-D infiltration



Shallow and steep slope failure?

(Collins and Znidarcic, 2004)

Slope failure under positive PWP & 1-D infiltration

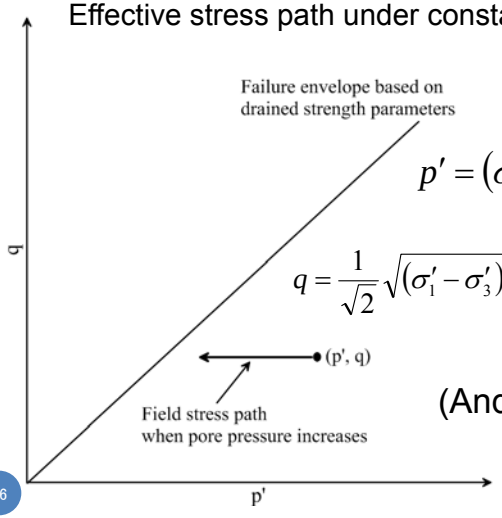


Deep seated below GWT failure?

(Collins and Znidarcic, 2004)

Field Stress Path

Effective stress path under constant shear



$$p' = (\sigma_1' + \sigma_2' + \sigma_3')/3$$

$$q = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1' - \sigma_3')^2 + (\sigma_1' - \sigma_2')^2 + (\sigma_2' - \sigma_3')^2}$$

(Anderson & Sitar, 1995)

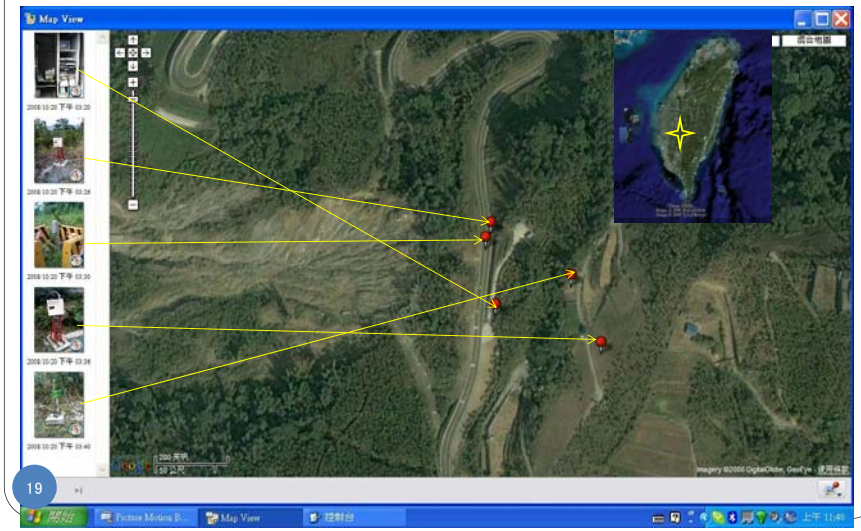
To materialize the stress based warning method…

- Need realtime pore water pressure (PWP) profile measurements
- Need engineering properties of the slope material – strength & hydraulic conductivity parameters
- Further improvement can made with rainfall measurements, realtime seepage analysis, and landslide motion prediction

Integrated field monitoring and mechanics based realtime warning system – for one borehole location

- Identify critical locations of potential slope failure – drill borehole for field testing/sampling & monitoring
- Conduct in situ tests or take soil/rock samples and perform laboratory tests – establish the failure criteria for the target slope
- Monitor PWP profile within the given borehole(s)
- Perform total stress analysis for the slope – establish initial stress state of the borehole location
- Determine effective stress states based on PWP measurements in the borehole

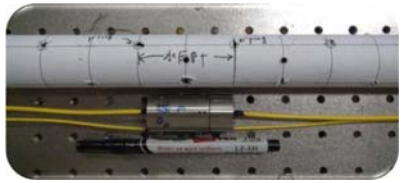
Highway slope at Five Turn Point Highway 18, Jia-Yi, Taiwan



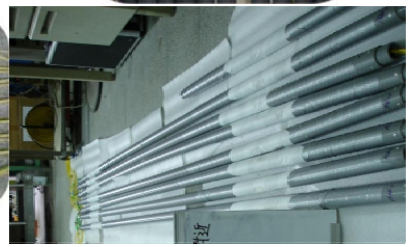
Fiber optic sensored field monitoring

- Based on optical fiber Bragg grating (FBG) sensors
- Immune to electric magnetic interference & lightning
- No short circuit
- Capable of (partially) distributive sensing – easily attached into a string for profile measurements
- Low attenuation – connections of sensors at 10's of km apart with optical fiber

FBG piezometers

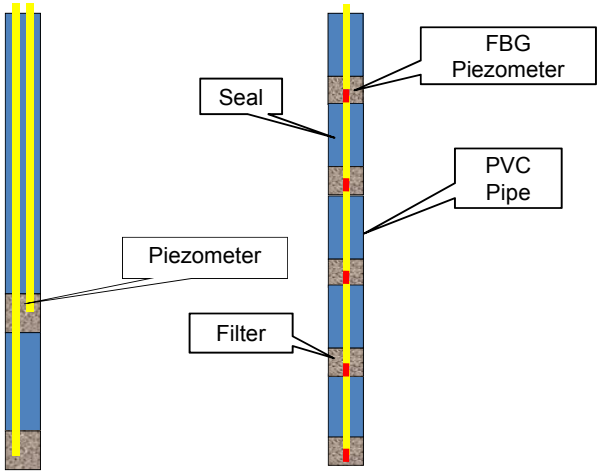


FBG pressure sensor



The FBG-IPI

FBG piezometer array versus open end piezometers in a single borehole



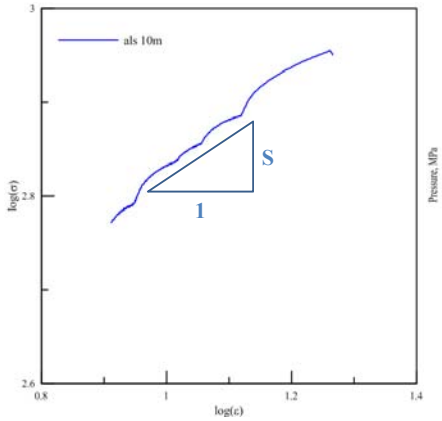
FBG piezometers spaced at 5m in PVC pipes and their installation in a 60m borehole

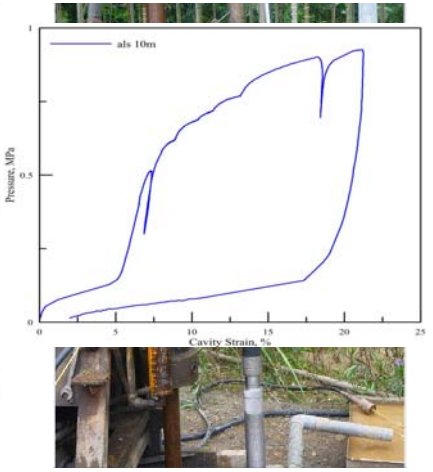
Placement of Spacer and Bentonite Pallets

$$\sin\phi' = \frac{s}{1+(s-1)\sin\phi'_{cv}}$$

$$\phi'_{CV} = 30^\circ$$

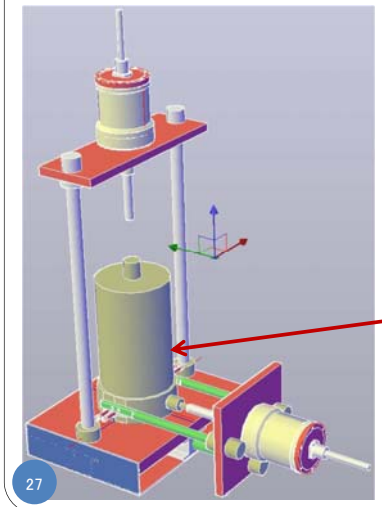
$\phi' = 40^\circ +$

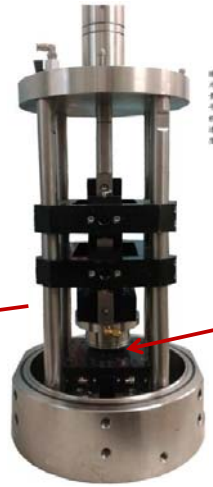


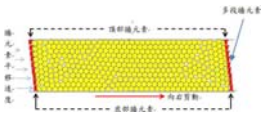


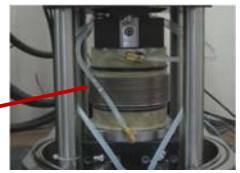
PMT in colluvium

Simple shear test on colluvium

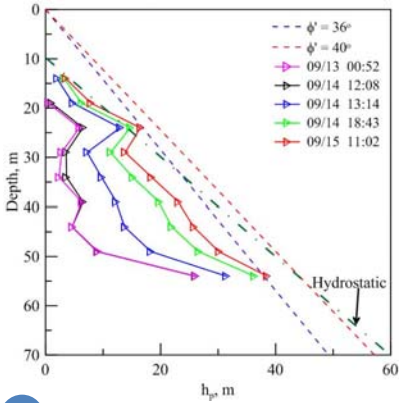


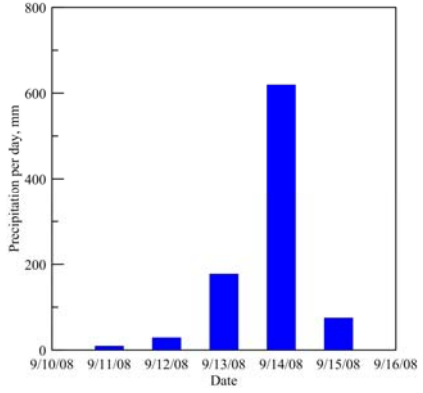




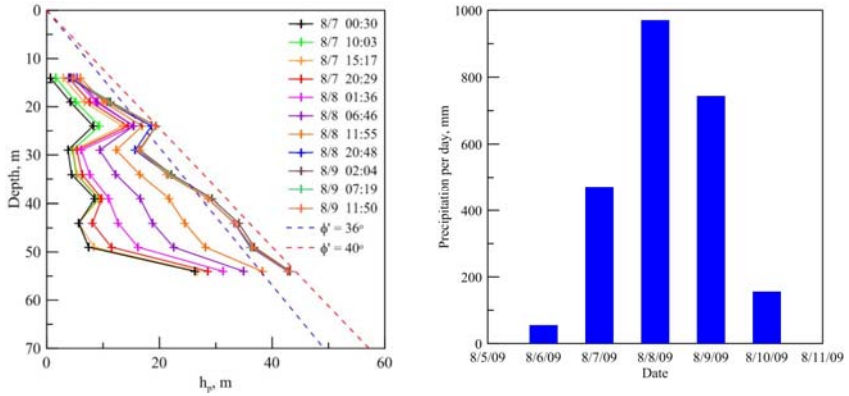


PWP profile at Ali Shan during Sinlaku Typhoon

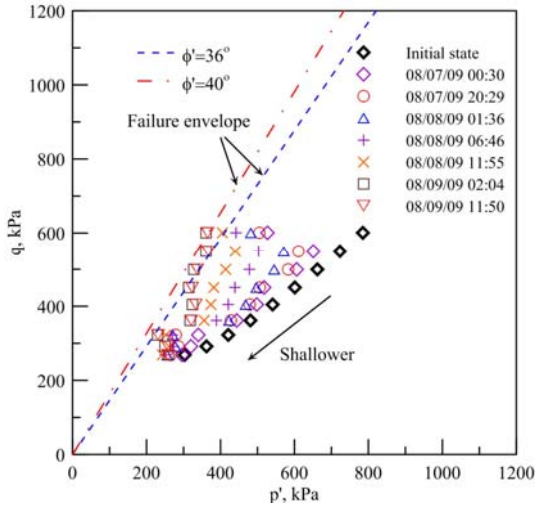




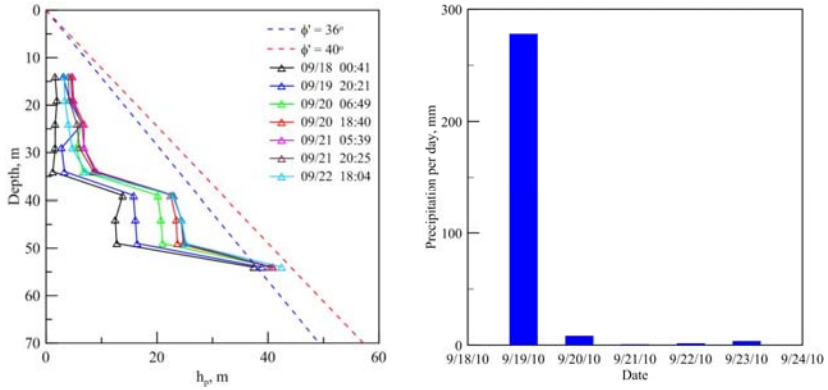
PWP profile at Ali Shan during Morakot Typhoon



Field stress paths at Ali Shan during Morakot Typhoon



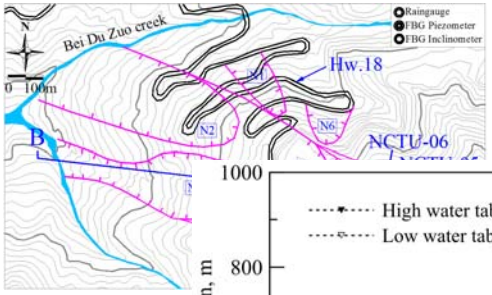
PWP profile at Ali Shan during Fanapi Typhoon



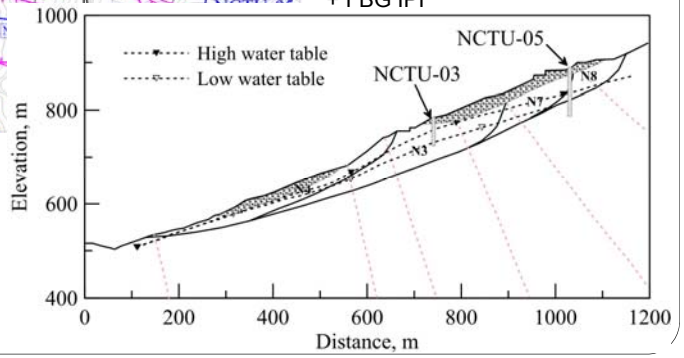
For a slope cross section w/ further warning time

- Field hydraulic conductivity tests – determination of K values
- 2D numerical transient seepage analysis
  - Boundary influx – up-slope PWP profile measurements
  - Surface runoff – dual-band realtime rainfall measurements over the target slope
- Calibration of seepage analysis w/ mid-slope PWP profile measurements
- Safety based on effective stress state versus failure envelope

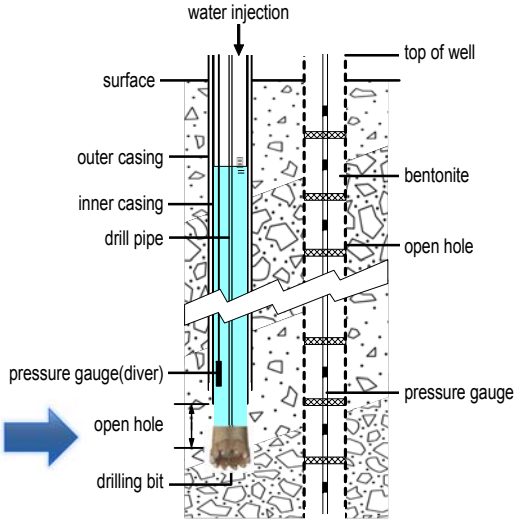
Installation of sensor arrays



NCTU03 – 60 m w/ 10 FBG piezometers
NCTU05 – 100 m w/ 10 FBG piezometers
NCTU06 – field permeability tests + FBG IPI

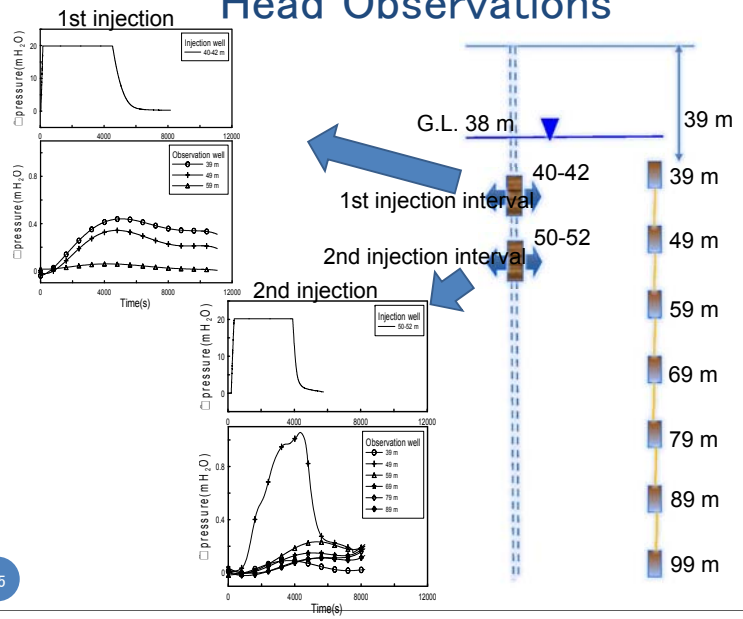


Field hydraulic conductivity tests



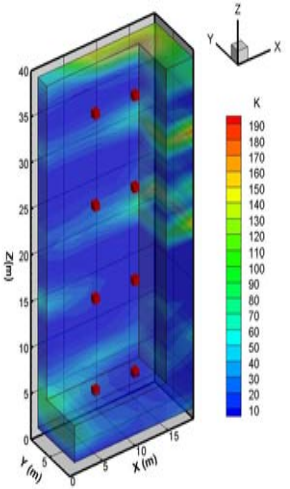
Test interval
1.0 m

Head Observations

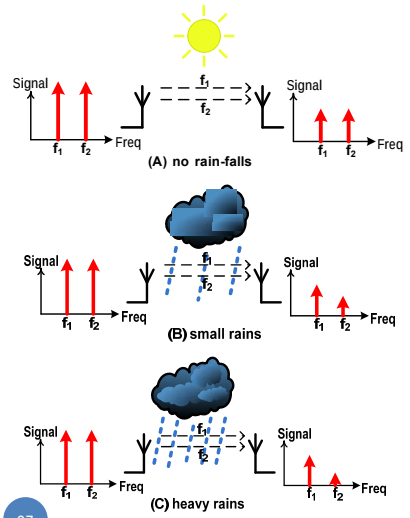


Conceptual Model For Estimating K

- 20x10x40(m)
- 1000 elements
- 1386 nodes
- 4 injection stresses

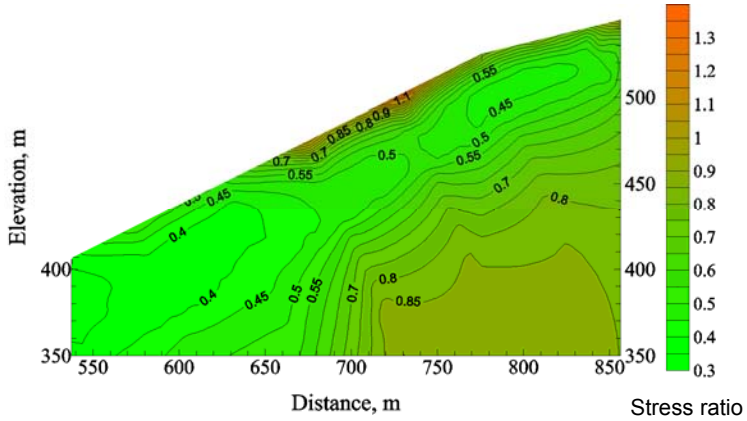


Dual-band R.F. rainfall monitoring



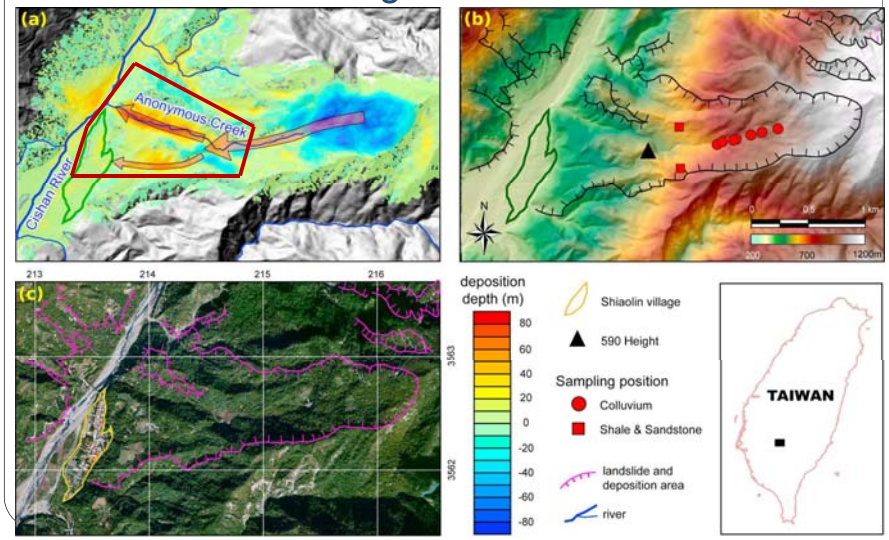
- Use dual-band transceiver networks to monitor large-scale hourly basis weather conditions.
- Use wireless transceivers to collect point-to-point path loss data.
- A topography computation to reconstruct short time frame weather conditions.

Conceptual view of the slope cross section



Landslide motion prediction

Hsiaoling landslide



Concluding remarks

- More suitable for large scale, deep seated landslides
- Useful in revealing the potential failure mechanism of a given slope – valuable for corrective measure designs
- Can be simplified with much lower costs
- Accumulation of field data can lead to more reliable empirical rainfall or ground displacement thresh-hold based methods