The effect of selected climate change scenarios on engineering risk associated with slope stability of embankment dams

M-C. PREZIOSI, City University London, UK
T. MICIC, City University London, UK

SYNOPSIS. This paper presents the application of Advanced Probabilistic Slope Stability Methodology for Precipitation Effects (APSMP), developed to evaluate the notional probability of slope failure of earthfill embankment dams when exposed to future climate change scenarios. For this analysis the selected climate change scenarios are defined using the UKCP09 future climate projections. Notional probabilities are presented for the selected dam site, specific soil and climate scenarios. Using data collated from APSMP, the engineering risk associated with such failure events will be established and can then be related to the risk qualification. Using this approach, it will be possible to quantify the impact future climate change scenarios will have on the engineering risk associated with specific dam failure.

INTRODUCTION

With the recent introduction of the Flood and Water Management Act 2010 several reservoirs that previously did not fall under the Reservoir Act 1975, but whose capacities are greater than 10,000m³, will now be categorised as 'large raised reservoirs' and must comply with the new Act (The UK Statute Law Database, 2010). Since it was not a legal requirement for such structures to be regularly monitored, there is likely to be incomplete or limited data, and in some cases noticeable differences in the data relating to specific properties of the embankment dam. Merely carrying out a deterministic assessment for the safety of the reservoir's embankment may be insufficient and more sophisticated models that reflect uncertain conditions of the embankment dam are required. The overall safety of the reservoir, in relation to this particular form of failure, can therefore be expressed in terms of engineering risk. Engineering risk in respect to an event (such as failure) is defined as the product of the probability of the event, P_f, and the consequence of the event (Hartford & Baecher, 2004), Eqn. (1).

$$\text{Risk} \equiv P_f \times \text{Consequence} \qquad (1)$$

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Here, 'Consequence' relates to the consequences caused by dam failure and could be associated with impacts on the downstream slope, including any areas surrounding the dam or appurtenances. The current guidelines define dam failure as low probability, high-consequence events (Hartford & Baecher, 2004). However, the probability of a failure scenario occurring would have a significant effect on engineering risk. There could be a high variation in engineering risk that a dam is exposed to in different seasons, due to dam soil composition its configuration, etc. Thus, due to the high level of uncertainties associated with old embankment dams we propose that it is necessary to implement a probabilistic approach and determine their risk classification according to engineering risk, as defined in Eqn. (1).

As recorded by Johnston et al. (1999) seepage, piping, foundation instability, deformation etc. can all be attributed to the failure of earthfill embankment dams, which are themselves influenced by changes in the surrounding environment due to climate change (Preziosi & Micic, 2009; 2011). For completeness, a sample dam can be assessed for all specific failure events and a realistic engineering risk exposure quantified for a variety of climate change scenarios, using Eqn. (1). To demonstrate relevant methodology, in this paper we will only consider the notional probability of failure of the embankment's slopes subject to precipitation scenarios associated with climate projections, as defined in UKCP09.

THE APSMP MODEL

The Advanced Probabilistic Slope Stability Methodology for Precipitation Effects (APSMP) was developed as a tool that could be used to evaluate the quantitative effect that variable precipitation will have on the slope stability. APSMP is a probabilistic model that encompasses the uncertainties associated with the embankment fill's mechanical and hydraulic properties, the geometry of the embankment, the reservoir's headwater height and the rainfall parameters. In this paper, we will demonstrate how APSMP can be applied to the downstream slope of an embankment dam on a particular site in South East England, with alternative embankment fills subjected to future rainfall patterns. From the results obtained, the change in the slope's probability of failure (P_f) will be extracted and a more detailed evaluation of the notional level of engineering risk associated with the embankment dam, including any future conditions at the dam site, discussed. Effectively, APSMP models the change in the embankment's strength due to rainfall infiltration. APSMP therefore characterises embankment failure as a form of failure due to slope instability (structural failure).

Embankment physical model

Within the APSMP the embankment physical model, Figure 1, is based on a long established homogenous earthfill embankment dam, whose reservoir has reached its maximum allowable capacity and where no drainage is currently adopted at the downstream toe.

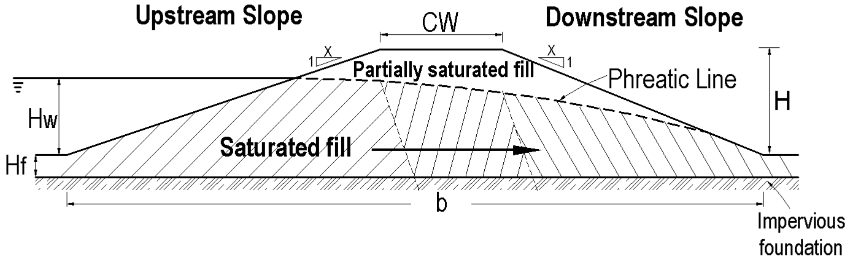

Figure 1. The embankment physical model (Preziosi & Micic, 2011)

The standard seepage theory (Cedergren, 1989) was implemented to define the trajectory of the phreatic line as a function of the reservoir's headwater height, the embankment's slope gradients and geometry (Preziosi & Micic, 2011). Thus the saturation levels and variations in the unit weights of the embankment fill above and below the phreatic line, including the pore water pressures present within the fill, are easily identified. Thus the position of the phreatic line is established to reflect the site specific uncertainties associated with the dam. However, any variation in the position of the phreatic line only represents fluctuations due to uncertainty and does not consider the effect of sudden changes, such as rapid drawdown, of the reservoir.

For the expression of the limit state function, APSMP applies the Sliding Block Method (Tancev, 2005), Figure 2. The shear strength and resultant active (P_a) and passive (P_p) earth pressures are calculated using the sliding block formulation. The parameters themselves are sensitive to the soil's effective strength parameters and pore water pressures present within the fill, Figure 2. As an extension in the presence of precipitation the Sliding Block Method provides a convenient model to evaluate the overall stability of the embankment slopes when rainfall has traversed through the embankment. The relevant pore water pressure within the partially saturated fill, above the phreatic line, have to be included within the sliding block formulation.

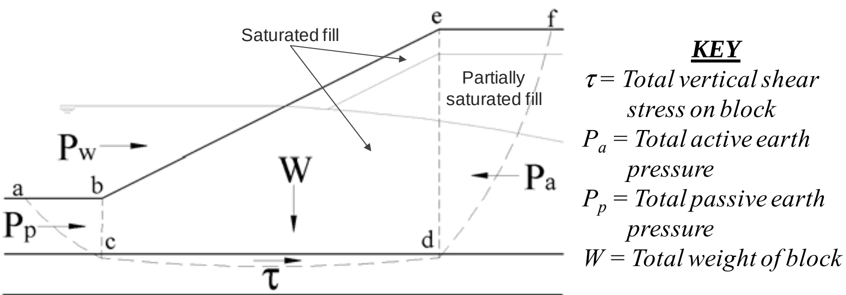

Figure 2. Application of Sliding Block Method for slope stability analysis with precipitation

Infiltration model

For the evaluation of the impact that a future precipitation pattern is expected to have on the dams, the depth that rainfall has traversed through the embankment's fill is needed. The model needs to capture the variability in the soil's hydraulic properties in relation to the specific moisture content of the partially saturated fill, so the widely-used van Genuchten method (van Genuchten, 1980; Zhou & Yu, 2005) is applied. The van Genuchten method enables formulation for the soil's relative hydraulic conductivity, as a function of the saturated hydraulic conductivity and the effective saturation of the soil or corresponding soil water potential. Thus, we use the soil-water retention curve to characterise the relative hydraulic conductivity at a specific depth (effectively a function of the moisture content). Once the relative hydraulic conductivity and the wetting front suction head are obtained for the soil's saturation level, the depth of rainfall infiltration through the embankment's core and slopes, for specific rainfall durations and intensities, are quantified using the applied Green-Ampt method (Chow et al., 1988; Chen & Young, 2006) as demonstrated by Preziosi & Micic (2012). By incorporating the applied Green-Ampt methodology into the sliding block model, the increase in the fill's saturation level and the presence of pore water pressures within the newly saturated fill layers, due to the infiltrated rainfall, are easily established (Preziosi & Micic, 2012). Once these properties are formulated the sliding block is used to define the failure events from the form of equilibrium equations.

Probabilistic model

Here, the relevant failure modes that govern the dam's long-term performance refer to failure of the upstream and downstream slopes and their limit state functions are defined by sliding block equilibrium equations, Eqns. (2 & 3) respectively.

$$g(\text{upstream}) = \tau_{\text{RIup}} - \left(P_{a_{\text{RIup}}} - P_w - P_{p_{\text{RIup}}}\right) \tag{2}$$

$$g(\text{downstream}) = \tau_{\text{RIdwn}} - \left(P_{a_{\text{RIdwn}}} - P_{p_{\text{RIdwn}}}\right) \tag{3}$$

Where:

P_w = Pore water pressure from the reservoir acting on the upstream section;

$P_{aRIup/RIdwn}$ = Total active pressure acting on the upstream/downstream sections during the rainfall event;

$P_{pRIup/RIdwn}$ = Total passive earth pressure on the upstream/downstream sections;

$\tau_{RIup/RIdwn}$ = Coulomb's shear strength during rainfall event.

Though Eqns. (2 & 3) appear linear, they are in fact non-linear as sliding block equilibrium equations are dependent on the trajectory of the phreatic line, soil properties and rainfall scenario as defined above. The input variables identified as deterministic (saturated hydraulic conductivity and saturated moisture content) will be defined in terms of their characteristic value, whereas the probabilistic variables will be characterised in terms of their mean (μ) and standard deviation (σ). Due to the high variability of the soil's hydraulic conductivity, representing it as a random variable would be too significant a simplification (Preziosi & Micic, 2012). For each limit state function, Eqns. (2 & 3), a generic notation X_i can be introduced and the probability of failure (P_f) for both failure modes defined in Eqns. (2 & 3) is established, Eqn. (4).

$$P_f = P[\mathrm{g}(X_i) \leq 0] = \int_{\mathrm{g(x)}\leq 0} f_g(x)dx \qquad (4)$$

Here, g is the limit state function of the uncertain variables (X_i) and $f_g(x)$ is the joint probability density function for the g function. In reality $f_g(x)$ is not readily available for complex structures so approximate methods are implemented to evaluate the above integral. Thus, the probabilistic methodology is integrated with the modified deterministic slope stability model. The Advanced First Order Second Moment Reliability Method (Hasofer & Lind, 1974) is implemented and features the Hasofer-Lind transformation method (FORM/SORM) that can be applied to linear and nonlinear limit states. In order to ascertain the most probable failure point within the failure domain of the limit state function, the standard Rackwitz-Fiessler iterative approach (Haldar & Mahadevan, 2000), has also been incorporated into the probabilistic methodology. The results obtained for each failure mode include the failure probability (P_f) and sensitivity factors (α_i), which reflect the contribution of the inherent variability of the random variable (X_i) (on the probability of failure) with respect to each limit state (Haldar & Mahadevan, 2000).

UKCP09 - FUTURE CLIMATE PROJECTIONS

UKCP09 presents the future climate projections as probabilistic ranges (Gething, 2010). These reflect the uncertainties associated with the limitations of the climate model, including the climate's natural variability (Jenkins et al., 2009). From the data obtained using the UKCP09 User Interface, future trends for UK seasonal, annual and monthly temperature, precipitation, etc. can be obtained in a probabilistic form (Jenkins et al., 2008). However, UKCP09 cannot estimate future changes relating to soil moisture or the effect on probability of failure.

Firstly, for future precipitation projections, UKCP09 that combines the climate change projections with the precipitation recorded during the baseline period (1961-1990) is used. The projections are identified Cumulative Distribution Functions (CDF) providing the projected distributions for specific climate variables relative to the baseline period. These are available for the projected annual/monthly/seasonal change in precipitation for a given emission scenario (low, medium or high), probability level, 30 year time period (2010-2039, 2020-2049,…, 2070-2099) and location (Jenkins et al., 2009). Figure 3 shows the CDF graphs plotting the change in precipitation in SE England for high emission scenarios for December and August as defined by UKCP09.

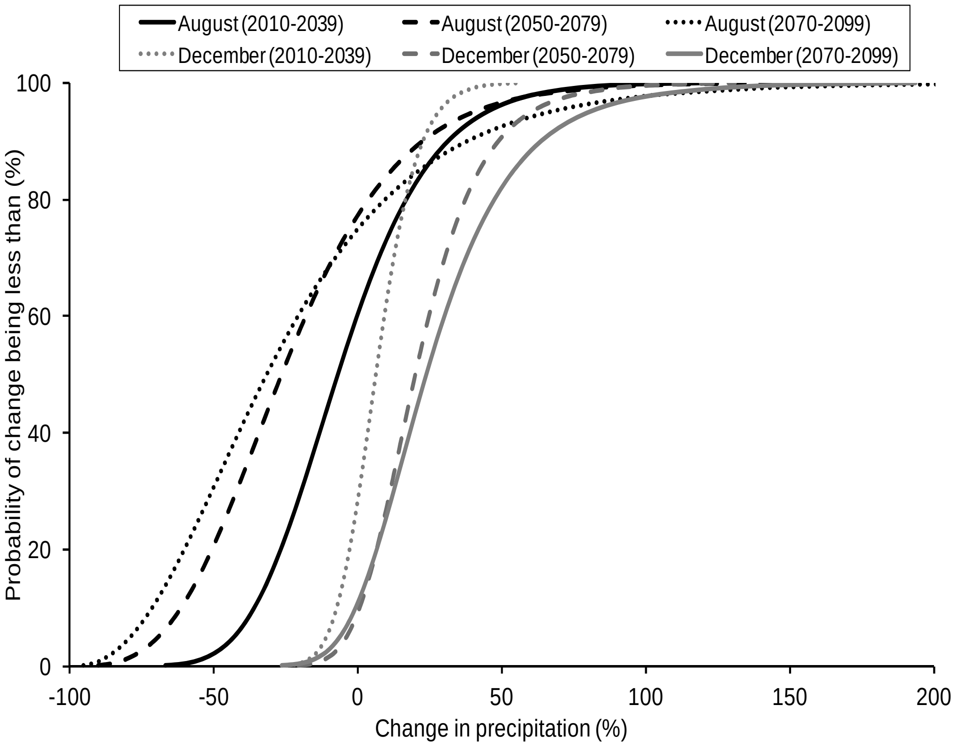

Figure 3. CDF of change in precipitation for high emission scenarios for December & August in SE England: data source UKCP09

Using the UKCP09 climate projections shown in Figure 3, different precipitation scenarios were developed to understand how they could affect the notional level of engineering risk associated with the embankment dam (slope instability). Here, the future precipitation patterns for December and August, between 2010-2039 and 2070-2099, were extracted. The next step was to obtain the quantitative measure of change in precipitation. This is increase in average rainfall for the selected UKCP09 climate projections. Thus, the future rainfall intensity (RI) for a prolonged rainfall event for December and August between 2010-2039 and 2070-2099 were generated using the 95^{th} fractile and are shown in Table 1. The average rainfall rates were then incorporated into the probabilistic model.

Table 1. Probable future rainfall intensities over SE England incorporating UKCP09 climate projections

UKCP09 Precipitation Scenario (Month & 30 year period)	*UKCP09 Change in precipitation*[#]	*Predicted future RI over 7 days (mm)*	*Average Rainfall Rate (mm/day)*
December 2010-2039	22.6 %	93.4	13.3
December 2070-2099	63.8 %	124.8	11.3
August 2010-2039	31.6 %	78.9	17.8
August 2070-2099	38.2 %	82.9	11.8

[#]95th fractile of the percentage increase in average rainfall for UKCP09 climate projections for high emission scenarios

By using the predicted rainfall intensities defined in Table 1 within APSMP, variations in the depth of water infiltrated through the dam's embankment fill, should it rain over seven days, can be established. Using the results produced from APSMP, it will be possible to detect if the embankment's slopes are at risk when subject to specific conditions. Variable soil saturation levels will also be considered here, as the embankment slopes are more vulnerable during the wetter months, primarily in winter and at the beginning of spring.

APPLICATION OF APSMP

In order to demonstrate the applied methodology for failure mode (downstream slope failure), two comparable clay-like soil types (Soil A & B) have been considered for the embankment fill. Their standard, deterministic, embankment fill properties, derived saturated unit weight of soil, effective internal friction and cohesion of are listed in Table 2.

Table 2. Soil properties & unit weight of soil for Soil A & B

Soil Properties	*Units*	*Soil A*[*]	*Soil B*[**]
Void ratio (e)		0.83	0.54
Moisture content (θ)	%	34.5	26.5
Cohesion (c')	kN/m²	12	14.4
Internal friction (φ')	°	23	20
Saturated unit weight of soil	kN/m²	19.0	20.8

[*]Data extracted from Carder & Barker (2005);
[**]Data extracted from Cherubini (2000)

As demonstrated by Preziosi & Micic (2012) accurately measuring the embankment's geometry is difficult, especially if the dam remains operational. Therefore, the embankment's physical model is treated as uncertain where the mean values and standard deviation of the embankment's height, crest width and foundation are modelled using a normal distribution, Table 3. When modelling the phreatic line, larger visible changes are more commonly associated with rapid drawdown or overtopping. However, less visible changes to the reservoir level can be attributed to environmental effects, such as rainfall or evaporation, or even due to sedimentation within the reservoir basin which will reduce the reservoir's capacity and its depth. Therefore, the reservoir's headwater height also treated as uncertain with a normal distribution, see Table 3. A variety of sudden changes to dam parameters could initiate different failure modes however for simplicity are not taken into account here.

Table 3. Probabilistic modelling of the input parameters for Soil A & B

All variables normally distributed		*Unit*	*Mean (μ)*	*Standard deviation (σ)*
Height (H)		m	3.0	0.03
Crest Width (CW)		m	2.8	0.028
Height of foundation (H_f)		m	0.5	0.01
Headwater height (H_w)		m	2.0	0.10
Unit weight of soil factor (γ_{fc})		kN/m²	1.0	0.10
Rainfall Intensity factor (RI_{fc})		Mm	1.0	0.10
Soil A	Internal friction (φ') ✦	°	23.0	3.45
	Cohesion (c') ✦	kN/m²	12.0	3.60
Soil B	Internal friction (φ') ✦	°	20.0	3.00
	Cohesion (c') ✦	kN/m²	14.4	4.32

✦Negatively correlated (-0.5)

As stated in the JCSS Probabilistic Model Code (Baker & Calle, 2006) and by Liang et al. (1999), for any geotechnical probabilistic analysis, the unit weight, internal friction and cohesion of the soil must be deemed uncertain with normal (Gaussian) probability distribution, see Table 3. A unit weight of soil factor (γ_{fc}) is also introduced, to account for variations between soil samples. The soil's internal friction (φ') and cohesion (c') are also negatively correlated (-0.5). However, the applied probabilistic model does not address the high uncertainty associated with saturated hydraulic conductivity, which remains a limitation of APSMP and is an area for future development.

RESULTS

Due to environmental changes the embankment fill's saturation level, relative hydraulic conductivity and unit weight of soil above the phreatic line will be affected. Differences will be most notable between the wetter and drier months. For the current parametric study the impact of future precipitation scenarios, as defined in Table 1, on the downstream slope's probability of downstream slope failure, will be presented. It is assumed that the embankment fill has a high saturation level and the considered consequences are identical for the selected precipitation scenarios.

The graphs presented in Figures 4 & 5 demonstrate how the rainfall duration and intensity affect the slope's probability of failure when constructed of two comparable, clay-like soils. By considering the outcomes for Soil A and Soil B, there is a clear correlation between P_f and the precipitation scenario, effectively rainfall intensity and its duration.

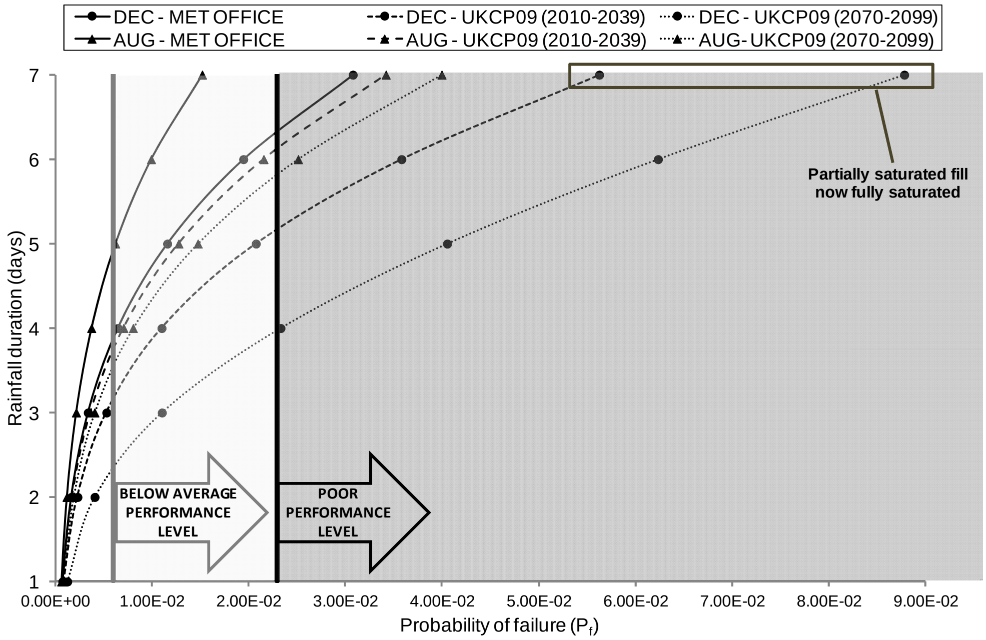

Figure 4. Change in P_f for downstream slope failure under variable precipitation scenarios for Soil A

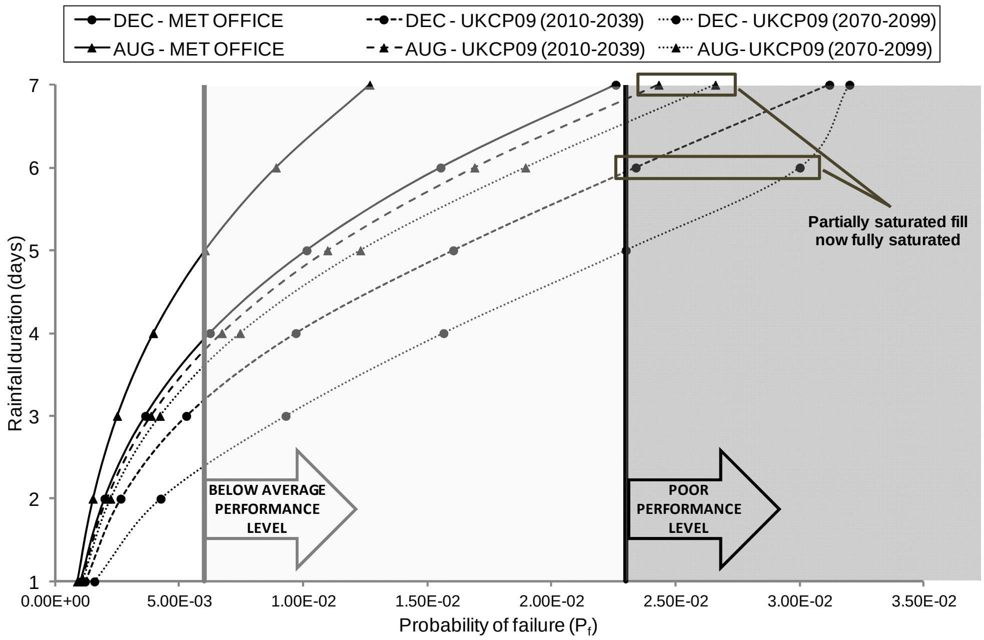

Figure 5: Change in P_f for downstream slope failure under variable precipitation scenarios for Soil B

As demonstrated in the graphs, the performance of the downstream slope is noticeably reduced over the rainfall's duration. The failure can be defined in two ways:

i) the partially saturated zone above the phreatic line becomes fully saturated as the rain water infiltrates through the fill.

ii) a certain notional probability of failure has been reached.

For the second failure criteria we implemented the approach that has already been proposed by the U.S. Army Corps of Engineers (1997), namely that the expected performance levels can be defined using a notional probabilistic measure. Thus, in Figures 4 and 5 by considering the probabilities of failure that could be deemed to indicate 'below average' and 'poor' performance levels the critical precipitation effects are identified.

It is clear that for both soil types, Soil A and Soil B, unsatisfactory performance would have been reached before the rainfall infiltrated as far as the phreatic line. The graph in Figure 4 clearly indicates that for Soil A the slope's partially saturated fill above the phreatic line will become completely saturated within 7 days when the precipitation events Dec UKCP09 (2010-2039) and Dec UKCP09 (2070-2099) occur. Whereas during the same precipitation events the partially saturated fill for Soil B becomes completely saturated within six days. Furthermore for the embankment dam with Soil B fill summer precipitation scenarios for Aug UKCP09 (2010-2039) and Aug UKCP09 (2070-2099) the phreatic line would be reached within seven days.

In reality there are other failure modes (such as overtopping, runoff, surface erosion, etc.) that could also develop, but these would require further probabilistic analyses to be carried out on the embankment dam. Engineering risk exposure for the selected dam will be clearly variable between seasons and time horizons and be dependent on embankment fill composition, vegetation, any past strengthening, deterioration, etc.

While only extreme saturation scenarios were considered here, in practice it is possible to use APSMP for genuine site specific conditions and climate scenarios. Crucially the information about the reservoir and its embankments are dependent on the quality of the measurements taken at the dam site, thus it is important to consider carrying out an engineering risk analysis to acquire a more complete picture of the specific reservoir's behaviour during extreme precipitation events. In order for APSMP to be applied at multiple sites, specific guidelines are required to address the quality of sources of information and appropriate modelling techniques, such as those in outlined by Stephens (2010), that must be used to interpret dam site measurements.

CONCLUSIONS

The impact of UKCP09 future climate projections on the notional level of engineering risk associated with dam failure, in this case downstream slope instability, has been considered using the Advanced Probabilistic Slope

Stability Methodology for Precipitation Effects (APSMP). It is recommended that further studies are need to address the network level implementation of the procedure as well as required modelling for alternative failure modes, interdependency between modes of failure and effects of any maintenance or strengthening carried out during the dam's lifecycle.

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