# Climate resilient design and rehabilitation of embankment structures

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# Contents

# Motivation for the study

- Embankment structures are the most common geotechnical structures, and the response is influenced by climatic factors
- They are part of  transportation infrastructure, water storage reserviors etc. Yet, many codes do not adequately address the requirements of stability and deformation response under various conditions and methods of analysis.  Recent IRC and Railway codes do not adequately address them. Several failures of these structures have been common every season.


# Failure due to erosion and mud pumping

# Failure during first filling of the reservoir

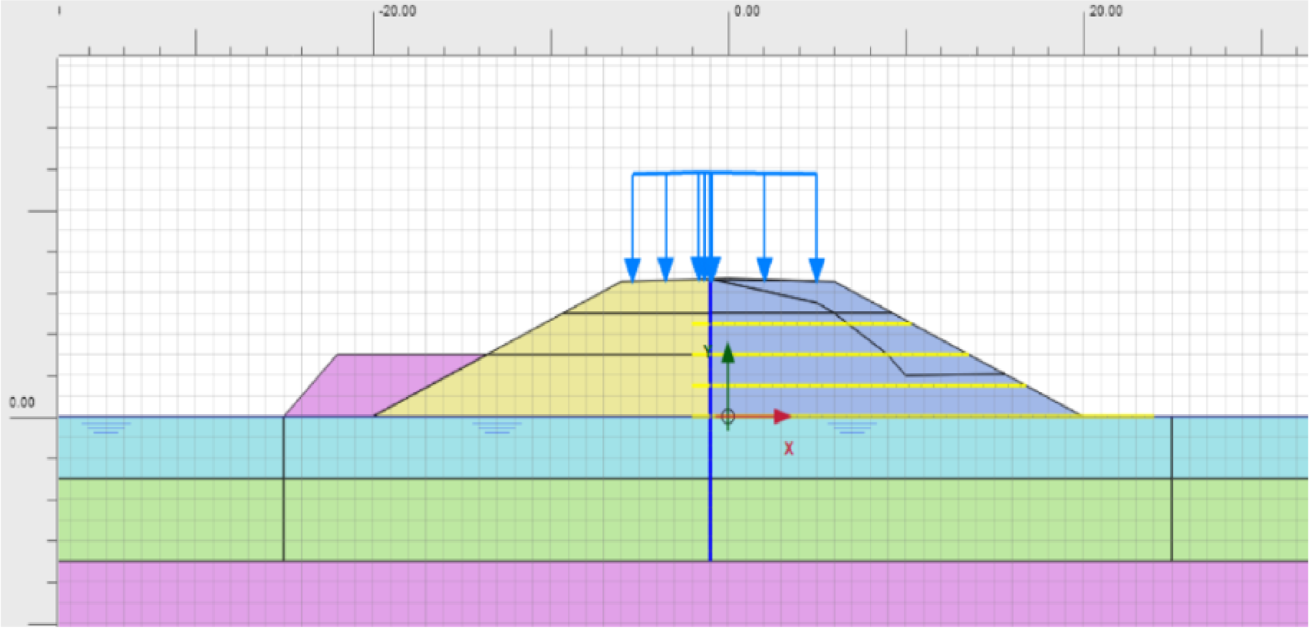
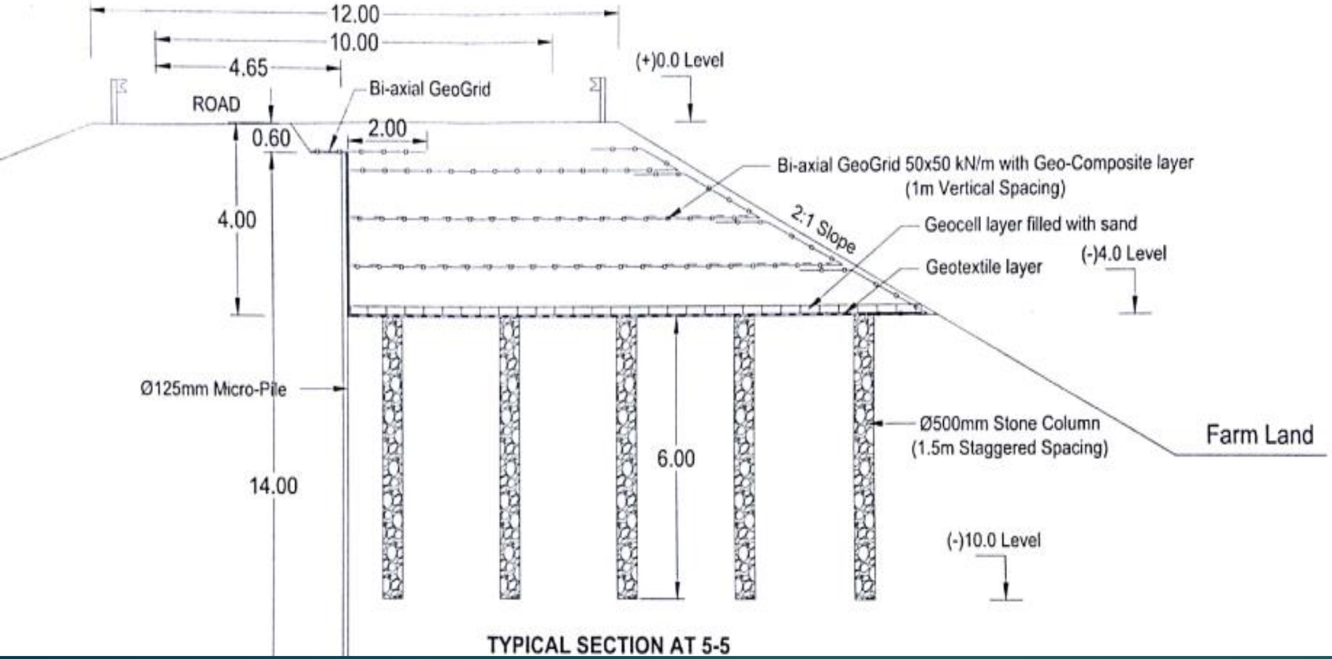
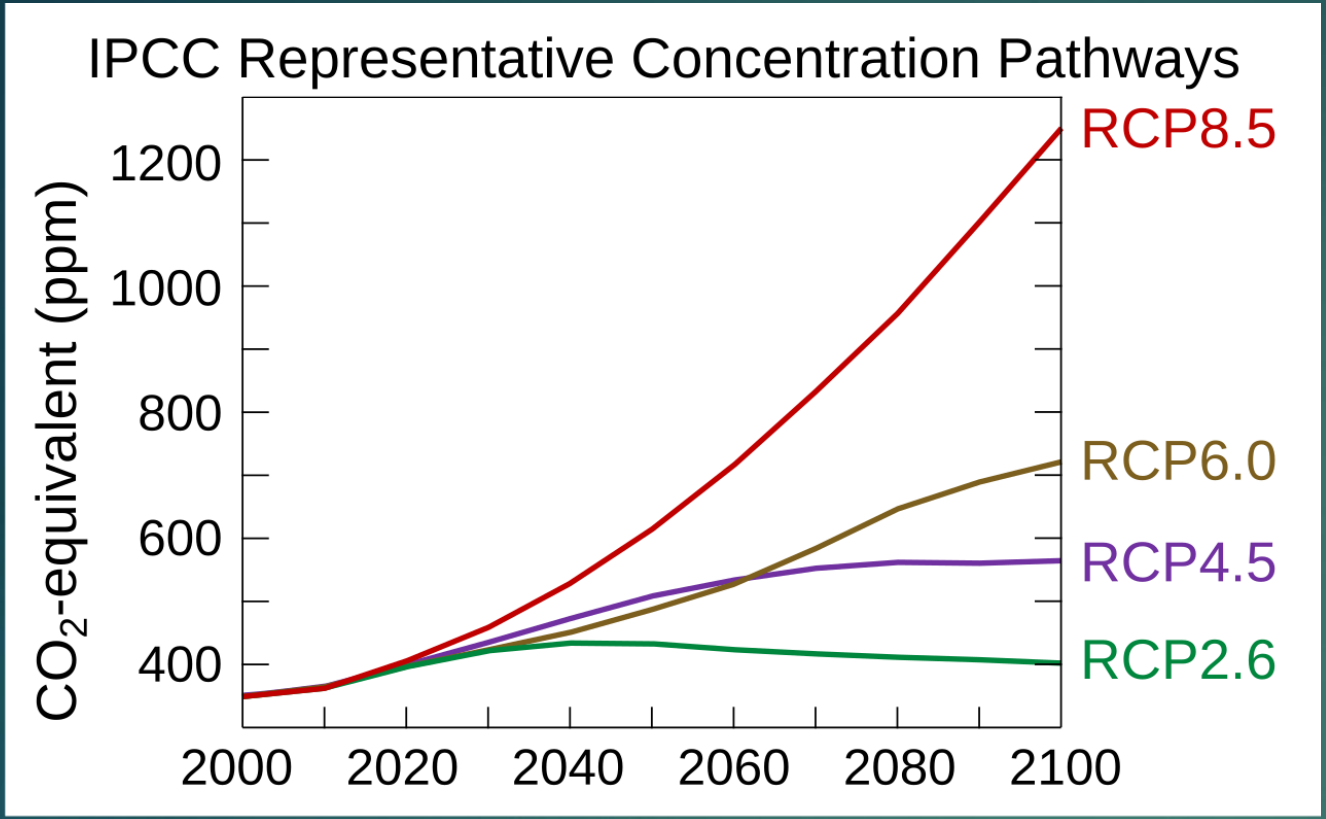



Figure 3. Final stability of the embankment after reconstruction (FS 1.92)

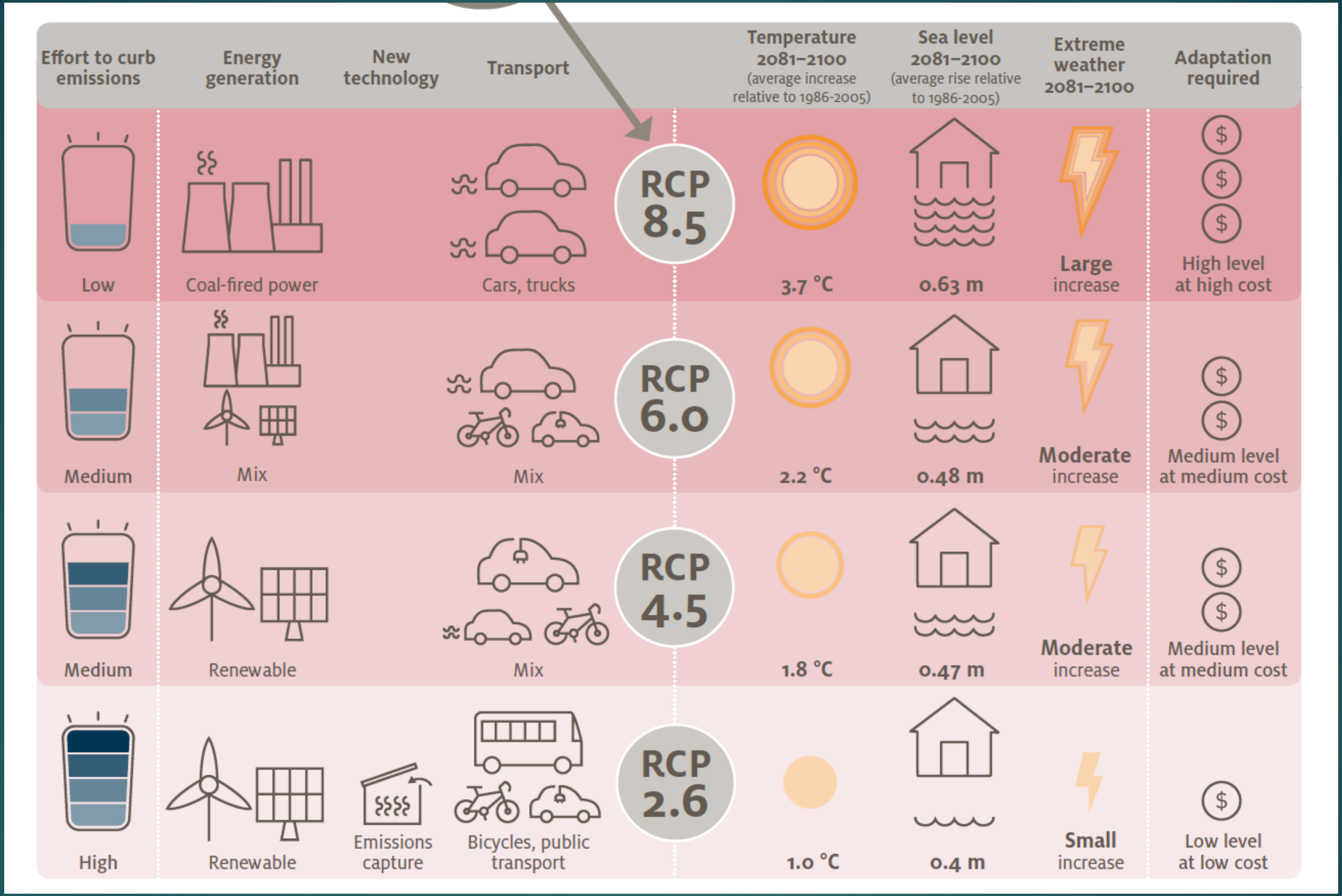



- Design of embankments and provision of remedial measures need to be rational. Frequent failures and repairs lead to high carbon emissions
- Embankments are always unsaturated in their initial state and there is a need to address the role of unsaturation and variation in design!
- Climate resilient design and analysis of embankments is the need of the hour!

# Climate change effects

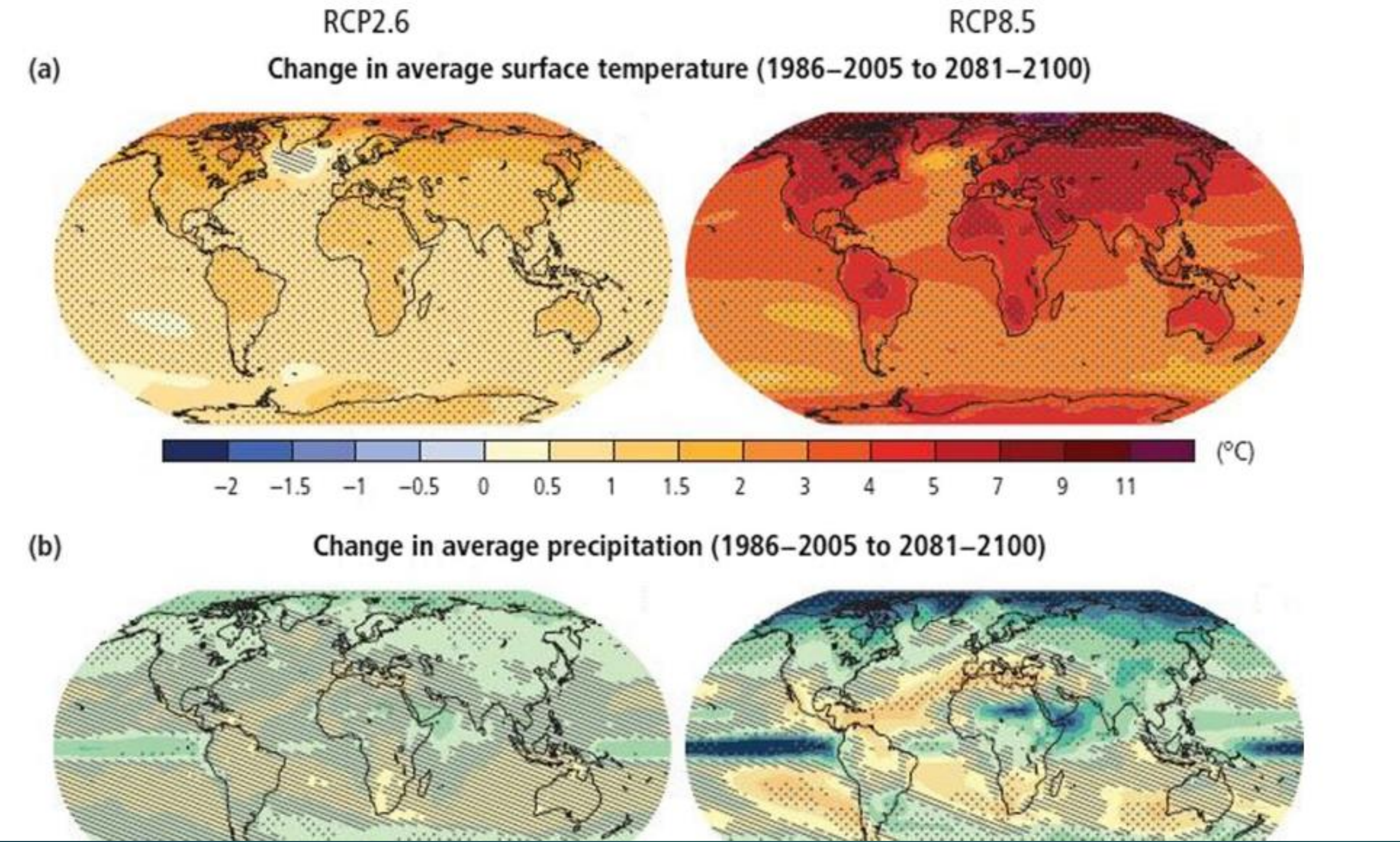


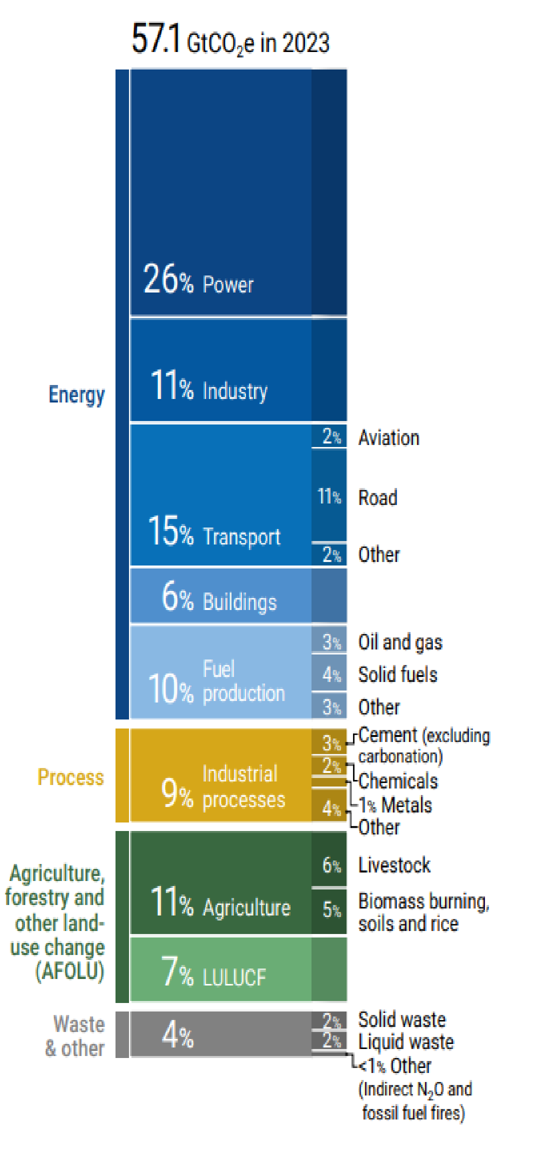

Climate change basically refers to the long-term shift in daily, seasonal, and inter-annual temperature and weather patterns and carbon emissions have significantly contributed to climate change effects. RCP 2.6 is an optimistic action plan, whereas RCP8.5 assumes almost no-action as per IPCC (2014).



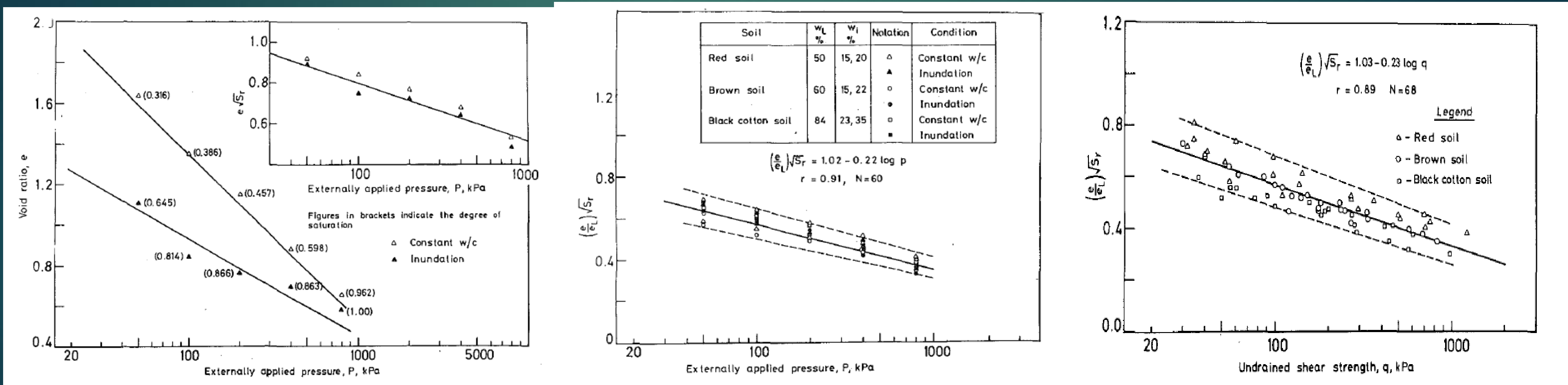

Peak radiative forcing of 3 $W/m^2$ at some time before 2100 will reduce to 2.6 $W/m^2$ by 2100

# 11% is the contribution of transport Sector in global emissions



# Results on unsaturated soils (ASCE, 1992)




**Matric suction and degree of saturation are related.**
**Complete stress strain response and deformation analysis as a function of stress level are required.**

# How Does Climate Change Affect Stability? Geotechnical perspective

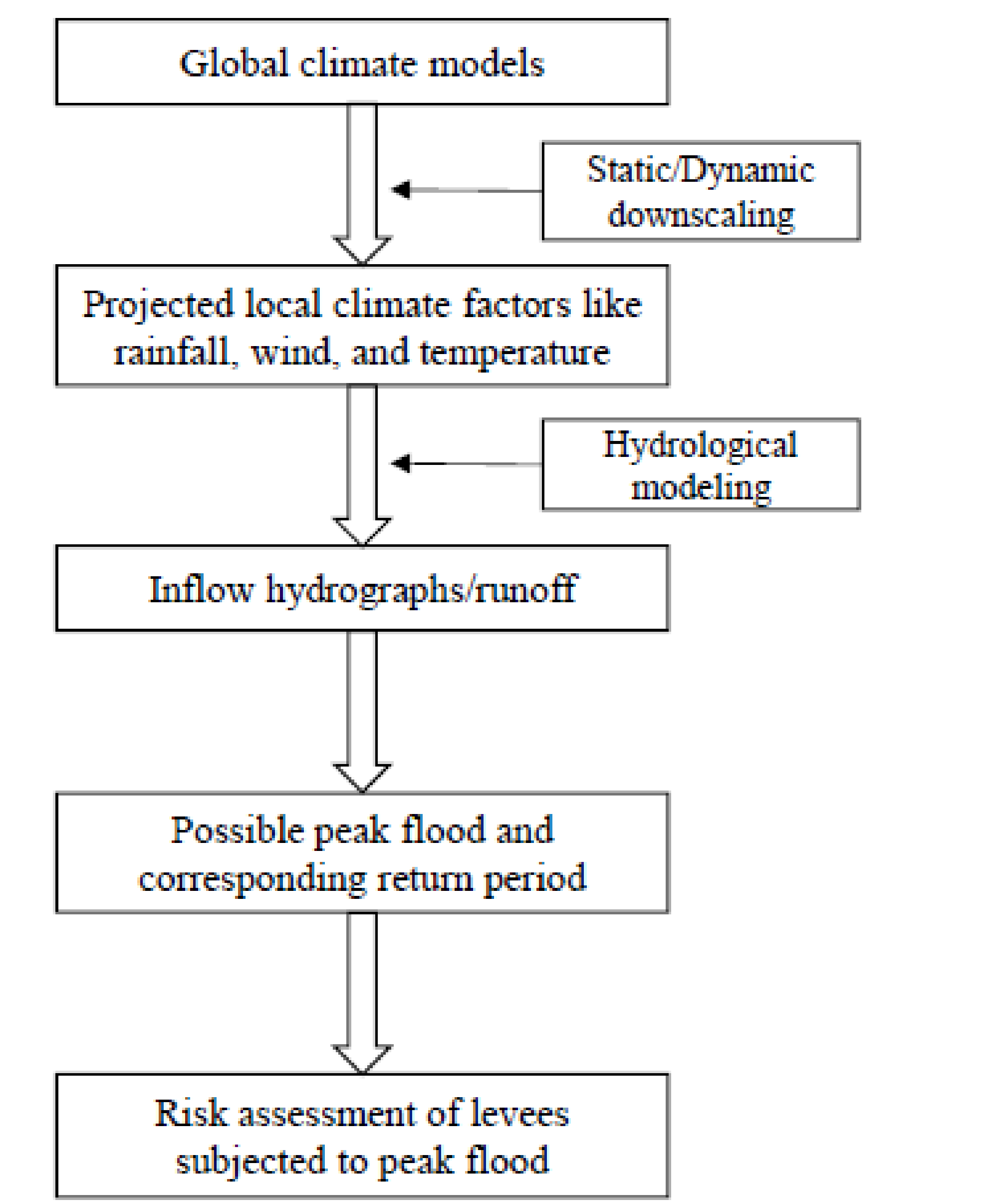
- **Soil response**
- Changes in soil moisture due to erratic rainfall patterns can reduce shear strength, leading to potential slope failure**. How does FS change?**
- Results in differential settlement, compromising structural integrity. **How does serviceability change?**
- **Hydrological Cycle**
- Increased variability in the hydrological cycle can affect the water table and stress conditions within the embankment dam. **How do load variability change?**
- Potential for erosion and internal piping due to fluctuating water levels.

# IDF Curves in the Context of Climate Change

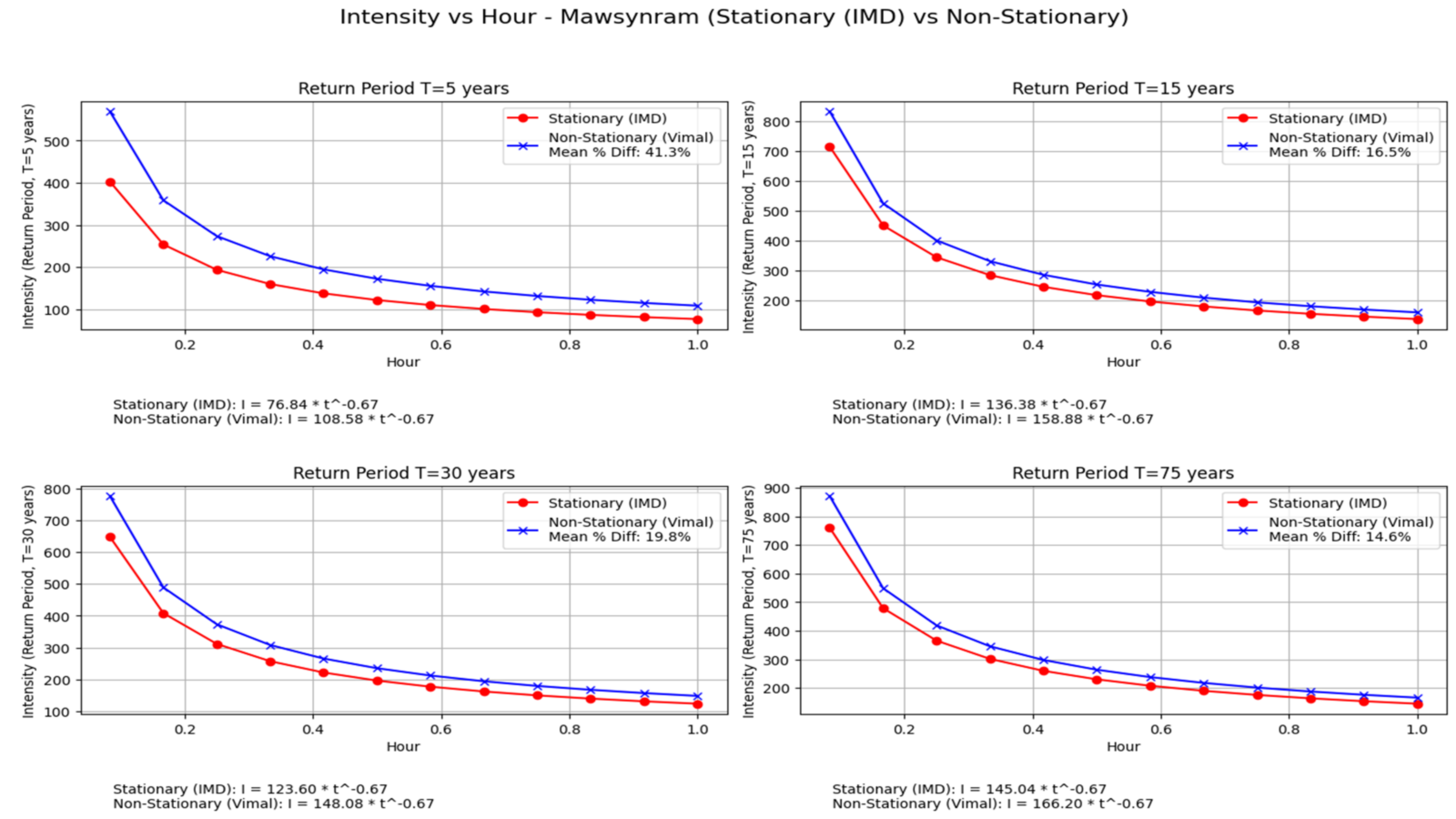
- IDF Curves and Stationarity Assumption:
- Traditional Intensity-Duration-Frequency (IDF) curves assume historical rainfall is stationary (unchanging over time).If rainfall patterns change due to climate change, IDF curves may give inaccurate estimates of future rainfall. This can lead to under-designed or overdesigned engineering projects.
- Evolving Nature of Climate Science:
- Using GCMs: Scaling IDF curves with projected rainfall from General Circulation Models (GCMs) can account for climate-induced changes in rainfall. This method theoretically includes changes caused by temperature and other weather patterns.

# Approach

- Challenges with GCMs
- Coarse Spatial Resolution:
- Biases.
- Downscaling and Bias Correction:
- Statistical Downscaling:
- Relies on distribution and relationship between observed and projected historical data.
- Dynamical Downscaling:
- Uses regional climate models forced by GCMs but requires significant computational resources and may still need bias correction.



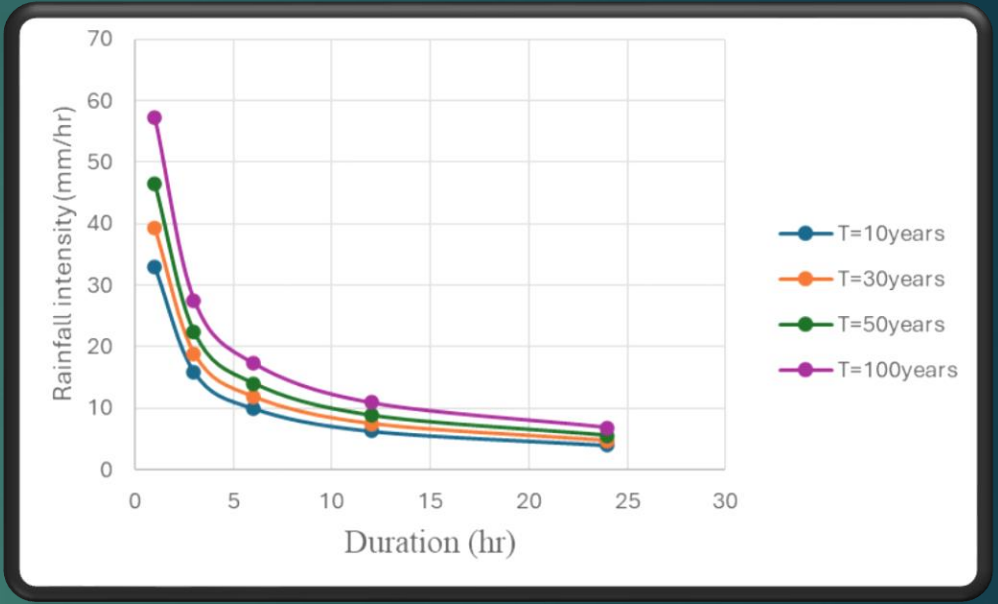
# Effect of climate change on IDFs



# Stationary IDF

The data is disaggregated for durations less than 1 h and various return period by using Eq. which is the most common rainfall disaggregation model of IDF relationship applicable to most of the geographical locations.

$$I\left(\frac{mm}{hr}\right) = A * (t + t_0)^B$$

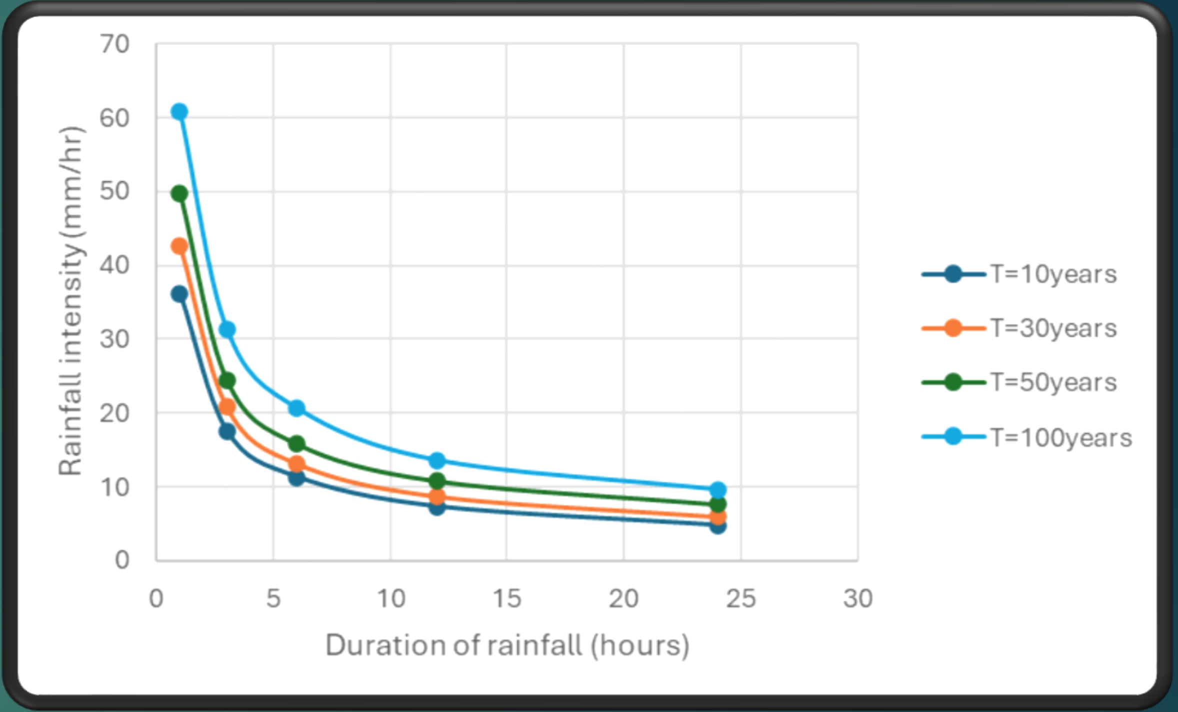



| T (years) | Coefficient A | Coefficient B | Coefficient $t_0$ |
|---|---|---|---|
| 10 | 35.8 | -0.795 | 0.1034 |
| 30 | 46.7 | -0.813 | 0.112 |
| 50 | 58.0 | -0.857 | 0.124 |
| 100 | 63.8 | -0.882 | 0.128 |

# Non stationary IDF

| T (years) | Coefficient A | Coefficient B | Coefficient $t_0$ |
|---|---|---|---|
| 10 | 36.1 | -0.745 | 0.1124 |
| 30 | 47.2 | -0.803 | 0.120 |
| 50 | 58.4 | -0.827 | 0.131 |
| 100 | 64.5 | -0.842 | 0.136 |

For the same duration, intensity of rainfall is higher.



## Effective Stresses in unsaturated soils

Terzaghi's Effective Stress (1923)

$$\sigma'_{ij} = \sigma_{ij} - u_w \delta_{ij}$$

Assuming the volume distribution in the porous medium, Bishop (1959) proposed a modified effective stress equation to take into account the effects of surface tension given by

$$\sigma'_{ij} = (\sigma_{ij} - u_a \delta_{ij}) + \chi (u_a - u_w) \delta_{ij}$$

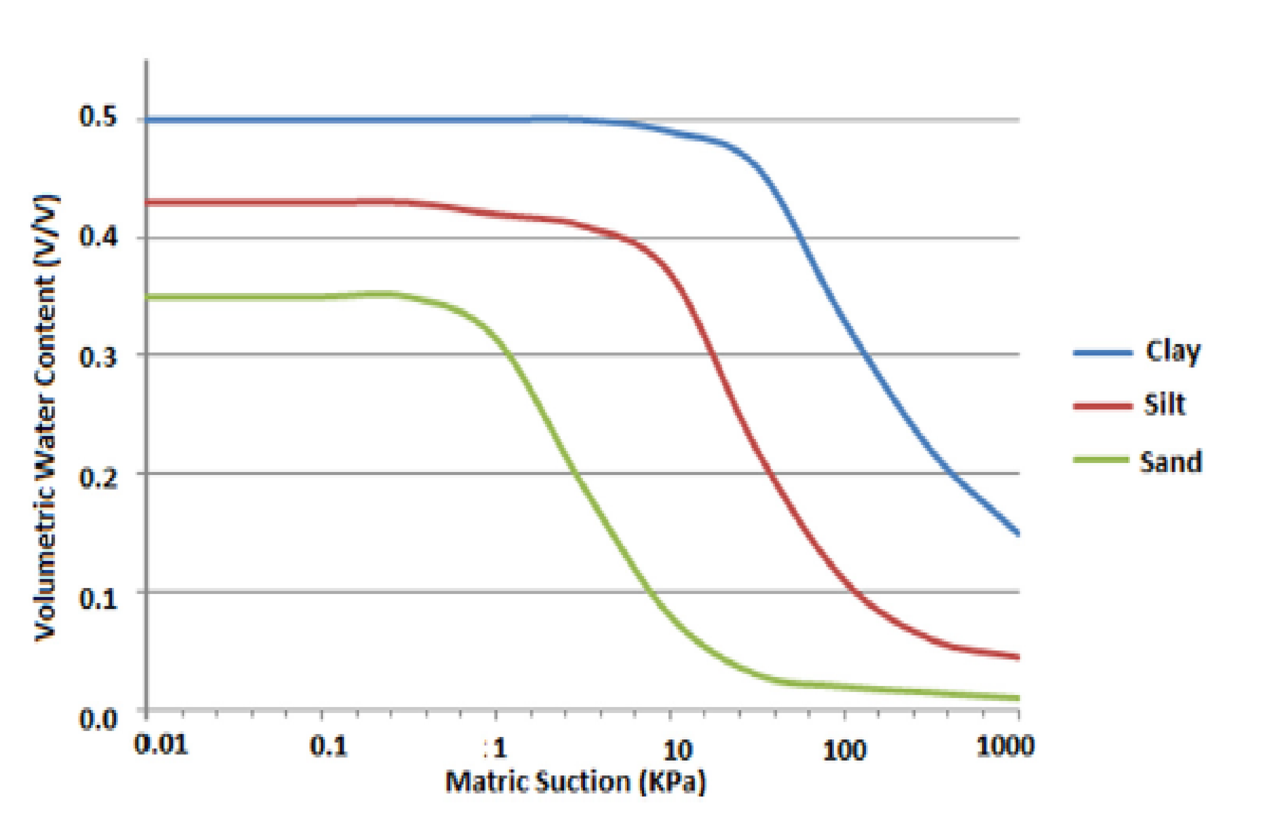
Effective Stress Parameter (χ): Varies with degree of saturation.
Limitation: Determining χ can be challenging and varies with soil conditions.

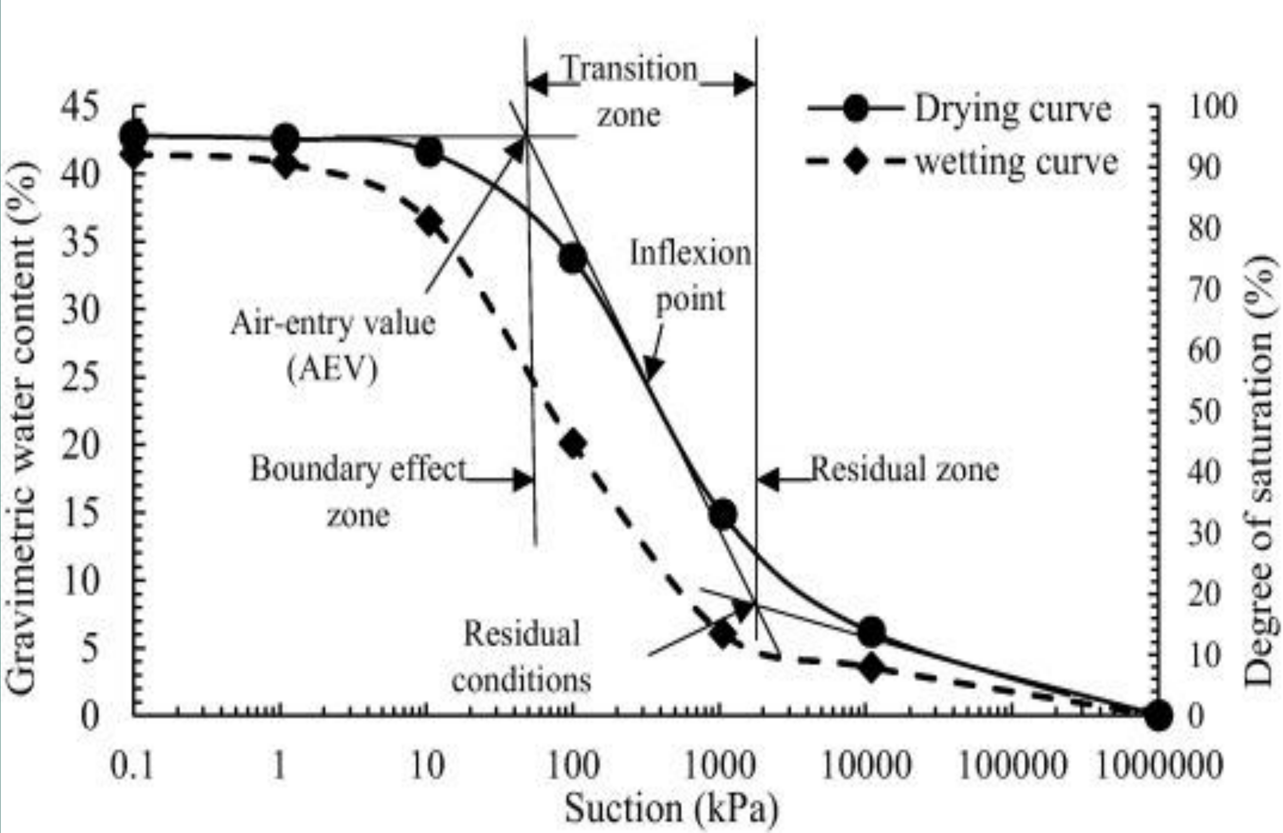
- **Inability to Explain Wetting Collapse:**
  - Wetting can lead to plastic compression not captured by traditional models.
- **Need for Multiple Stress Variables:**
  - Two stress variables proposed for better description.

$$(1)\ (\sigma - u_a)\ \text{and}\ (u_a - u_w)$$

$$(2)\ (\sigma - u_w)\ \text{and}\ (u_a - u_w)$$

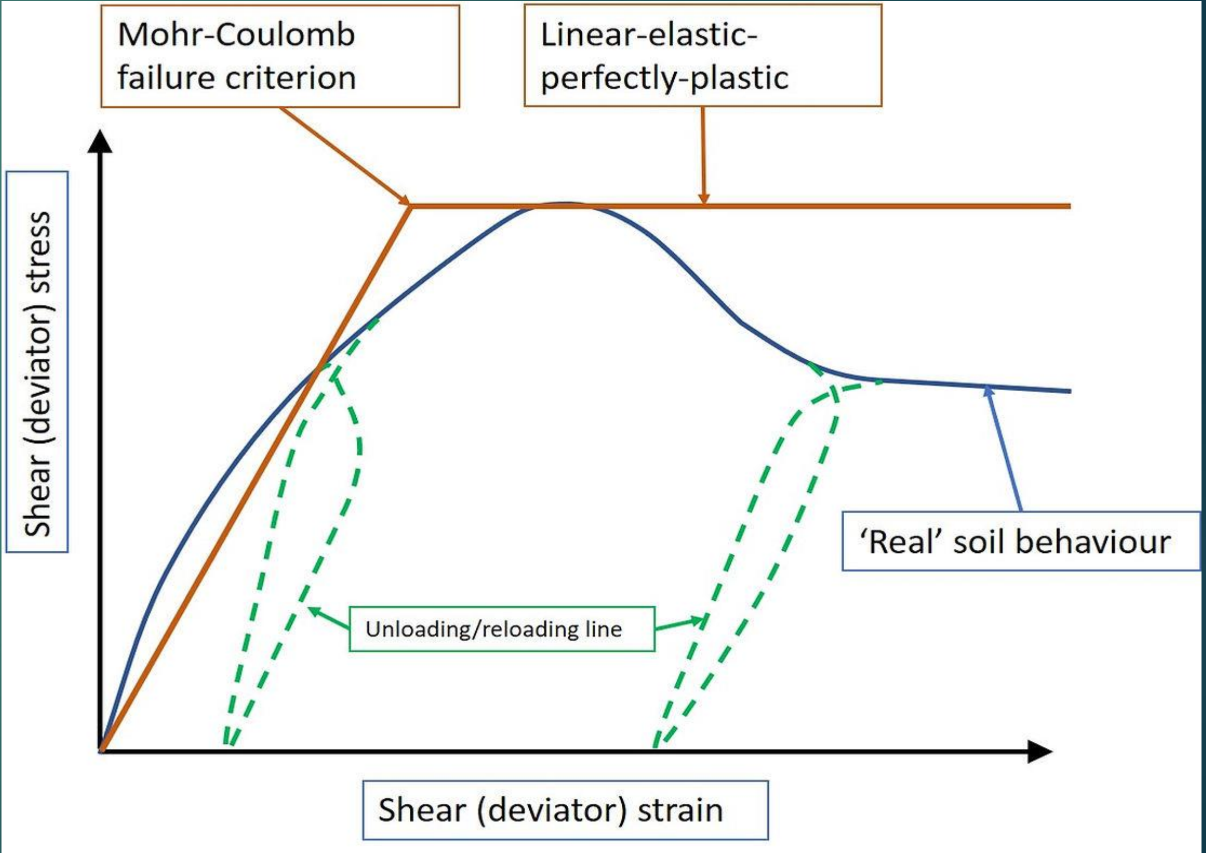
**Benefits:** Improved description of unsaturated soil behavior.
The elasto-plastic approach considers two effects of suction:
– a change in the effective stress of the skeleton with respect to equation;
– an induced suction-hardening.




# SWCC and terminology

- Mohr- Coloumb Model assumes perfect plastic behaviour, so no hardening or softening.
- It doesn't consider the impact of intermediate principal stresses
- The model approximates the failure surface to be a straight line which may not be the case.
- It doesn't consider the impact of suction.
- It doesn't consider overburden pressure.
- It predicts continuous dilation which may not be the case.



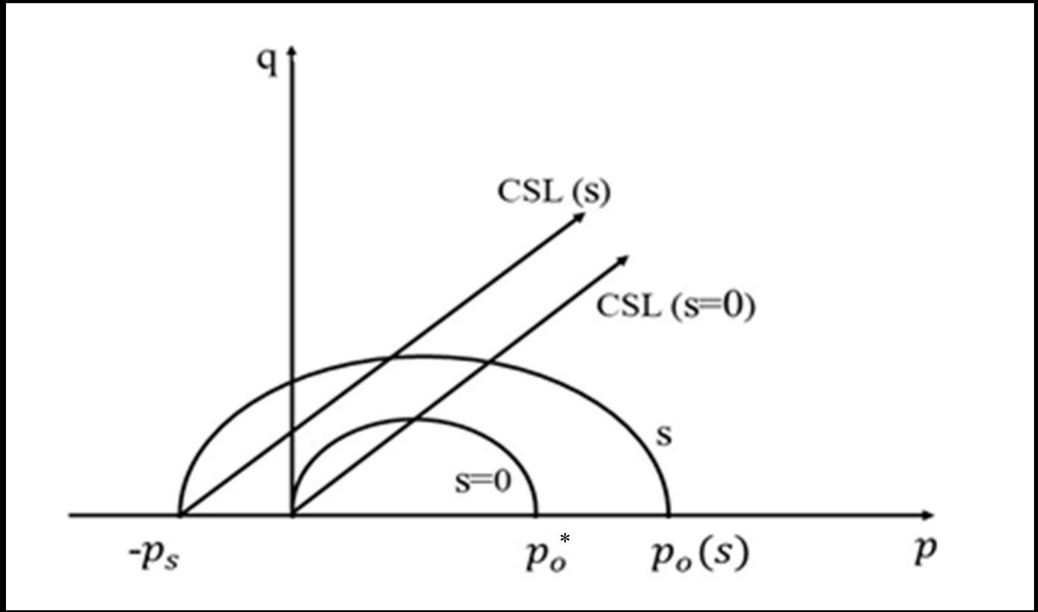

Advanced elasto-plastic critical state models should be used

# Modelling Soil Response In The Framework Of Critical State Models

- **Barcelona basic model (BBM) (Alonso et al. 1990)**

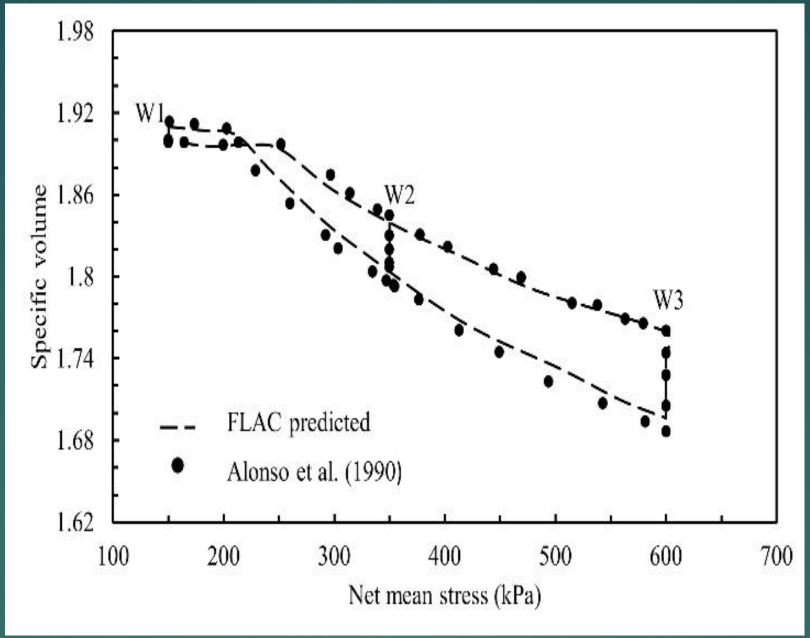
The BBM yield surface $F$ establishes a series of elliptical yield curves in the p-s (mean stress-suction) space with each curve associated with a specific preconsolidation pressure $p_o(s)$value as given by:

$$F = q^2 - M^2(p' + k_c s)(p_o(s) - p')$$




$$p_o(s) = p^c \left[\frac{p_o^*}{p^c}\right]^{\frac{\lambda(0)-k}{\lambda(s)-k}}$$

$$\lambda(s) = \lambda(0)\,[(1-r)e^{(-\beta s)} + r]$$




Comparison of the implemented BBM model in FLAC with results reported in Alonso et al. (1990)

Parameters for reference soil (Alonso et al. (1990))

| G(MPa) | $M$ | $\lambda(0)$ | $k$ | $P_0^*(MPa)$ | $k_{su}$ | $k_c$ | $r$ | $\beta$ (MPa$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| **10** | 1 | 0.2 | 0.02 | 0.2 | 0.008 | 0.6 | 0.75 | 12.5 |

# Anisotropic Barcelona Basic Model

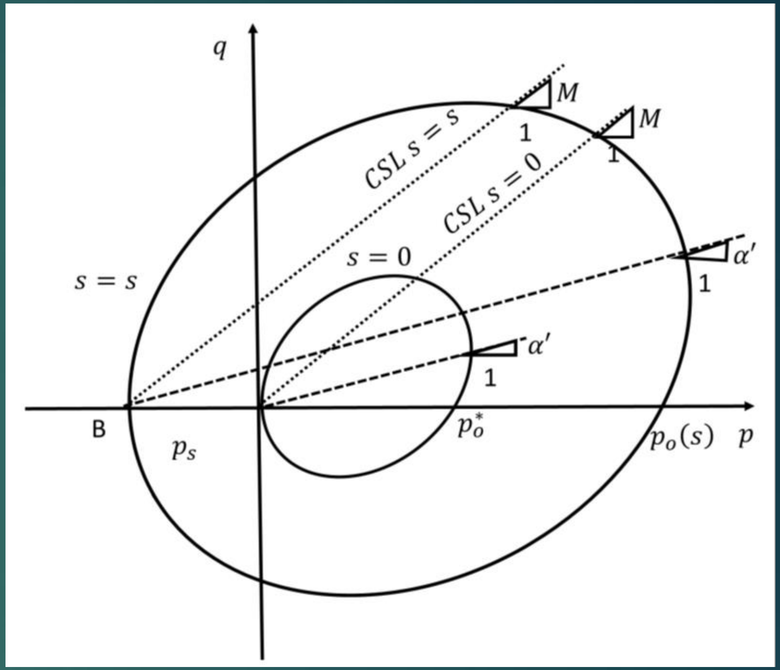
- Proposed by Al-Sharrad and Gallipoli (2014)

- By adding the computational subroutines in the fish code of Barcelona Basic model to account for anisotropic unsaturated soil behaviour

- This model assumes that anisotropy develops due to both plastic volumetric and deviatoric strains.

- The yield surface is represented by a distorted ellipse
  $f = (q - \alpha'(p + p_s))^2 - (M^2 - \alpha'^2)(p + p_s)(p_o(s) - p') = 0$
  Where $p_s$ represents the intercept of yield surface and the CSL
  as given by $p_s = a_s\left(1 - exp\frac{-s}{a_s}\right)$

- The model assumes an associated flow rule $\frac{d\varepsilon_q^p}{d\varepsilon_v^p} = \frac{2(\eta - \alpha\prime)}{(M^2 - \eta^2)}$



- To define the evolution of anisotropy in the stress space

$$d\alpha = \mu(f(\eta) - \alpha)\left[(d\varepsilon_v^p)^2 + \frac{9}{2}(d\varepsilon_q^p)^2\right]^{\frac{1}{2}}$$

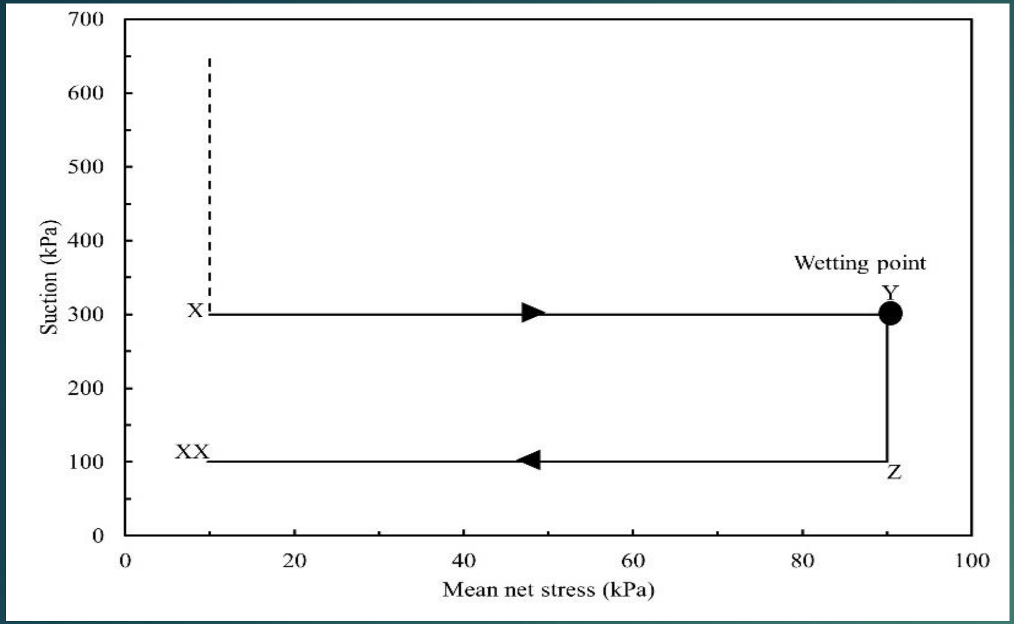
- The anisotropic distortion parameter $\alpha$ is influenced by both the plastic volumetric and plastic deviatoric strains, $d\varepsilon_v^p$ and $d\varepsilon_q^p$ and they both change the $\alpha$ value towards $f(\eta)$.

## Validation of Implemented ABBM in FLAC

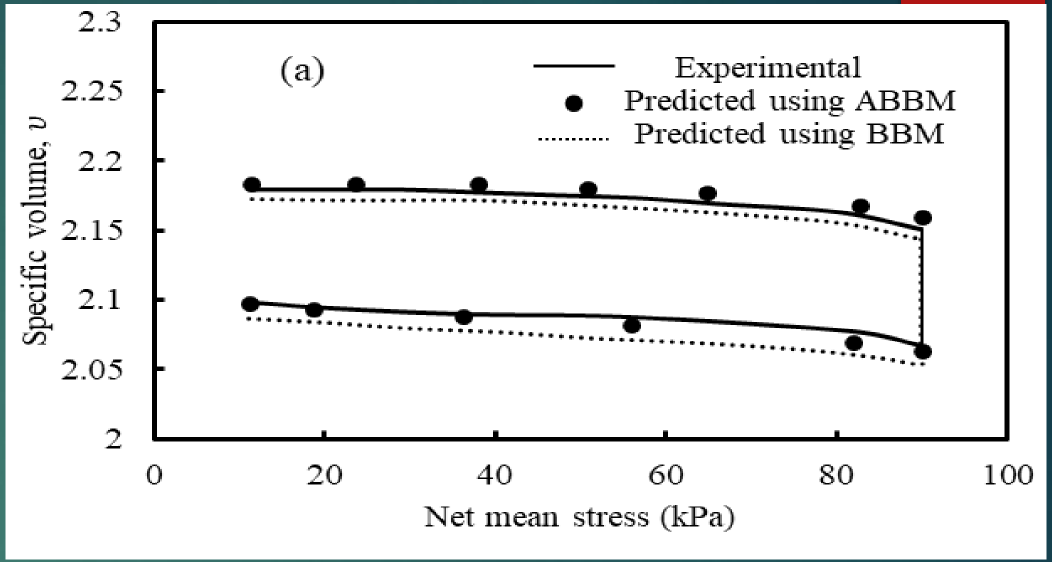
An experimental triaxial test (Bd100) involving wetting-induced collapse performed by Al-Sharrad (2013) was taken as a reference for verification of the implemented model.

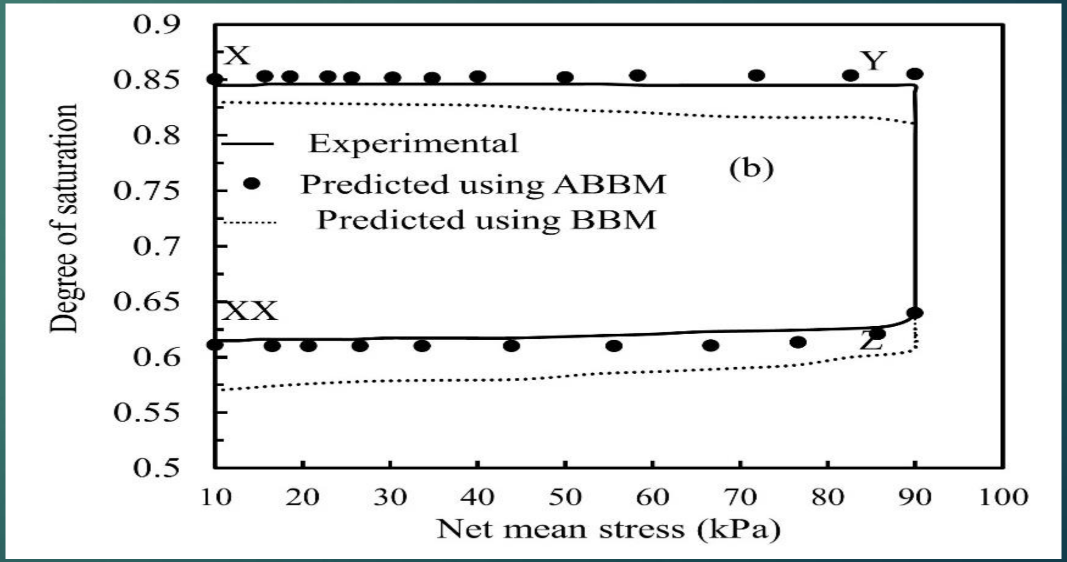
- Parameters taken for ABBM

| | | |
|---|---|---|
| $k$ = **0.012** | $r$=**4.55** | $N(0)$=**1.80** |
| $k_{su}$=**0.004** | $\beta$=0.0008kPa$^{-1}$ | $a_s$=216.6kPa |
| $G$=**9960MPa** | $M$=0.737 | $\mu'$=15.24 |
| $\lambda(0)$=**0.157** | $p^c$=696kPa | $c''$=0.294 |




Stress path for the wetting-induced collapse



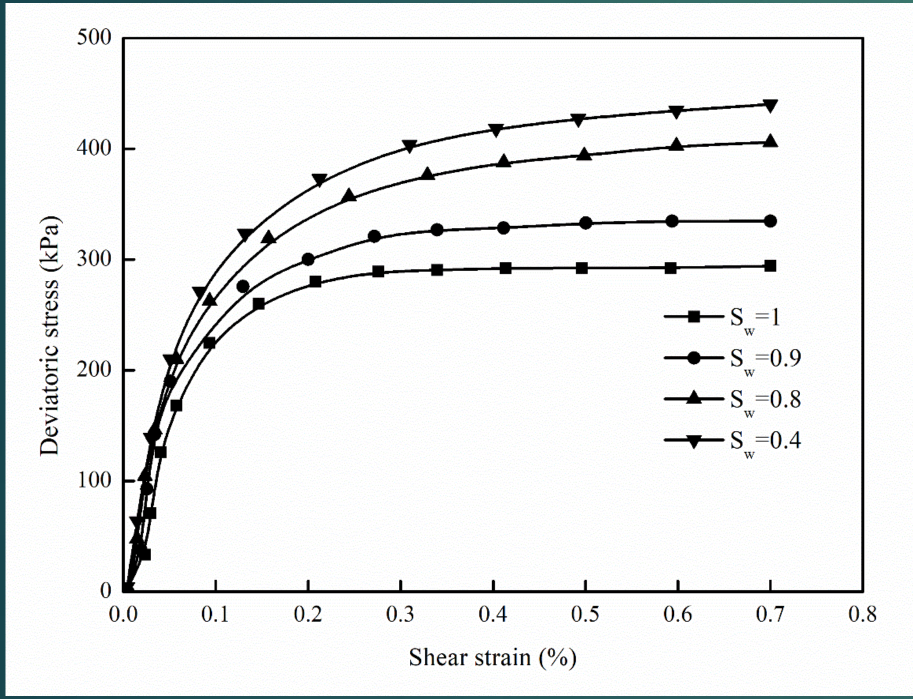




Verification of the implemented ABBM model a) Specific volume plot b) Degree of saturation vs net mean stress

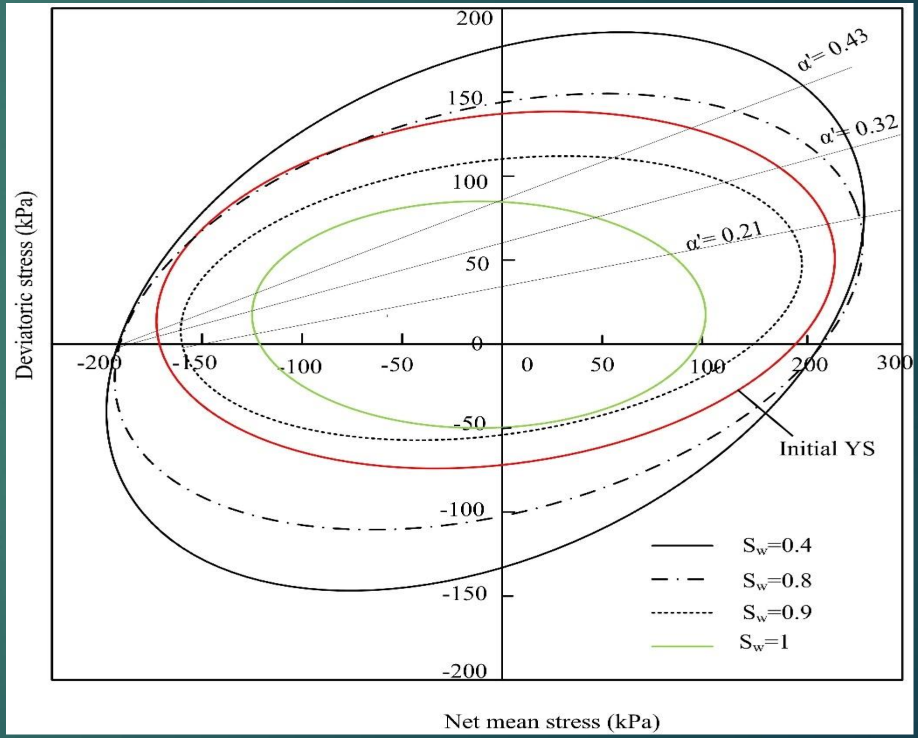
# Relationship Between Degree Of Saturation ($S_w$) And Fabric Anisotropy ($\alpha'$)

- Estimation of collapse is necessary for the performance assessment of the embankment upon rainfall.

- To establish an explicit relationship between $S_w$ and $\alpha'$, data was taken considering the work of researchers like Romero and Jommi (2008); Al-Sharrad (2013); Chen et al. (2019); Ip and Borja (2022) $\alpha' = -1.69\, S_w^2 + 1.76\, S_w$




Stress strain plots at various degree of saturation

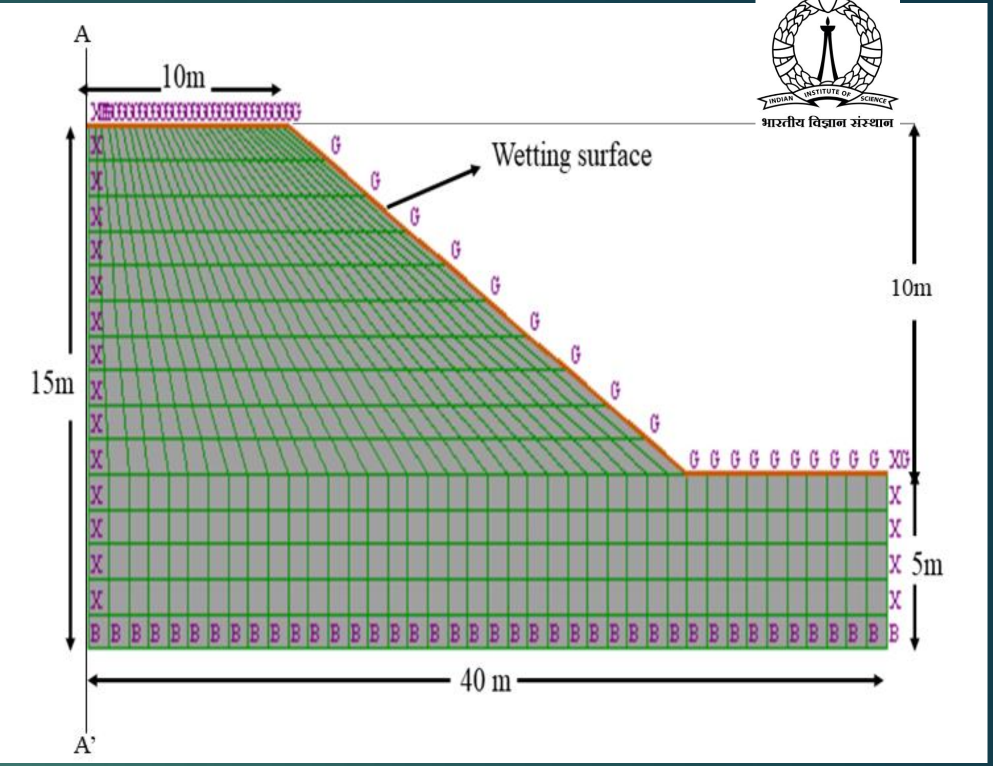



Evolved yield surfaces at various degrees of saturation

# Simulation of Embankment response

The analysis was conducted in FLAC, in which the model was created and subjected to gravity and two-phase flow

| Parameter | Value |
|---|---|
| **Wetting fluid density (kg/m$^3$)** | 1000 |
| **van Genuchten parameter, n** | 0.336 |
| **van Genuchten parameter, $P_O$ (Pa)** | 15000 |
| **Wetting fluid modulus (MPa)** | 1.0 |
| **Non-wetting fluid modulus (Pa)** | 1.0 |
| **Residual saturation** | 0.0 |
| **Mobility Coefficient (m$^2$/(Pa-sec))** | $10^{-9}$ |
| **Initial void ratio** | 0.5 |

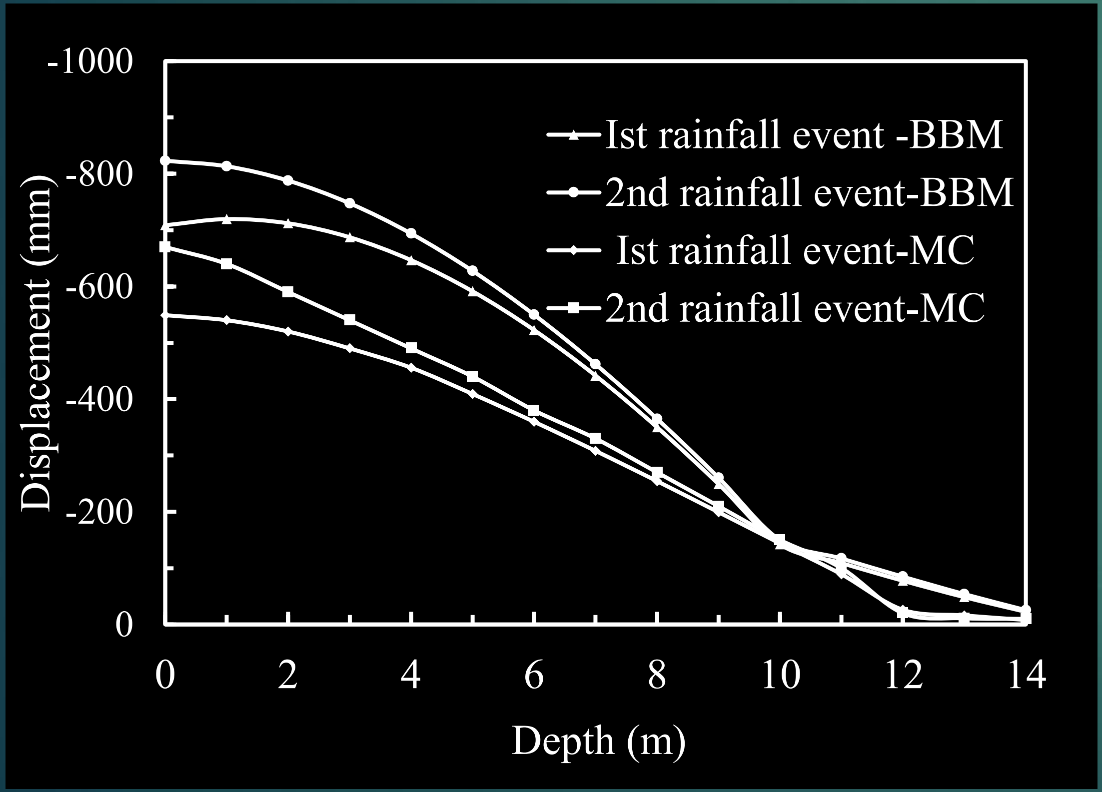


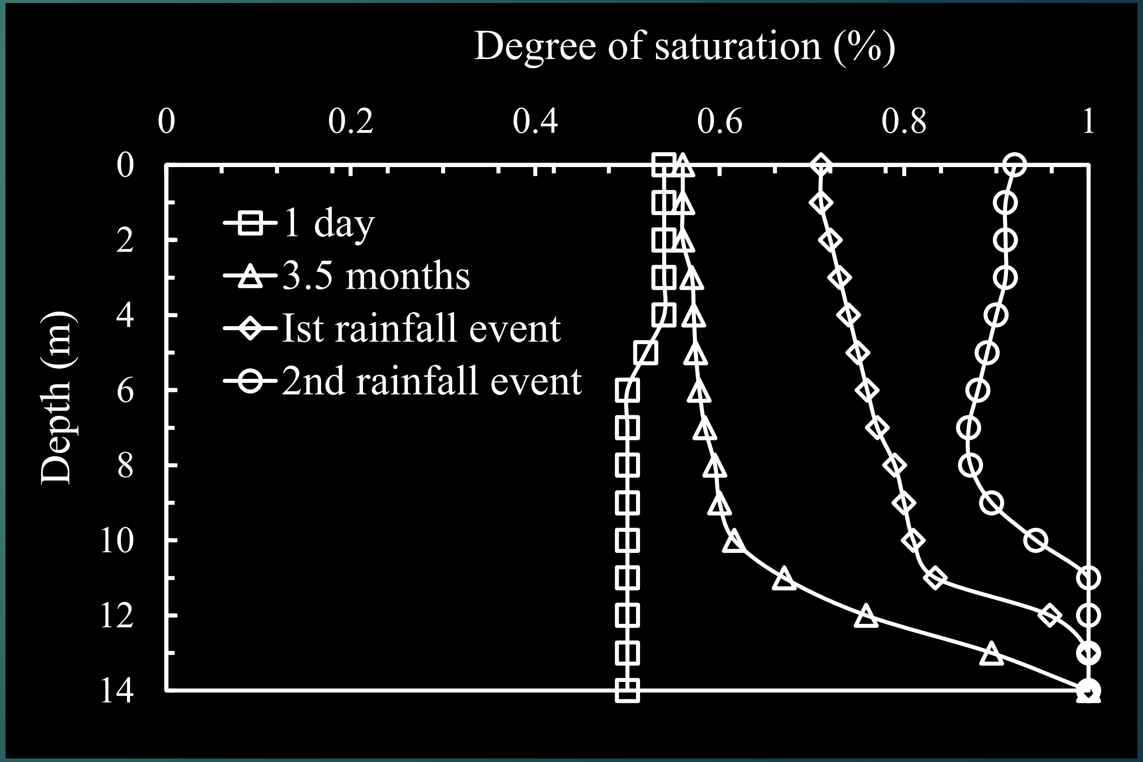

To introduce anisotropy in the embankment, the top 10m of embankment fill with a slope angle of 26.5° was constructed in 10 lifts

# Deterministic Analysis of Embankment Based On BBM

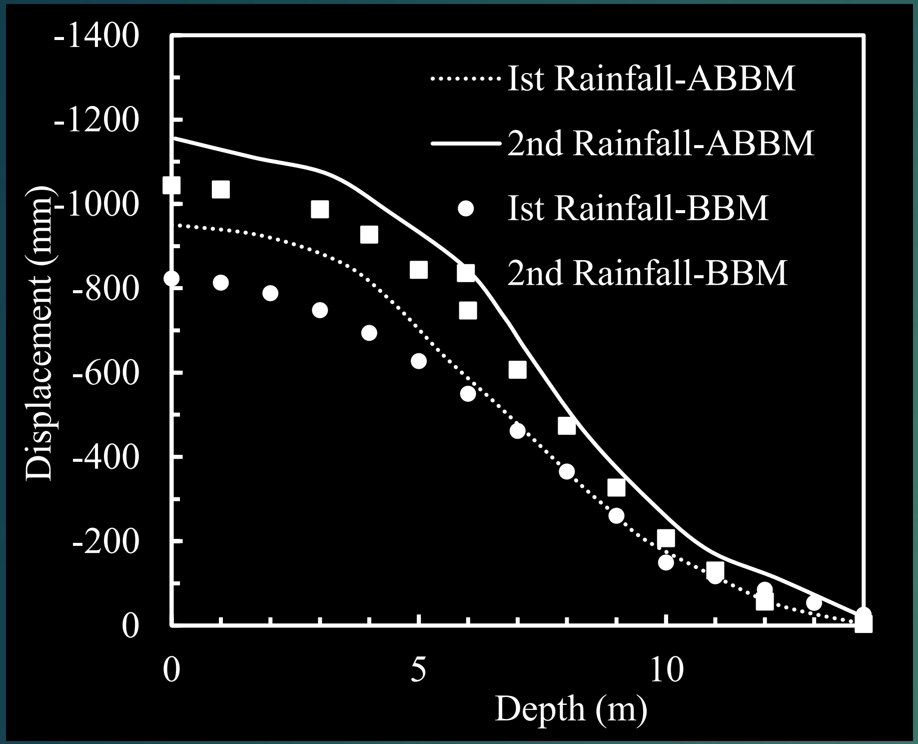
Mohr-Coulomb model with friction angle equal to 23º, and secant modulus $E$ equal to 32 MPa

- Rainfall infiltration was applied over the slope by considering two rainfall intensities viz; first 560mm of rainfall accumulated for a period of 7 months and second rainfall of 312mm accumulated for four days.

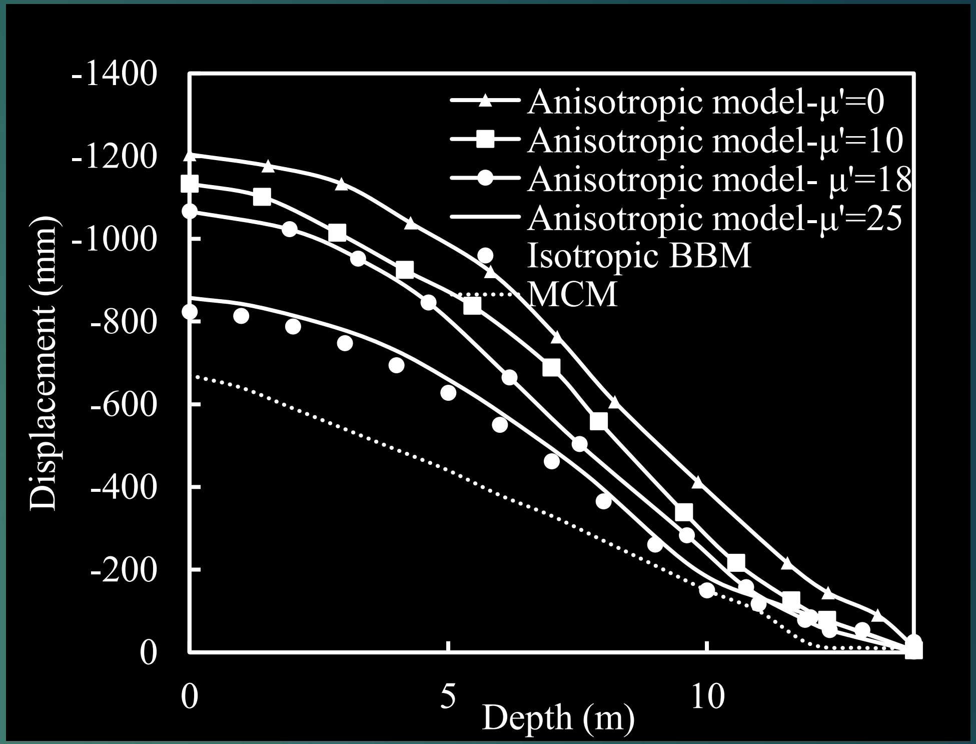


# Deterministic Analysis Based on ABBM




Displacements generated using ABBM and BBM




Variation of surface displacements at various values of $\mu'$

# Variability (in CoV)

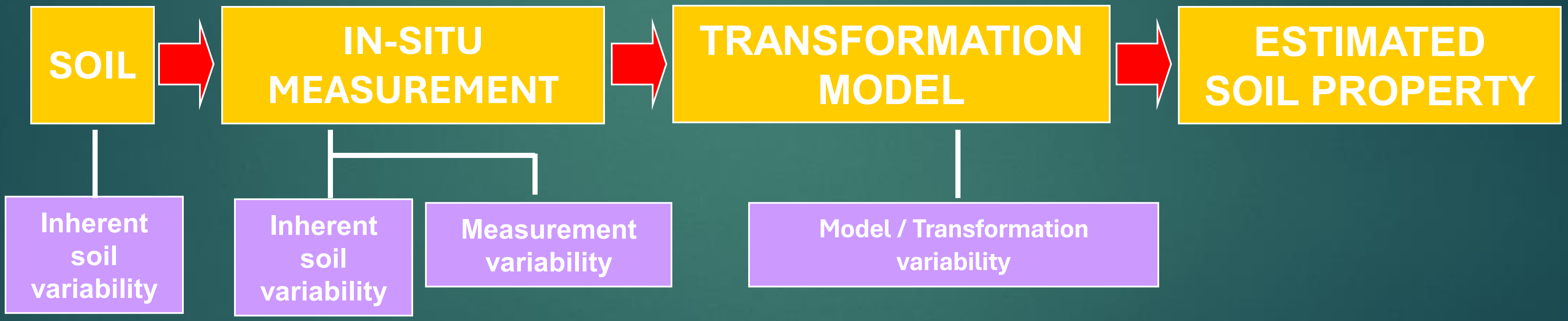
| | | |
|---|---|---|
| Concrete flexure beam | 8%-14% | Concrete, steel, aluminum are manufactured in controlled condition |
| Short Columns | 12%-16% | |
| Steel member | 11% | |
| Aluminum member | 8% | |
| Timber beam | 18% | |
| **Undrained shear strength of soil** | **13%-40%** | **Natural material, formation under complex processes** |
| **Coefficient of permeability** | **68%-90%** | |
| **Coefficient of consolidation** | **33%-68%** | |
| **SPT-N value** | **15%-45%** | |
| **Cone penetration value** | **15%-37%** | |

**Variability associated with rainfall, wind loads, earthquake loads is very high.**

# Variability Models

- Aleatory: Natural variability of soil → **Inherent variability**

  Example: General soil profile
- Epistemic: Lack of knowledge → Variability due to simplified and idealized design calculation and statistical models. **Model variability/ Transformation uncertainty**
- Measurement variability: During field/laboratory tests

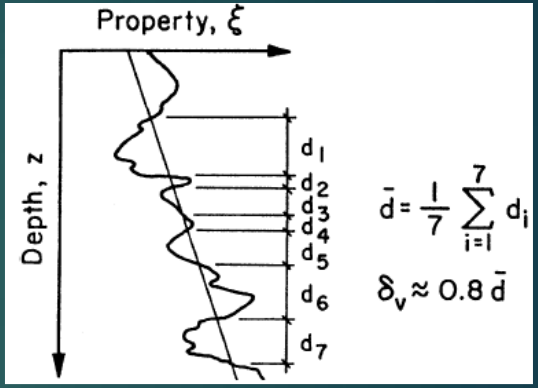


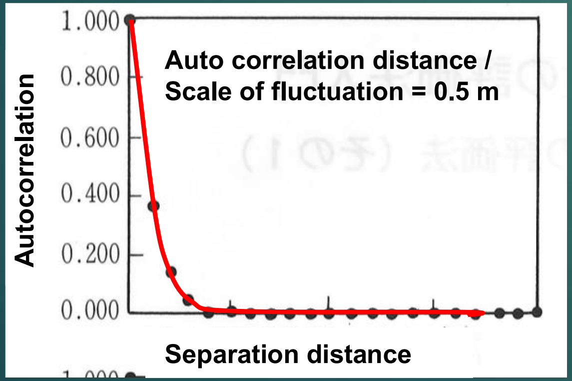

**Estimation of soil variability**

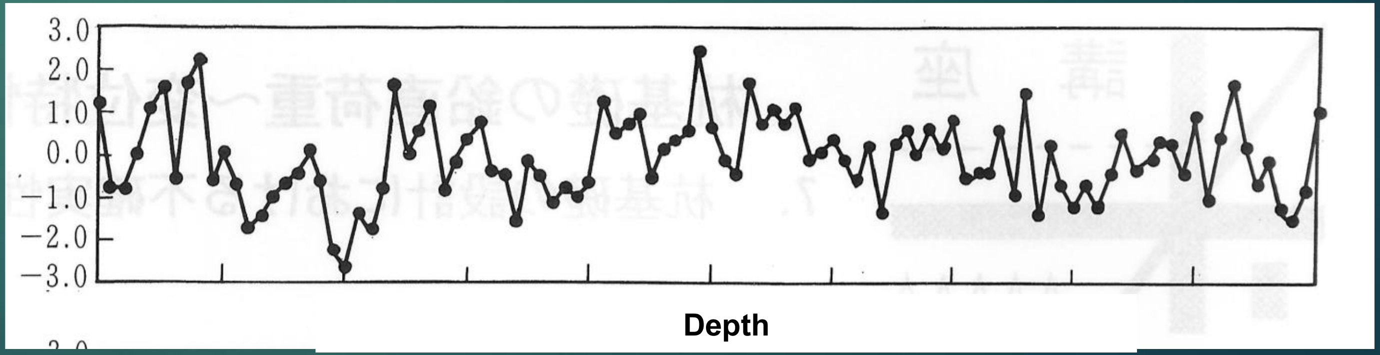
**Source: Phoon and Kulhawy (1999)**

# Variability Models

- Mean values, CoV, Autocorrelation functions for analysis and design
  - **Scale of fluctuation**: Measure of the distance of separation at which two soil samples are considered reasonably correlated
  - **Random field:** Soil properties vary from point to point of any soil deposit → random field theory→ (inherent variability, scale of fluctuation)



# Basic Design Philosophy

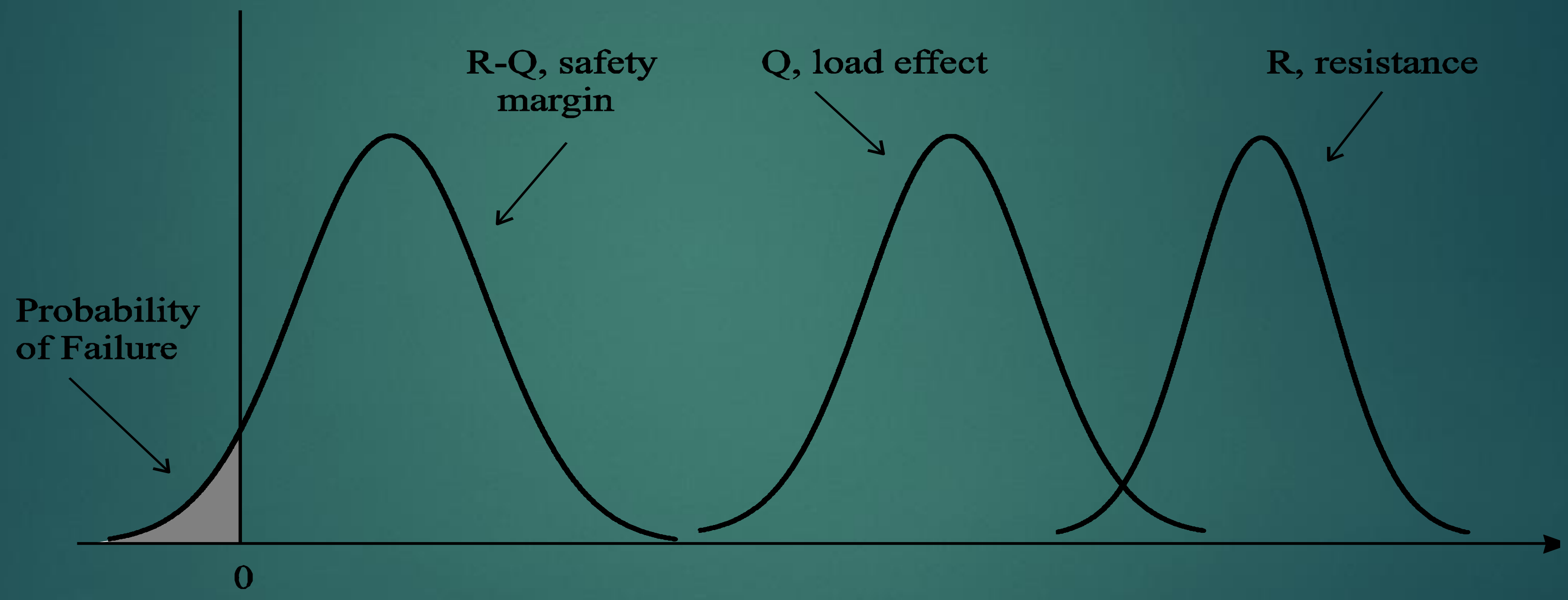
**Capacity (C) > Demand (D)**
**Resistance (R) > Load (S)**

**FS=C/D or R/S**

**How much capacity should be more than the demand?**

- Theoretically, just more
- However, designers provide a lot more
- Why? Because of Uncertainty and Unforeseen factors

# Safety Margin, g = R – Q
# what is the probability g < 0?



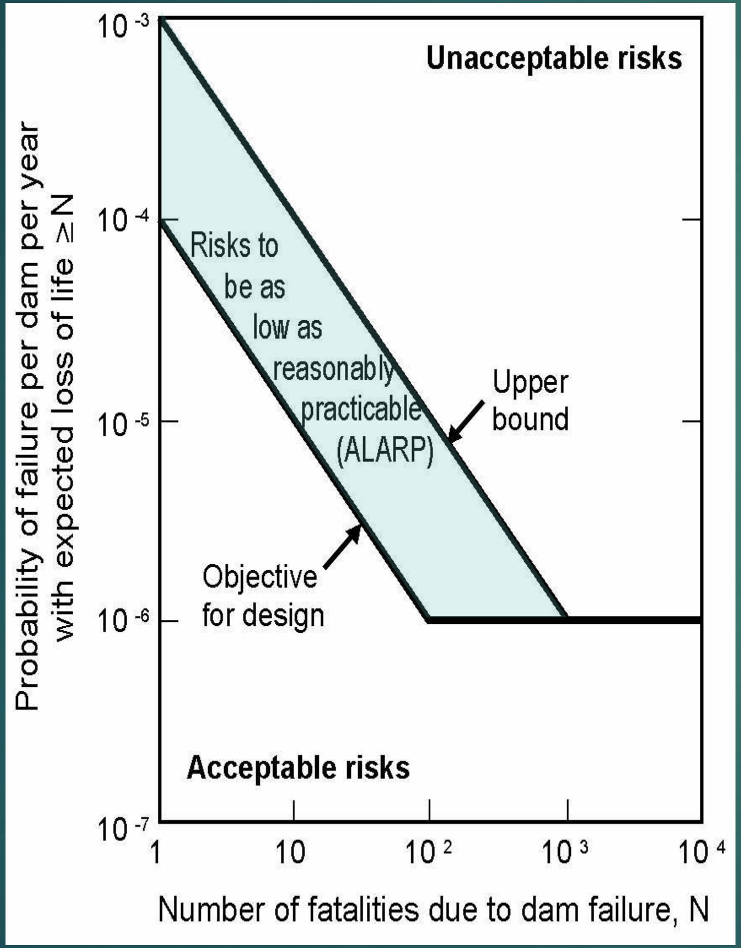

**Pdfs of load, resistance and safety margin**

# Reliability and Risk (Probability of Failure)

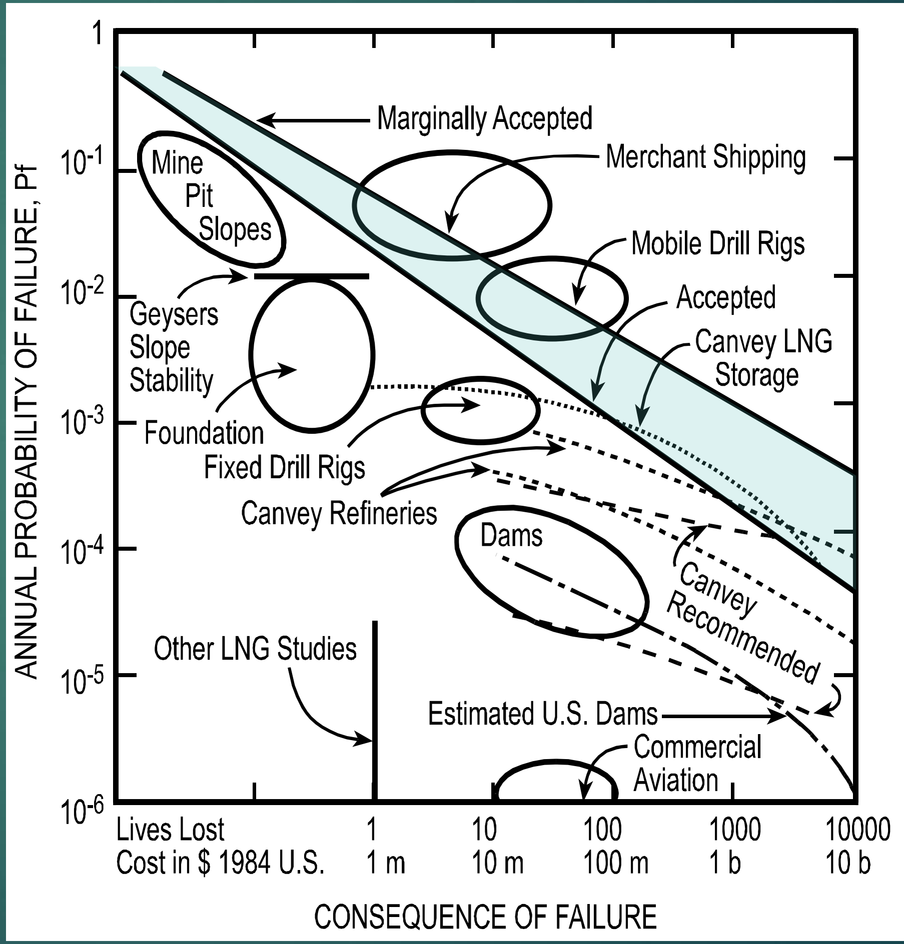
- Reliability = probability that the structure will perform its function during the predetermined lifetime
- Risk (or probability of failure) = probability that the structure will fail to perform its function during the predetermined lifetime
- Risk also includes consequences in terms of expected losses of lives, Number of persons exposed to a hazard, monetary units

# Acceptable risk






ANCOLD(1996)



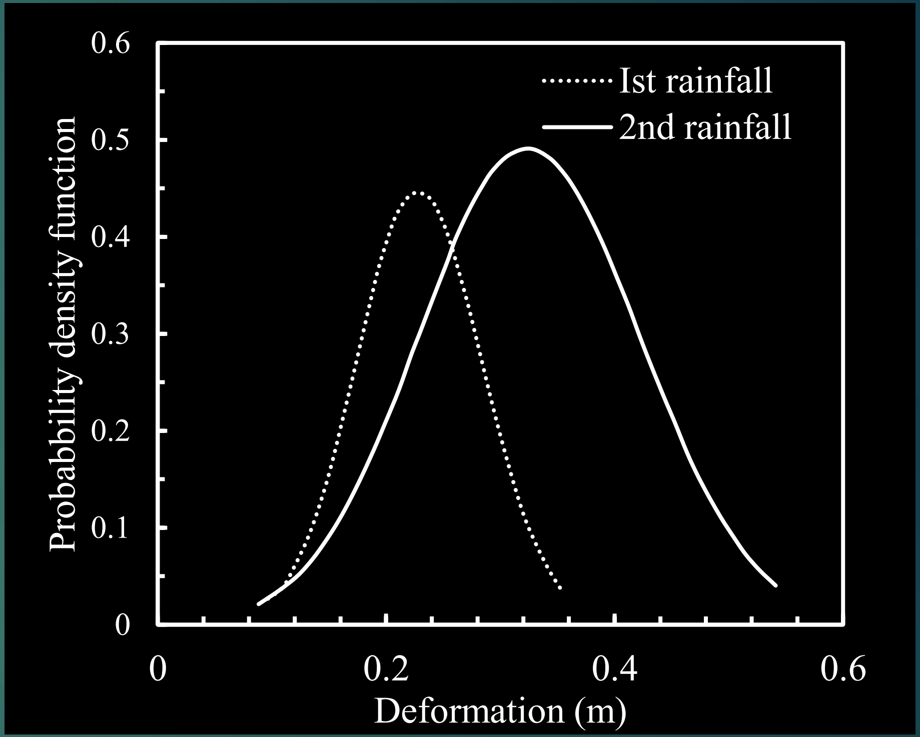

WHITMAN (1984)

# Need for reliability and risk-based designs

- Factors of safety for design do not consider variability explicitly
- Geotechnical Infrastructure needs better design procedures
- Natural causes (rainfalls, earthquakes, floods, multi hazards)
- Man-made causes (poor maintenance, quality control measures, contamination in the case of geoenvironmental engineering problems)
- Limited available resources (the needs must be prioritized, Cost optimization considering safety is required)
- Methods for design are well developed, but methods of uncertainty analysis need to incorporated in design.

# Reliability Analysis

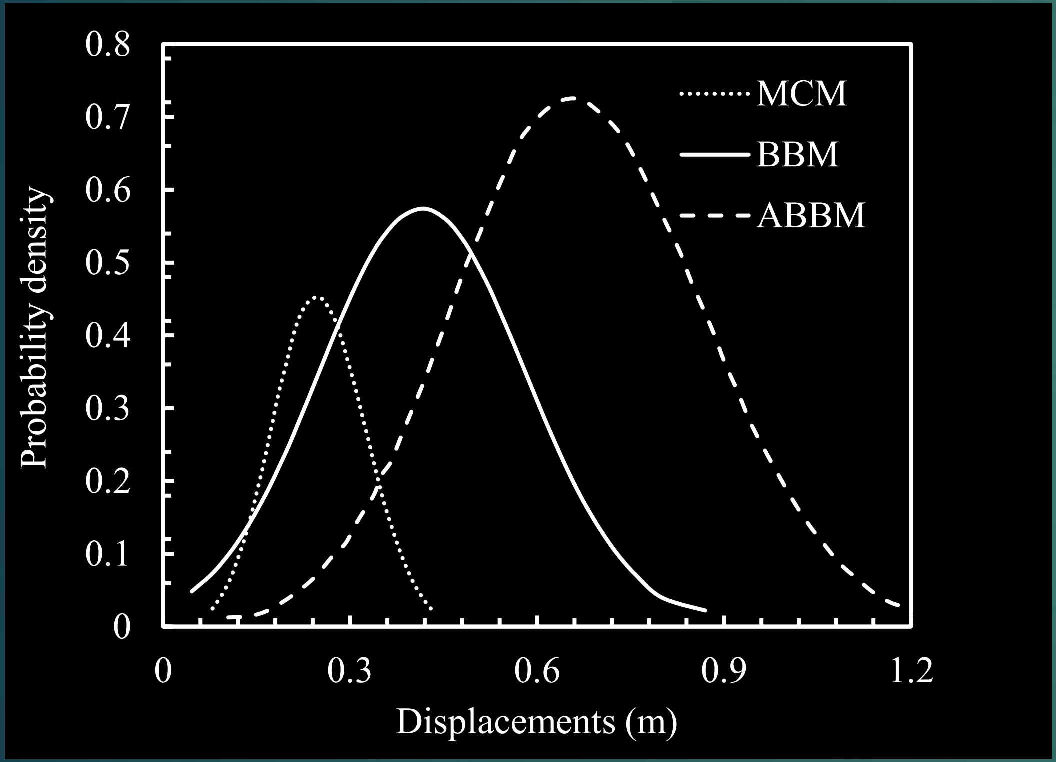
- Normally distributed with COV's to be 20% for $m$, 20% for $\alpha$ and 80% for $k_s$ (Babu and Srivastava 2008, Raghuram and Basha 2018).
- $10^5$ simulations using MCS were found to give accurate results with a correlation coefficient of 95%.



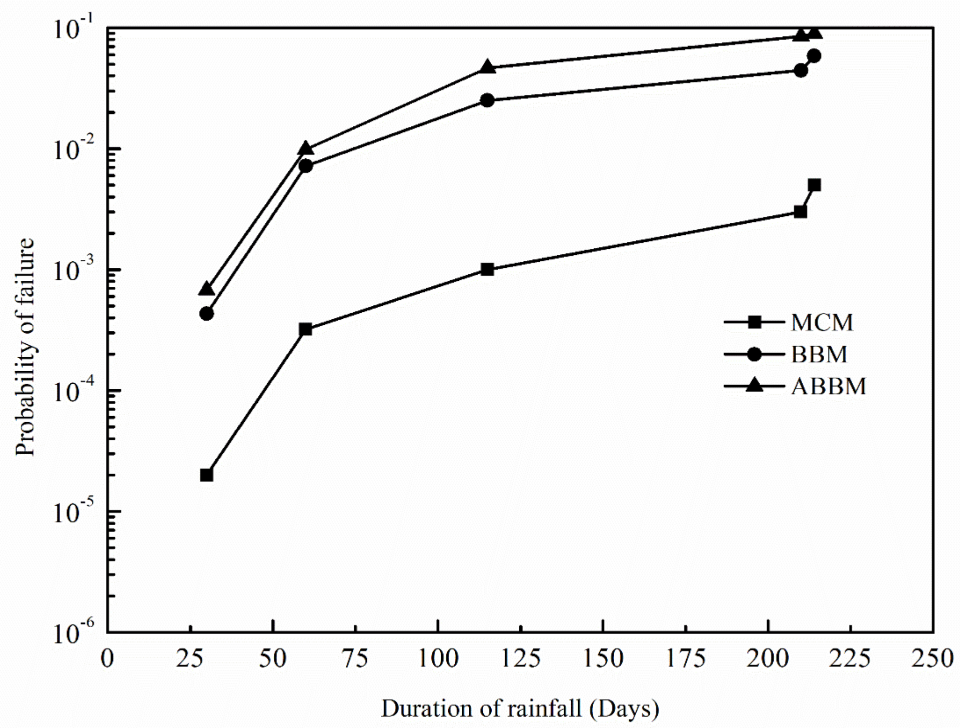

After carrying out MCS, it was observed that

$P_f$ increased after the end of second rainfall

- **Monte-Carlo Method Based on Comparison of Different Constitutive Models**
- The mean and COV of the random variables ($E$ , $\phi$) are provided as 10000kPa and 12% and 31° and 10%, following a normal distribution




Probability distribution of displacements using MCM, BBM and ABBM




Variation of $P_f$ of the embankment with the duration of rainfall

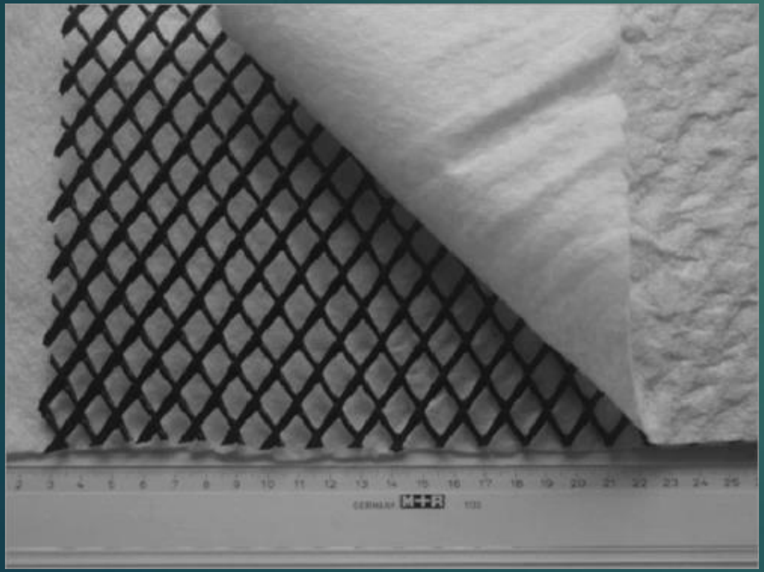
# Analysis of embankment dam response with geocomposite

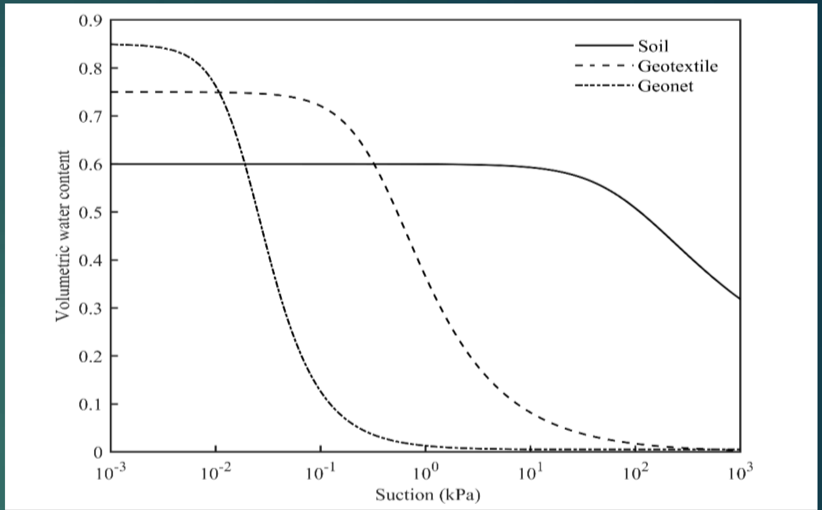
- To study the effect of geocomposite layer on the hydraulic and mechanical behaviour of an unsaturated embankment
- To carry out the probabilistic analysis (variables; hydraulic parameters of soil like hydraulic conductivity ($k\_sat$ ) and SWCC parameters ($\alpha$,$m$).
- To carry out a sensitivity analysis to determine the parameters which mostly influence the drainage behaviour.

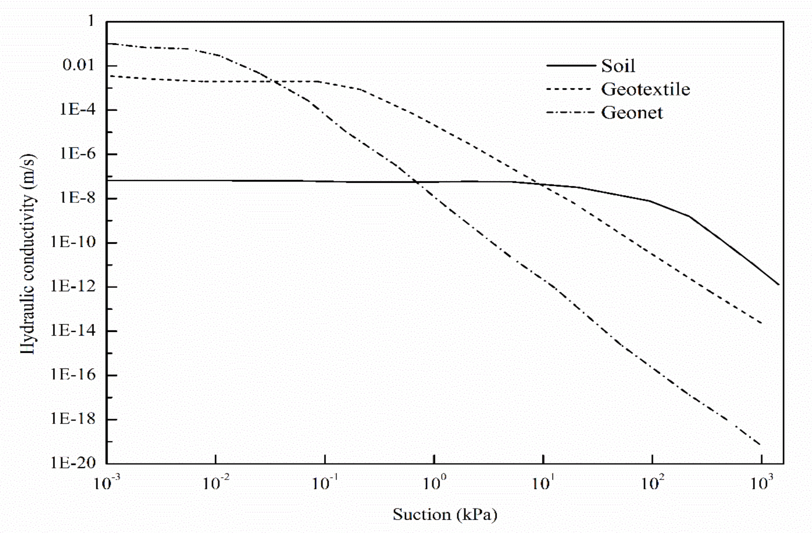
# Hydraulic Characteristics Of Soil And Geocomposite

## Hydraulic properties of soil and geocomposite

| Materials | $S_{rmax}$ | $S_r$ | α (1/kPa) | $n$ | $k_{sat}$(m/s) |
|---|---|---|---|---|---|
| Embankment soil | 0.38 | 0.05 | 0.065 | 1.506 | $10^{-6}$ |
| Geotextile layer (Stormont and Ramos,2001) | 0.75 | 0 | 2.577 | 1.68 | $2.89 \times 10^{-3}$ |
| Geonet (Ramos, 2001) | 0.85 | 0.005 | 50.251 | 2.19 | $1 \times 10^{-1}$ |





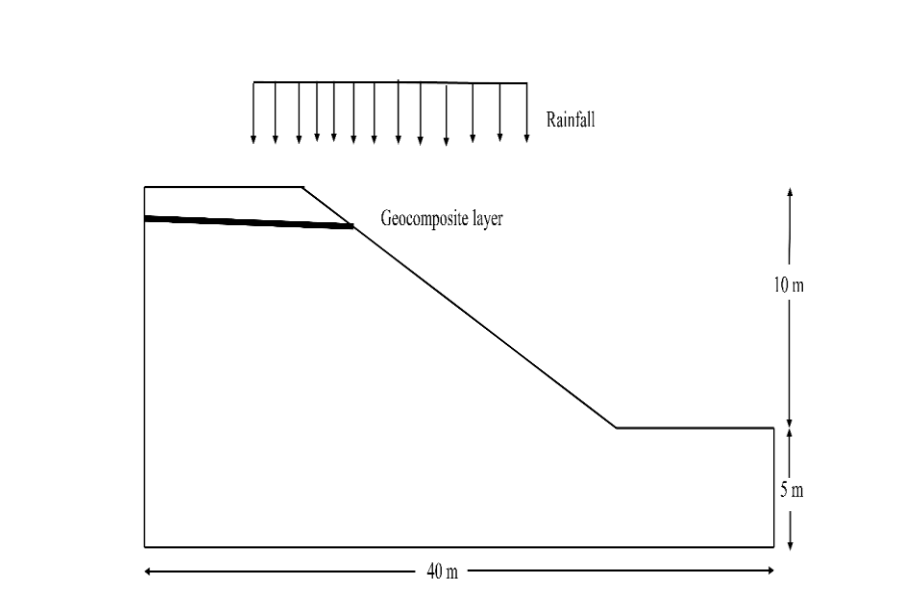

Hydraulic conductivity curves of soil and geocomposite layer

# Deterministic Analysis Of Drainage Layer

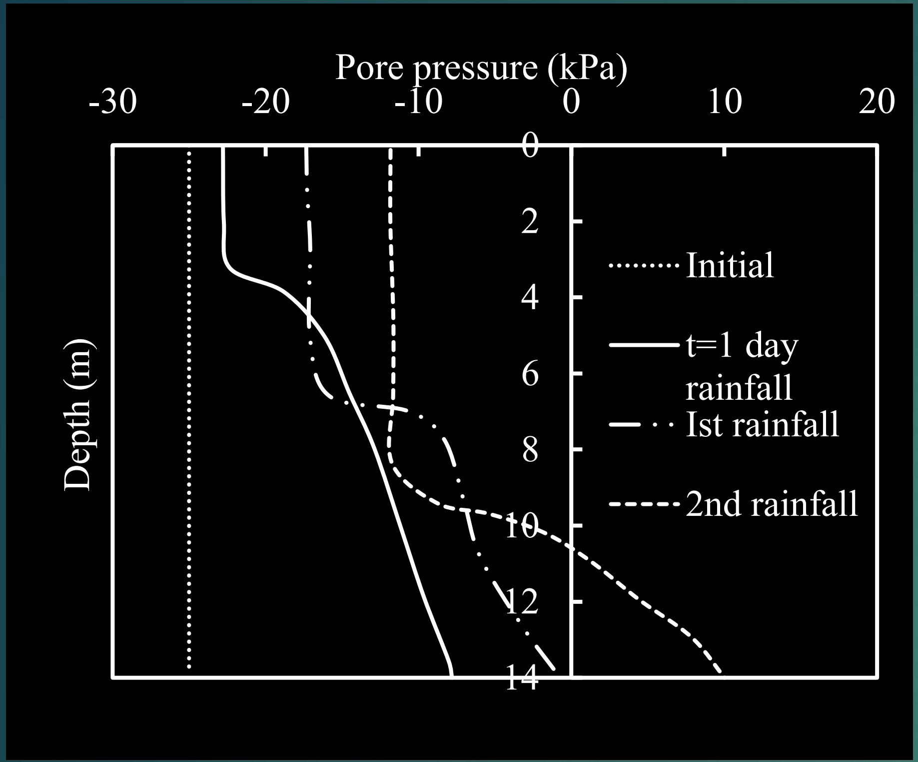
For modelling drainage in FLAC, the geocomposite layer was modelled by suitability of grid points and fixing the pore pressure equal to zero along the nodes

A geocomposite layer with geonet of thickness 3mm and 5mm thick geotextile was placed at a slope of 3% and at a depth of 1m from the top surface in the embankment

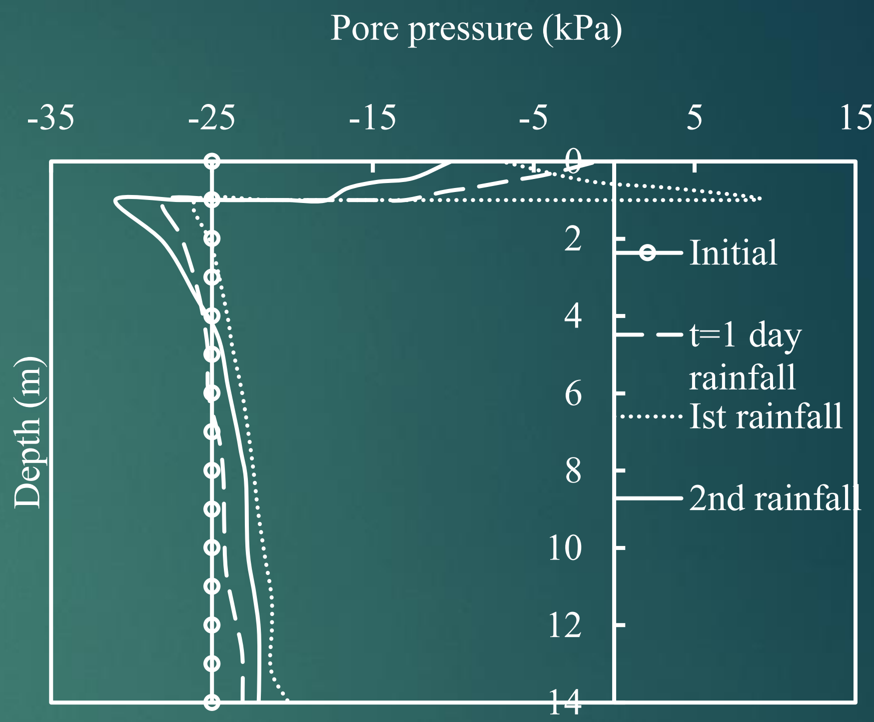
Rainfall infiltration was applied over the slope by considering two rainfall intensities viz; first $1.59\times\ 10^{-7}$m/sec for a period of 25 days and second rainfall of $9\times10^{-7}$m/sec accumulated for four days.



# Effect Of Rainfall Infiltration on The Response of Embankment

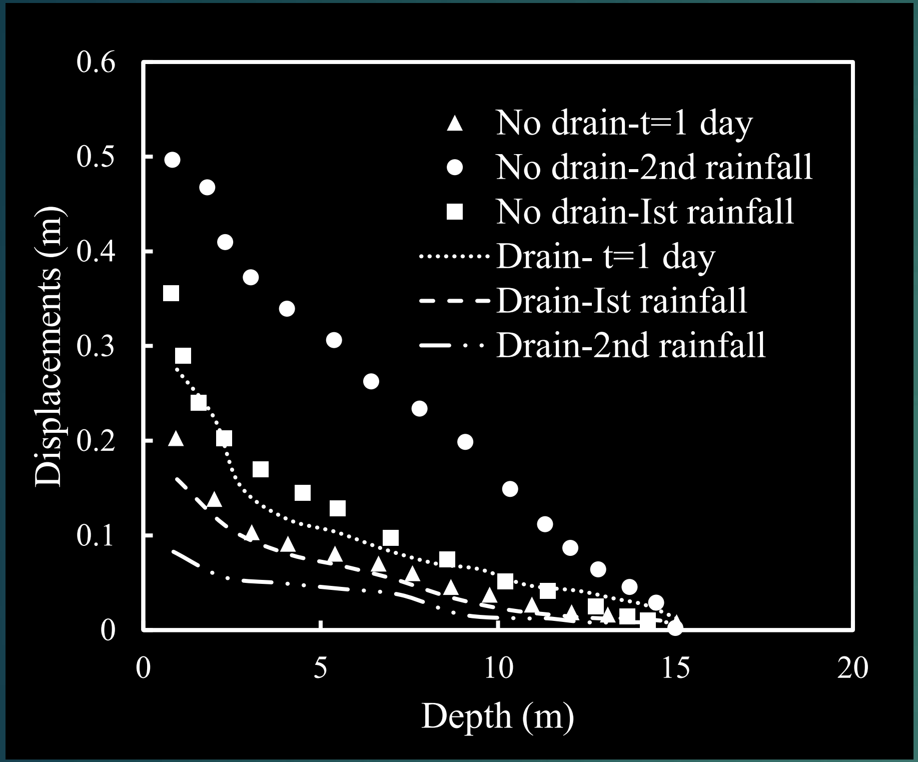



Pore pressure variation in the embankment without geocomposite layer

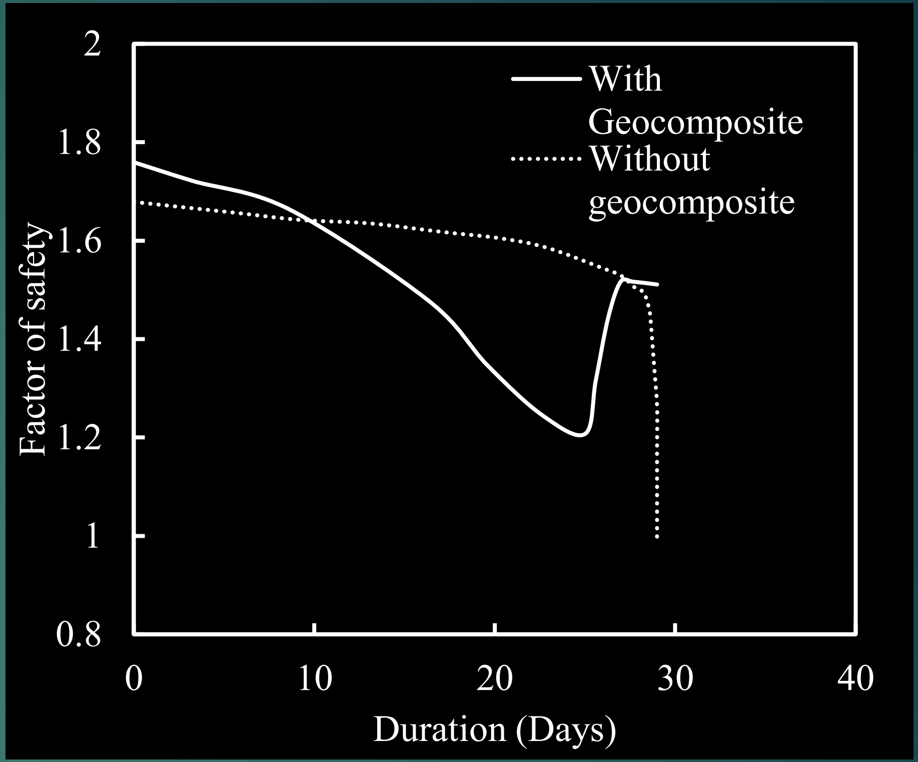



Pore pressure distribution in embankment with Geocomposite

# Effect Of Geocomposite Layer On The Displacements And Factor Of Safety




Displacements generated due to inclusion of geocomposite




Variation of FOS of embankment

## Reliability Analysis

- First step using Monte-Carlo simulations (MCS) to determine the probability of failure
- The hydraulic parameters including saturated hydraulic conductivity, $k_{sat}$ , SWCC parameters i.e, $\alpha$ and $m$ were taken as random variables

A quadratic response surface was created in MATLAB to act as a surrogate

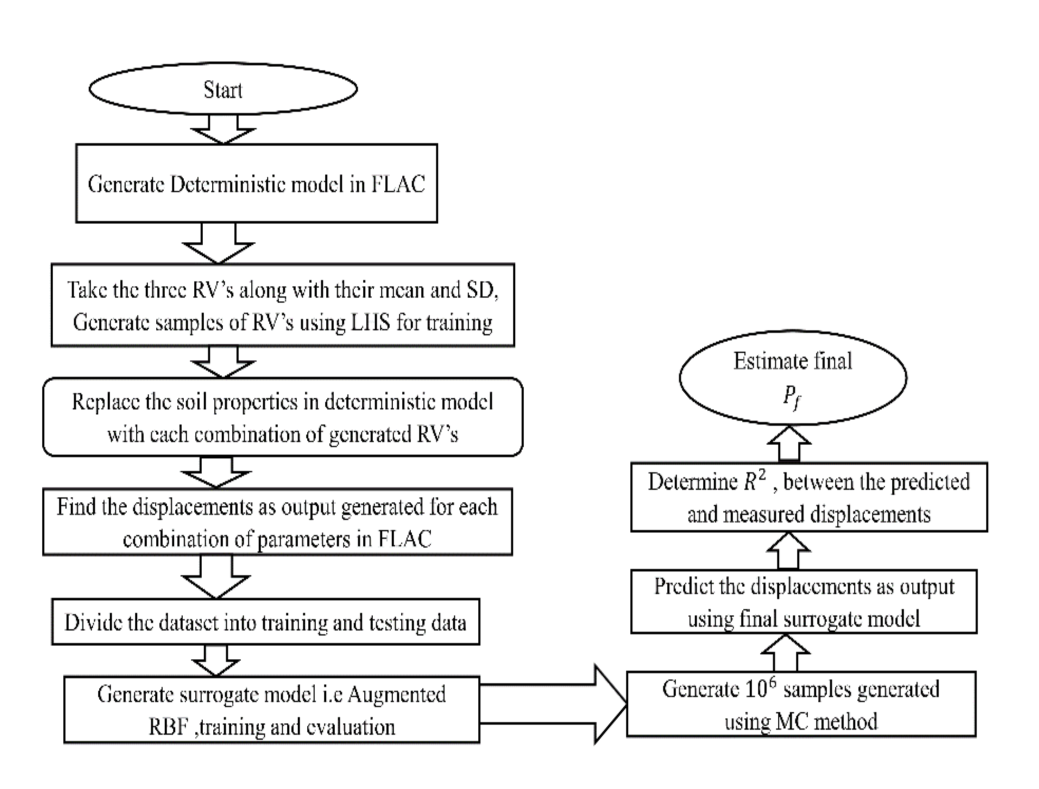
For accurate estimation of $P_f$, $10^6$ simulations were performed with input parameters taken from generated random realizations. From this analysis, $P_f$ was found to be 1.43e-$^{04}$ with reliability index of 3.3

| **Parameters** | **mean** | **COV (%)** |
|---|---|---|
| $k_{sat}$ | $10^{-6}$ | 80% |
| $m$ | 0.336 | 20% |
| **α** | 15kPa | 20% |

# Using Augmented Radial Basis Function

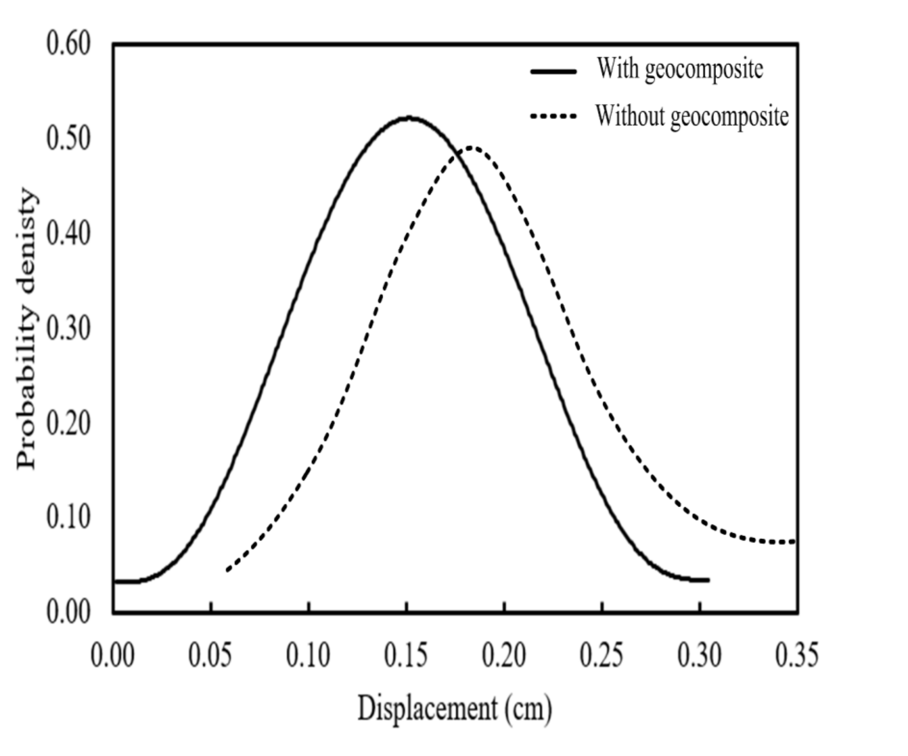
- First it involves the construction of deterministic model in FLAC, then generate an initial design of sample space based on random variables and compute the model response using the deterministic model and construct RBF model based on input parameters

LOOCV is carried out in MATLAB (2019).

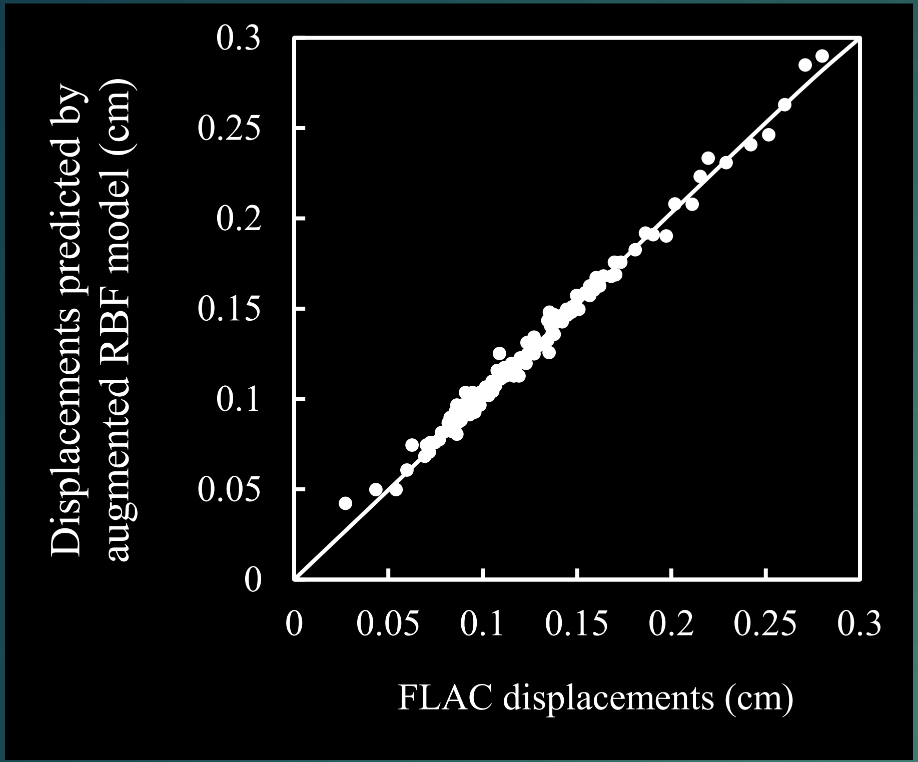


# Statistical parameters obtained from probabilistic analysis

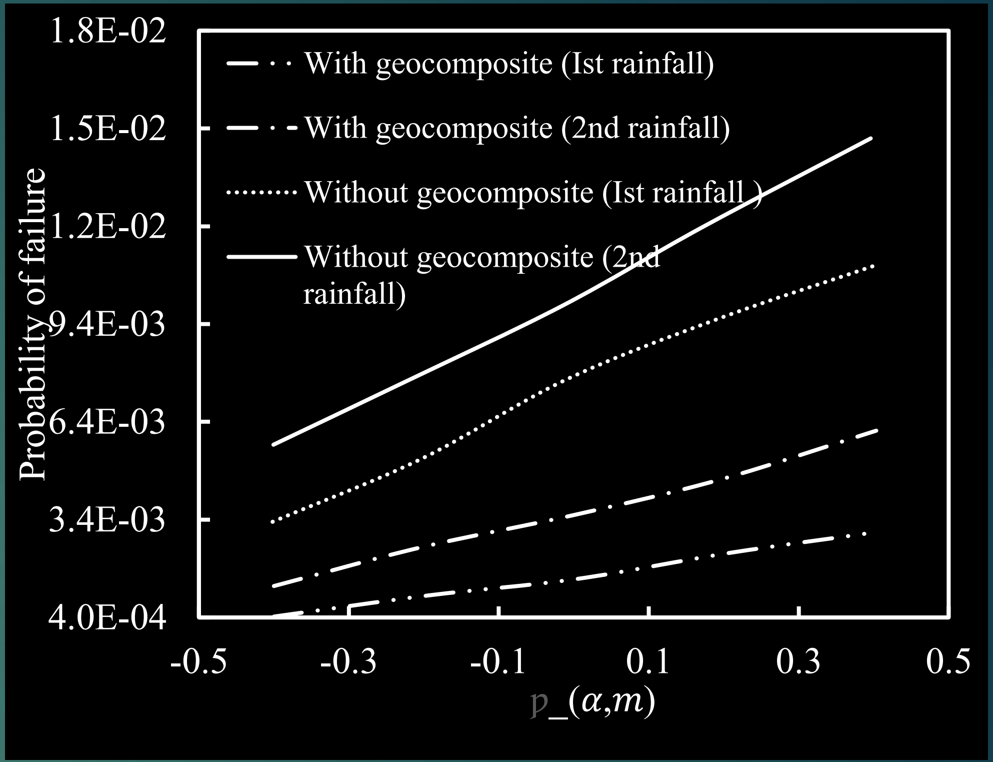
| Parameters | Value (with Geocomposite) | Value (without Geocomposite) |
|---|---|---|
| Mean of displacements (cm) | 0.16 | 0.20 |
| COV of displacements (%) | 0.21 | 0.3 |
| Reliability index | 3.4 | 3 |
| Probability of failure | 1.8e-04 | 1e-03 |
| Expected performance level | Above average | Above average |




Probability density function of displacements

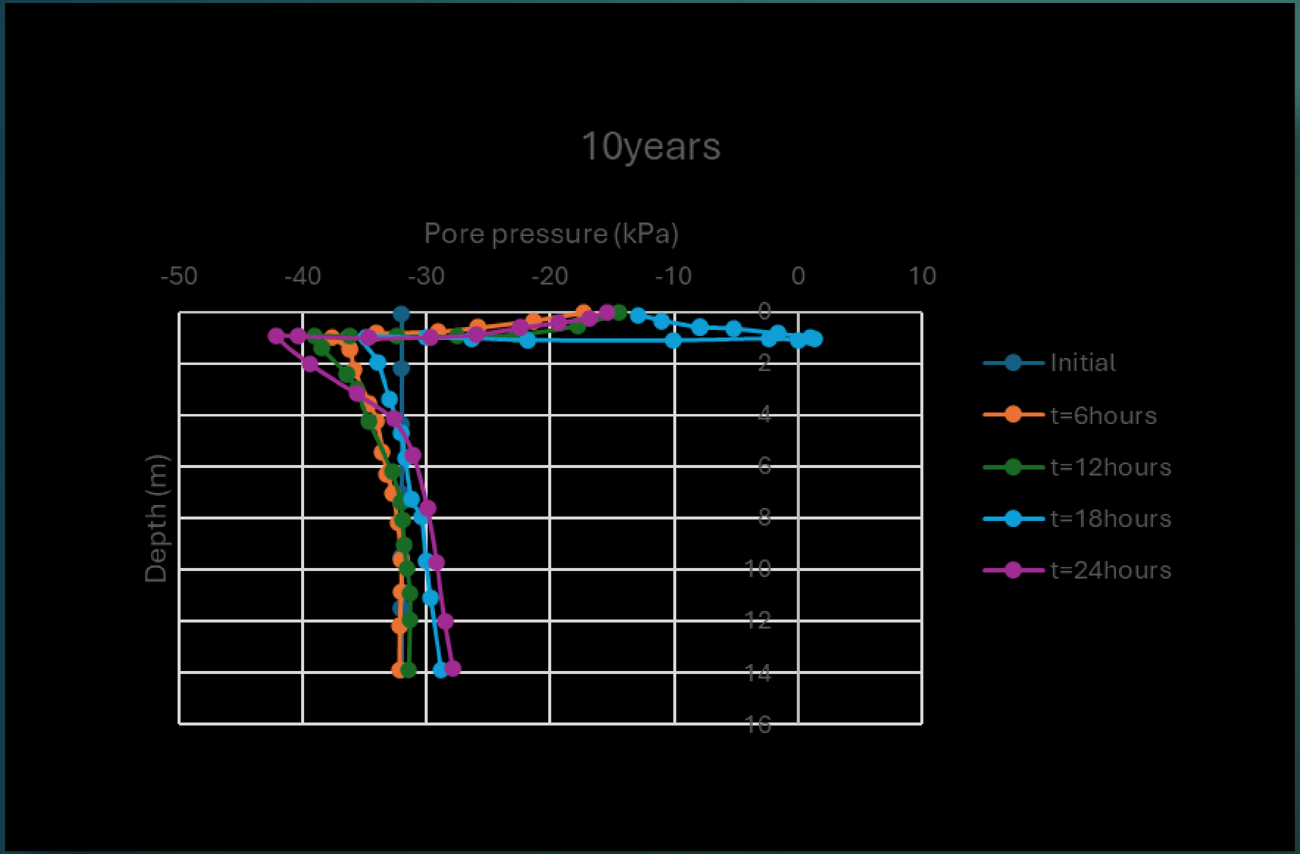


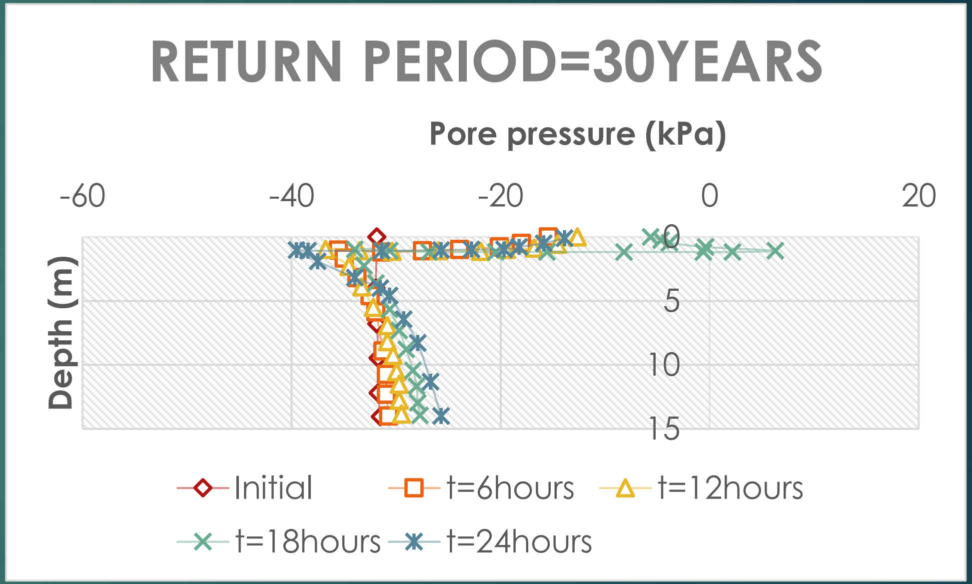

Comparison of displacements predicted by FLAC and the augmented RBF model



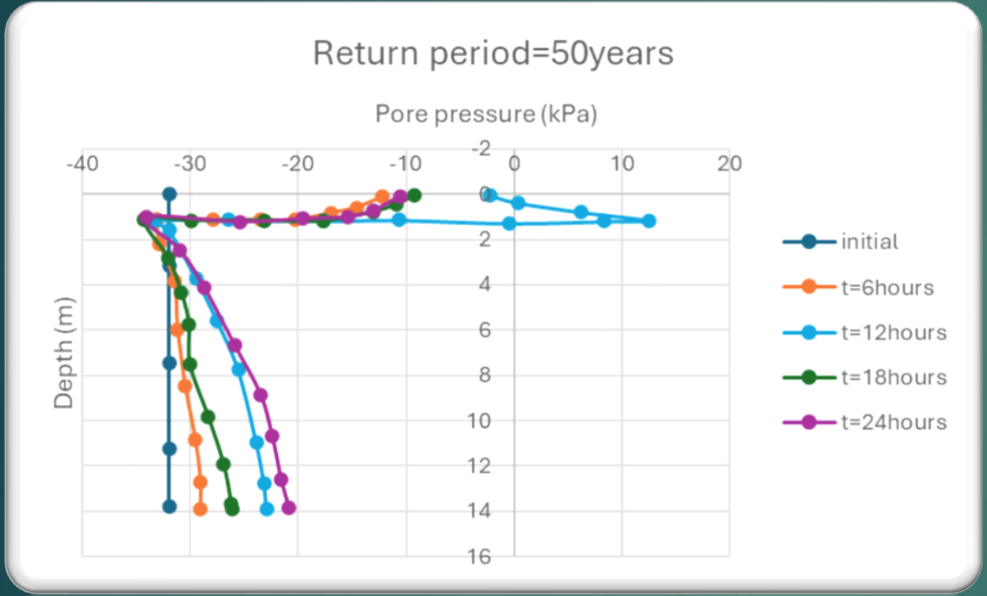

Variation of Probability of failure with $\rho_{\alpha,m}$ *(correlation coefficient between , $\alpha$ and $m$*

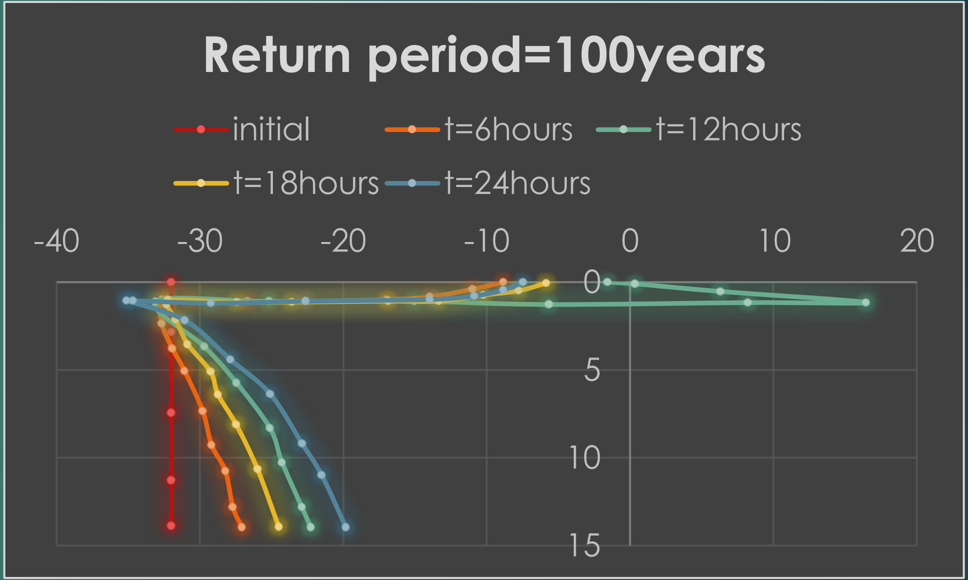
# Response for different return periods



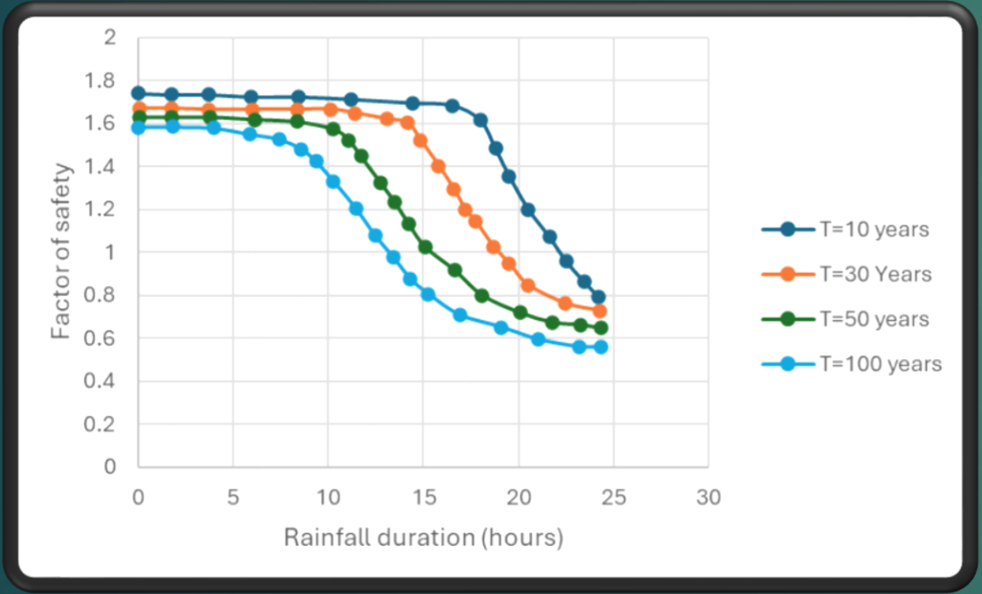



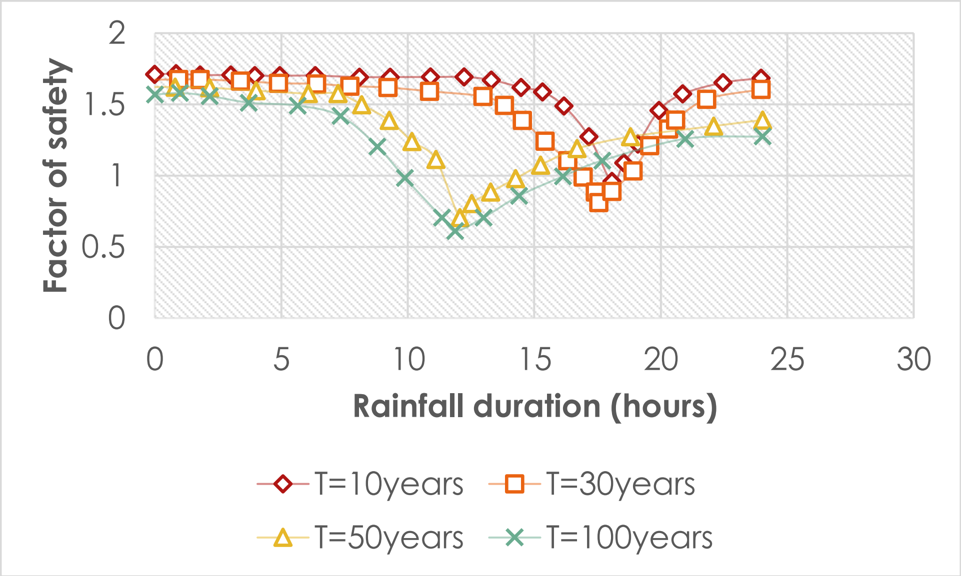
# Response for different return periods



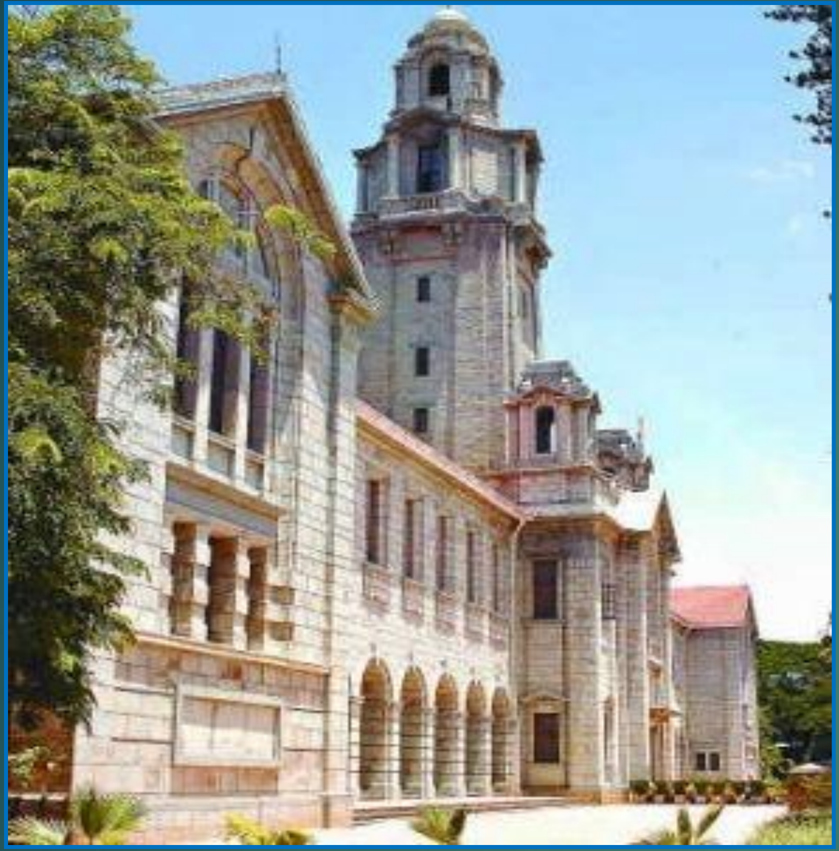
# Effect of geosynthetics in performance



# Summary

- Climate resilient design of embankment structures is required to reduce the number of embankment failures
- Methods for understanding the effects of climate change, mechanics of failure of embankments are available
- Understanding unsaturated soil mechanics significantly helps the design process
- Mohr Coulomb model underpredicts the deformations compared to that of BBM and ABBM and evaluation of bias factors and model errors is necessary for better understanding.
- Provision of geocomposite results in enhancing the FOS  preventing failure and this approach can be used for reanalysis and design of embankments as well as for remediation.

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# Thank you for your attention