An Adaptive Methodology for Risk Classification of Small Homogeneous Earthfill Embankment Dams Integrating Climate Change Projections

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This paper presents the application of the advanced probabilistic slope stability model with precipitation effects (APSMP) developed to assess the performance of small homogeneous earthfill embankment dam slopes, when exposed to future seasonal precipitation scenarios. Here, the UKs latest probabilistic climate model known as UKCP09 is applied. To reflect the critical conditions conducive to slope failure, a benchmark has been developed to identify the change, if any, in the risk classification of the slope's performance level due to precipitation. Thus, enabling the reassessment of the dam's risk classification, as categorized by the Flood and Water Management Act 2010. Such an approach could therefore be well placed to support and enhance the decision making process, its impact on the public, especially in relation to future climate effects.

Keywords: climate change; failure classification; precipitation; risk; slope instability.

Subject classification codes: include these here if the journal requires them

1. Introduction

The UK public bodies and insurers are starting to take a greater interest in the impact that extreme rainfall events could have on failure at key dam sites. Therefore, analytical models that reflect uncertain conditions of the dam's embankment are required, as even small dams can still cause damage to their surrounding environments. Furthermore, with the recent introduction of the Flood and Water Management Act 2010, many smaller reservoirs whose capacities are greater than 10,000 m^3 that were previously not governed by the Reservoirs Act 1975 will now have to comply with the new Act, as they are re-categorized as large raised reservoirs (UK Statute Law Database, 2010). This new legislation also includes new arrangements for reservoir safety based on risk rather than just on the reservoir's capacity. As indicated by Hughes et al. (2009) approximately 5,400 more reservoirs in England and Wales could now fall within the new Act, a significant increase from the 2,100 reservoirs that currently comply with the Reservoirs Act 1975.

As documented by Hamilton-King (2010) in the annual report for post-incident reporting for UK dams, one of the main triggers of dam failure is due to embankment stability caused by internal erosion through the embankment. However, earthfill embankments are also prone to damage due to external erosion, deformation, overtopping, seepage, etc. Due to the uncertainties associated with small homogeneous earthfill embankment dams, it is therefore important to analyse the impact new circumstances, such as extreme rainfall events, could have on the structure's reliability. This is crucial when assessing those dams that until now were legally outside the Reservoirs Act 1975, as it is unlikely that detailed consistent data about their condition is available. Thus, decision-makers can be faced with the problem of obtaining quantitative performance measures for structures where it is difficult to accurately assess their condition and the rate of deterioration.

Therefore, implementing a deterministic assessment for the safety of such structures will be insufficient and a more sophisticated model that can reflect the uncertain conditions of the dam's embankment is required. By applying a probabilistic climate model, it will be possible to obtain notional quantitative performance measures of the embankment's slopes and consequently risks associated with the dam's embankment in the future. In order to address the effect that future precipitation scenarios could have on these infrastructures, we have selected a …………….well know failure mode and applied UKCP09, which is the current probabilistic model used to generate future climate projections in the UK.

2. Future Climate Projections: UKCP09

Using the most recent regional climate model, UKCP09 climate projections were developed and present the climate scenarios as probabilistic ranges over seven overlapping 30-year time periods (Gething, 2010). These climate projections reflect the uncertainties caused by the climate's natural variability including the limitations of the climate model and by taking into account the main uncertainties associated with future climate predictions (Jenkins et al. 2009).

As identified by UKCP09, the UK's rainfall patterns are set to change significantly over the next century (Jenkins et al. 2008). Furthermore, as reported by Jenkins et al. (2009) and Gething (2010) there will be a clear change in future seasonal rainfall patterns as well as a change in the average seasonal rainfall durations and an increase in the average rainfall intensity in winter. Therefore, as the dam's embankment and reservoir are continually exposed to changes in its surrounding environment, it will cause the soil properties of the embankment fill's surface layers to vary. This will directly impact the slope's reliability, as the forces acting on the embankment's slopes are primarily affected by the soil's mechanical and hydraulic properties. It is well understood that the soil's average saturation level will fluctuate, both between the seasons and the regions. For instance, during the winter months, the partially saturated embankment fill will have a higher degree of saturation, and unit weight of soil, compared to that recorded over the summer months.

2.1. Application of the UKCP09 User Interface

UKCP09 User Interface combines the probabilistic climate change projections with the precipitation recorded during the baseline period (1961 - 1990). These projections are obtained as a Cumulative Distribution Functions (CDF) for specific climate variables relative to the baseline climate. These CDFs are available for the projected annual/monthly/seasonal change in precipitation, for a given emission scenario (low, medium and high), probability level, 30-year time period and location (Jenkins et al. 2009). Using the UKCP09 User Interface the sample CDF graphs, Figures 1a and 1b, were produced for South East England, where small homogeneous earthfill dams are present in large numbers, which show the changes in precipitation for the winter and summer seasons assuming high emission scenarios for the 30-year time periods 2010 - 2039, 2040 - 2069 and 2070 - 2099. For this case study, only high emission scenarios were selected as these are of most concern to the public over the next 100 years. We consider 30-year time periods using the available climate projections starting with 2010.

Figure 1a here (a)

Figure 1b here (b)

Figure 1. CDFs showing the change in precipitation for high emission scenarios for winter (a) and summer (b) in South East England: data source UKCP09

Comparing Figures 1a and 1b, the change in precipitation projections during winter and summer follow diverging trends. During winter, there is a projected increase in future precipitation for all three 30-year periods. However, this trend is clearly reversed for summer, as the CDF graphs indicate drier summers due to decreasing precipitation. In order to extrapolate the extreme future rainfall events for January and July between 2010 - 2039 and 2070 - 2099 for South East England, the specific probability level for the UKCP09 change in precipitation-for the selected 30-year time periods, under high emission scenarios, were extracted. Similar graphs are available for other seasons, emission scenarios and 30-year time periods, but this paper focuses on extreme changes in precipitation between winter and summer.

2.1.1. Selected precipitation scenarios

To obtain the quantitative measure of change in precipitation for South East England, the 95th fractile of the percentage increase in average rainfall for UKCP09 climate projections for high emission scenarios was calculated. This was possible as the data extracted from the UKCP09 User Interface is provided in a format that enables approximate evaluation of the selected parameter, in this case the change in precipitation. In order to estimate the future rainfall intensity over a given 30-year period, the first step is to determine the average, or mean, rainfall intensity recorded over the baseline (1961 - 1990) for South East England. Once the average rainfall intensity has been calculated, the future average rainfall intensity can be established for the selected 30-year period. Lastly, the variance and standard deviation for the selected future rainfall intensity can be obtained. Once the mean and standard deviation for the future extreme rainfall intensities for January and July between 2010 - 2039 and 2070 - 2099 have been established, their characteristic intensities for the 95th fractile (<μ>1-0.95) were ascertained and presented in Table 1. Here the rainfall durations (4 days, 3hrs and 1hr), see Table 1, were selected with reference to past extreme rainfall events recorded by the Uk's Meteorological Office such as Hampstead….(Preziosi, 2013). The average rainfall rates for the selected UKCP09 precipitation scenarios for South East England were then incorporated into the APSMP (Preziosi & Micic, 2012) probabilistic model and their effect on the notional level of engineering risk associated with the embankment dam (slope instability) quantified.

Table 1 near here

3. Probabilistic Slope Stability Model

3.1. Physical system modelling

APSMP was established to quantify the notional probability of upstream and downstream slope failure for homogeneous earthfill embankment dams, subject to variable precipitation scenarios. It encompasses the aleatory uncertainties associated with the embankment fill's mechanical and hydraulic properties, the embankment's geometry, the dam's reservoir level and precipitation, specifically the rainfall's intensity (Preziosi & Micic. 2011, 2012). For the expression of the limit state functions during the rainfall event, APSMP applies the Sliding Block Method (Tancev, 2005), Figure 2, which incorporates the modified Green-Ampt methodology (Chow et al. 1988, Chen & Young, 2006).

Figure 2 here

Figure 2. Application of APSMP the sliding block formulation, which incorporates the effect of precipitation through the surface layers of the embankment fill.

By incorporating the applied Green-Ampt methodology within the sliding block model, APSMP is able to capture (Preziosi & Micic, 2012; Preziosi, 2013):

- The depth of rainfall infiltration through the surface layers of the partially saturated embankment fill, for specific rainfall durations and intensities.
- The increase in the fill's saturation level.
- The presence of pore water pressures within the newly saturated fill layers over the rainfall's duration.
- The change in the shear strength and resultant active and passive earth pressure forces acting on specific embankment slopes due to the presence of water within the surface layers of the embankment fill.
- How the upstream and downstream slopes behave in relation to the whole structure by incorporating the forces acting on the interface of the slope from the core and opposing slope.

Effectively, APSMP models the change in the embankment's strength due to rainfall infiltration and characterizes embankment failure as a form of failure due to slope instability (structural failure), which is one of the most common forms of failure recorded in the UK (Charles et al. 2011). Alternative failures of earthfill dams can be attributed to seepage, piping, foundation instability, deformation, etc, which could be influenced by changes in the surrounding environment due to climate change (Preziosi & Micic, 2009; 2011), but also additional human factors such as vandalism. These alternative modes of failure would always be considered in practice but as they are very site specific they are not considered in this paper.

APSMP is implemented as it is able to capture in a consistent manner the impact future precipitation scenarios could have on the performance of the embankment's slopes, as a function of their notional probability of failure (reliability). The UKCP09 future climate projections for South East England were selected and different precipitation scenarios, for selected time horizons, developed.

3.2. Application of Reliability Analysis

For the applied probabilistic analysis, the relevant failure modes (FM) assumed to govern the dam's long-term performance refer to upstream (FM1) and downstream (FM2) slope failure (slope instability). Using the modified sliding block formulation, the limit state functions for FM1 and FM2 during the rainfall event, $g_{FM}(.)$,are defined using Equations 1 and 2.

$$g_{FM1}\left(X_i\right)=\tau'_{U_{RIup}}-\left(P_{x_{CRIup}}+P_{x_{DRIup}}\right)-\left(P_w+P_{p_{URIup}}\right) \quad (1)$$

$$g_{FM2}\left(X_i\right)=\tau'_{D_{RIdwn}}-\left(P_{x_{CRIdwn}}+P_{x_{URIdwn}}\right)-P_{p_{DRIdwn}} \quad (2)$$

where: P_w = Pore water pressure from the reservoir acting on the upstream slope; $P_{xCRIup/RIdwn}$ = Total active earth pressure force acting on the upstream/downstream slopes from the core during the rainfall event; P_{XDRIup} = Total active earth pressure acting on the upstream slope from the downstream slope during the rainfall event; $P_{XURIdwn}$ = Total active earth pressure acting on the downstream slope from the upstream slope during the rainfall event; $P_{pRIup/RIdwn}$ = Total passive earth pressure on the upstream/downstream slopes during the rainfall event; $\tau'_{RIup/RIdwn}$ = Coulomb's shear strength during the rainfall event.

For the limit state functions, a generic notation X_i was introduced and the probability of failure (P_f) for both failure modes (FM1 and FM2) evaluated using Equation 3.

$$P_f=P\left[g\left(x_i\right)\leq 0\right]=\int_{g(X_i)\leq 0} f_g\left(x_i\right)dx_i \quad (3)$$

Here, g is the limit state function of the uncertain variables (X_i) and $f_g(x_i)$ is the cumulative distribution function. However, Equation 3 is deceptively simple as the integral includes uncertainties associated with the joint density function $f_g(x_i)$ and the failure domain (when $g(x_i) \leq 0$). In reality, it is virtually impossible to obtain $f_g(x_i)$, so an analytical approximation has to be applied to the above integral, Equation 3. We use the reliability index (β) for the limit state function that is directly related to P_f, Equation 4.

$$P_f = \Phi(-\beta) = 1 - \Phi(\beta) \quad (4)$$

The probability distribution functions reflect the nature of uncertainty and in this case there is a significant diversity between geometric and soil properties. For the variables that define the geometry of the embankment, the equipment tolerances used to measure the embankment would be a significant factor, and the lack of sufficient samples from soil testing would have a major influence on the slope's probability of failure.

As summarized by Preziosi and Micic (2012), APSMP was developed by integrating the First Order Second Moment method (FOSM) (Haldar & Mahadevan, 2000) with the modified deterministic upstream and downstream slope stability models with precipitation and can be applied when the limit state functions, Equations 1 and 2, have correlated or non-correlated random variables. In order to determine the design point within the failure domain of each limit state function, APSMP also applies the Standard Rackwitz-Fiessler iterative approach (Haldar & Mahadevan, 2000; Preziosi, 2013). Thus, from the results obtained the change in probability of failure (P_f) for each failure mode (FM1 and FM2), subject to a specific rainfall event, is evaluated.

3.3. Modelling of aleatory variables

For APSMP to be applied at multiple dam sites, specific guidelines such as the Probabilistic Model Code developed by JCSS (2006) are required in order to fully address the quality of information and appropriate modelling techniques necessary for all relevant limit states. Due to extensive differences between dam sites, it is often the case that data is collected on the basis of expert opinion or some form of convention is implemented for modelling. Uncertainties are associated with the embankment's geometry (embankment height, crest width, foundation height), the embankment fill's soil properties (unit weight of soil, internal friction and cohesion) and the dam's reservoir level (Preziosi & Micic, 2011, 2012). As the rainfall's intensity and duration control the water's actual infiltration rate through the soil and are highly variable within a given catchment area, a rainfall intensity factor (RI_{fct}) has been introduced to account for the variability in the rainfall intensity measurements over the rainfall duration. RI_{fct} is also modelled using normal distribution and its mean and standard deviation such as presented in Table 3.

To reflect the relationship between the soil's internal friction (φ') and cohesion (c'), they are assumed to be negatively correlated. Due to the high variability of the soil's hydraulic conductivity, representing it as a single random variable throughout the embankment would be too significant a simplification (Preziosi & Micic, 2012). Therefore, to capture the variability in the soil's hydraulic properties for the embankment model in relation to a specific moisture content at a given depth, the widely used van Genuchten method (van Genuchten, 1980) is applied. Thus, the expressions for the unsaturated hydraulic conductivity as a function of the moisture content, or soil-water characteristic curve (SWCC), have been established (Preziosi & Micic, 2012). This modelling is deterministic and could be seen as a limitation of the APSMP model however, its impact on the risk classification would be insignificant, as the same model is always implemented.

Table 3 near here

3.4. Engineering risk analysis

Once we have a methodology for calculation of the probability of failure for the embankment's slopes, engineering risk can be considered. As defined by Equation 5, engineering risk is the product of the probability of the event (P_f) and the consequence of the event (such as dam failure, the cost of dam failure, fatalities, loss of services, etc.), (Hartford & Baecher, 2004). Consequently, the dam's risk classification, subject to its current conditions, can be ascertained.

$$Risk \equiv P_f \cdot Consequence \tag{5}$$

Once the engineering risk associated with such failure events is established, it will then be related to the risk classification, as categorized by the Flood and Water Management Act 2010. Currently the UK's Flood and Water Management Act 2010 reflects the view that dam failure is a low probability, high-consequence event (UK Statute Law Database, 2010). However, with respect to dam failure of small homogeneous earthfill embankment dams, it is unlikely to be a low probability, high-consequence event. For instance, such structures could have a high probability of failure due to accumulated uncertainties caused by poor and/or inconsistent monitoring and maintenance of the dam site. Furthermore, as the dam's embankment is continuously exposed to the varying seasons, its level of engineering risk could also vary due to changes in the embankment's soil saturation level, geometry, slope configuration, etc.

By analysing the probability of failure, established using APSMP, for the embankment's upstream and downstream slopes, the site-specific engineering risk, Equation 5, associated with slope failure can be established and its relation to the risk classification, defined in the Flood and Water Management Act 2010, ascertained.

4. Benchmarking of Probabilistic Analysis

With the recent introduction of the Flood and Water Management Act 2010, reservoir safety check will now be carried out using a risk-based approach in order to identify whether those classified as large raised reservoirs should be categorised as high-risk (UK Statute Law Database, 2010) as illustrated in Figure 3.

Figure 3 here

Figure 3. Classification of the risk targets associated with engineering risk

Considering Figure 3, it is evident that there is scope for a more comprehensive evaluation of risk that reflects both consequences and probability of event. However, the quantification of risk in the Flood and Water Management Act 2010 is based solely on the number of lives that might be lost because of dam failure, regardless of the probability of such an outcome. In practice, if a large raised reservoir were to be categorized as high-risk, the probability of a significant impact to the public due to dam failure would likely be smaller, on account of the vigorous regulations already in place to mitigate and guard against such incidents. In contrast small earthfill dams are often considered to have a relatively low impact on loss of human life should the failure occur, however their impact on economic activity, agriculture, etc. would be significant.

Implementation of a risk-based approach that can identify the critical conditions conducive to structural failure of the embankment is a relatively new development in the UK and, as a result, Preziosi (2013) and Preziosi and Micic (2013) developed a sample performance level benchmark, outlined in Table 4, in order to reflect the critical conditions conducive to slope failure (slope instability). Here, the slope's performance level is a notional quantitative measure (P_f), which is accepted in practice, whereas its behaviour is an indication for slope management. Furthermore, engineering risk classification, corresponding to probabilities of failure and associated consequences are included in Table 4.

Table 4 near here

As defined in Table 4, $P_f < 0.006$ is selected to indicate the slope is safe (stable) and is likely to be classified as having acceptable risk level, whereas a P_f between 0.16 and 0.07 is selected to reflect unsatisfactory performance and $P_f \geq 0.16$ signifies high risk due to complete slope failure, irrespective to consequences. Furthermore, when the slope's behaviour is classified as 'vulnerable', it indicates that risk reduction measures might be required. As Faber and Stewart (2003) pointed out engineering risk classification provides an objective tool for decision makers. It is the risk classification that is the most comprehensive measure of the infrastructure performance rather than notional P_f and/or simplistic consideration of consequences.

In practice, apart from fatalities, the failure of structures can have a significant impact through damage to neighbouring buildings and infrastructure. Thus, a small embankment dam in a specific location, could have a high probability of failure (P_f = 2.3 %) and diverse consequences (no loss of life and limited economic loss should dam failure occur). Whereas the same type of embankment dam in a different location could meet the safety standards (P_f = 0.003 %) in terms of loss of life due to a nearby road (but loss of life and higer economic loss could occur should dam failure occur). As a result, the latter would be considered as currently presenting a greater risk to public when climate change scenarios are included. However, in reality the former is also very relevant.

Comparing the slope's P_f obtained using APSMP with the risk targets defined in Table 4, a point of reference is provided that can be used as notional quantitative measure for the dam when subjected to a specific environmental effect, in this case the future precipitation scenarios defined in Table 1. While these classifications are dependent on the complexity of the applied methodology used to model the selected failure mode and aleatory variables, they do represent a sample demonstration for practical implementations.

5. Sample Analyses of Embankment Dam for Climate Scenarios

Using outcomes from the applied APSMP, the engineering risks associated with slope failure can be established for the considered dam site conditions and related to the benchmark performance levels, Table 4. For the following parametric analyses, according to benchmark conditions, complete failure of the embankment's slopes is identified when $P_f \geq 0.16$ indicating a hazardous level.

5.1. Embankment model

Within APSMP, the selected embankment model characterizes a well-established homogeneous earthfill embankment, where at the time of its construction no drainage was adopted at the downstream toe. To show validity of the APSMP formulation and as slope instability can arise due to shear failure within the embankment or its foundation, two embankment models (EMA and EMB) constructed of two comparable clay like soil (Soil C1 & C2) are considered here. These soils are typical for this type of embankment dam and the considered region (SE England) and the mean values for the properties of the selected clay like soils are defined in Table 2 (Cherubini, 2000; Carder & Barker, 2005).

Table 2 near here

For uniformity, both embankment models (EMA and EMB) are assumed to have two alternative initial slope gradient configurations, where the upstream slope has a gradient of 1.0 : 3.0 and the downstream slope's gradients are 1.0 : 2.5 and 1.0 : 4.0 respectively. To ensure comparable outcomes for both EMA and EMB, the ratio between the height of their embankment (H) and foundation (H_f) is the same for both embankment models. The developed methodology could be applied to larger embankment dams, but additional issues such as treatment of the core, the presence of a downstream toe, the foundation form, etc.

would need to be included. Their mean values and standard deviations are summarised in Table 3 and are modelled using normal (Gaussian) probability distribution as in reality they will be site specific but here, for simplicity, they are treated as Gaussian.

5.2. Prolonged low intensity precipitation scenarios

For this specific analysis, we focus on the winter season and assume that the embankment's partially saturated fill has a high saturation level (S_r = 76 %) to simulate winter conditions at the proposed dam site. The consequences of failure are identical for the selected dam and all precipitation scenarios. Figures 4 and 5 show the change in P_f for FM2 (downstream slope failure) for embankment models EMA and EMB when constructed of Soils C1 and C2 and exposed to a prolonged (4 day) precipitation scenario, as defined in Table 1.

Figure 4a here (a)	Figure 4b here (b)

Figure 4. Change in P_f for downstream slope failure for 3m high embankment (EMA) when S_r = 76 % for Soil C1 and C2 under future extreme precipitation scenario (4 days) January 2010- 2039 (Fig. 4a) and January 2070-2099 (Fig. 4b)

As shown in Figures 4a and 4b,for the small embankment model EMA, and referring to the performance levels and risk targets in Table 4, the embankment's downstream slope is deemed 'safe (stable)' when constructed of Soil C1, even after prolonged rainfall has occurred. Therefore, with specific conditions the downstream slope continues to have an acceptable risk level, 'low risk (Acceptable)' in Table 4. In contrast, when EMA was constructed of Soil C2, risk reduction is required for both slope configurations.

Figure 5a here (a)	Figure 5b here (b)

Figure 5. Change in P_f for downstream slope failure for 5m high embankment (EMB) when S_r = 76 % for Soil C1 and C2 under future extreme precipitation scenario (4 days) January 2010- 2039 (Fig. 5a) and January 2070-2099 (Fig. 5b)

Referring to the probabilities of failure presented in Table 4 and Figures 5a and 5b, they show that when the somewhat larger embankment model EMB is constructed of either Soil C1 or C2 and there is prolonged rainfall at the dam site the downstream slope becomes 'vulnerable' in terms of classification even though its performance level remains within the satisfactory bounds. This indicates risk reduction measures are required. In addition, when the embankment's downstream slope has a shallower gradient (1.0 : 4.0), the probabilities of failure indicate more satisfactory performance levels irrespective of the soil type used to construct the embankment. However, risk reduction is still required to ensure slope vulnerability is reduced.

As presented in Figures 4 and 5, the performance of the downstream slope, for both embankment models, is clearly dependent on the embankment's downstream slope gradient, embankment fill as well as the duration of the rainfall event. Consequently, if there was a prolonged rainfall at the dam site, and the embankment was constructed with a different soil type or slope gradient configuration, the dam's risk classification would need to be amended, as significant damage (not only in terms of loss of life) could eventually threaten the area downstream of the embankment due to complete slope failure.

5.3. Short high intensity precipitation scenarios

To identify the impact future short high intensity rainfall events, during the summer months, could have on the engineering risk associated with slope failure during July, it was assumed that the partially saturated fill had a lower saturation level (S_r = 57 %). As in the previous case, the considered consequences of failure remain identical for the selected precipitation scenarios. The presence of ponding on the surface of the embankment's downstream slope is also considered as over the dam's lifetime, especially well-established earthfill embankment dams, they will have been subject to rainfall induced erosion or changes to its protective vegetation cover (Hughes & Hunt, 2012) caused by either runoff or water remaining on the embankment's surface even after the rainfall event.

Table 5 near here

As shown in Table 5, if there is a short-high intensity rainfall (1 hr and 3 hrs) at the dam site during drier months, in this case July 2070 - 2099, there will only be a small change in the slope's probability of failure between 1 hour and 3 hours rainfall when the embankment has a shallower downstream slope. Thus, irrespective of the slopes gradient and soil type, the classification of the downstream slope's behaviour and performance level, in relation to rainfall-induced slope instability will be unaffected. As a result, the slope's classification will remain 'safe (stable)' for EMA and 'vulnerable' for EMB, as indicated in Table 4. Furthermore, the depth of infiltrated water through the slopes is very small (less than 5 cm), as the embankment fill cannot easily absorb the excess rainfall. This could eventually lead to either surface erosion, due to local runoff (hydraulic failure) or water remaining on the embankment's surface (ponding), or flooding downstream during or just after the rainfall event.

5.4. Observations from results

The parametric analyses show that the probabilistic methodology is able to quantify the effects of:

- Seasonal precipitation scenarios, in terms of rainfall intensity and duration, can have on a homogeneous earthfill embankment dam at a specific site.

- The embankment's geometry and fill composition (mechanical and hydraulic soil properties) on the overall behaviour and performance of the embankment's slopes.

Furthermore, when future climate scenarios are considered it will be possible to quantify the change, if any, in the slope's overall performance and risk classification. Therefore, risk classification on the basis of engineering risk can be site specific and better informed. In order to establish the dam's true risk classification, further development with respect to the probabilistic approach can be achieved by identifying and incorporating detailed models for alternative failure modes (such as overtopping, runoff and surface erosion) together with their related local factors. as alternative forms of failure could become more critical.

6. Conclusions

The APSMP can be used as tool to quantitatively measure the change in risk classification for homogeneous earthfill embankment dams against slope failure, when exposed to variable precipitation scenarios obtained using any given climate model. While here the UKCP09 climate projections were selected, it would be possible to implement alternative climate models.

It has been demonstrated that engineering risk associated with climate scenarios, specifically relating to precipitation is very sensitive to site specific conditions. This form of modelling can therefore be used as an additional tool to existing deterministic methods, as it includes a comprehensive precipitation model, which takes into account the soil and hydraulic properties of the embankment fill. It will also be possible to consider different limit states and consequences (such as loss of life, economic loss, etc.) associated with dam failure when determining the dam's risk classification. Hence, APSMP provides useful information about the behaviour of the embankment's individual slopes in the presence of site-specific uncertain factors and future precipitation scenarios. Therefore it is evident that this approach could be used for improvement of current regulatory practice and development of more sophisticated statutory guidelines.

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Table 1. Probable future rainfall intensities for South East England incorporating UKCP09 climate projections

Month & 30-year period	UKCP09 change in precipitation (%)**	Probable future extreme rainfall scenarios		
		Rainfall intensity (mm)	Rainfall duration	Average rainfall rate
January 2010-2039	16.98	174.13	4 days	43.5 mm/day
January 2070-2099	53.46	238.47	4 days	59.6 mm/day
July 2010-2039	44.23	133.61	1 hr	133.61 mm/hr
			3 hrs	44.54 mm/hr
July 2070-2099	26.81	113.33	1 hr	113.33 mm/hr
			3 hrs	37.78 mm/hr

**95th fractile ($<\mu>_{1-0.95}$) of the percentage increase in average rainfall for UKCP09 climate projections for high emission scenarios.

Table 2. Mean values for the properties of the selected clay like soils (Soil C1 & C2)

	Units	Soil types	
		Soil C1***	Soil C2****
Moisture content (θ)	%	34.5	26.5
Cohesion (c')	kN/m^2	12	14.4
Internal friction (φ')	°	23	20
Saturated unit weight of soil	kN/m^2	19.0	20.8

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

Table 3. Probabilistic modelling of the input parameters

	Variables	units	Mean (μ)	Standard deviation (σ)
	Rainfall intensity factor (RI_{fct})	mm	1.0	0.1
Soil properties	Unit weight of soil factor (γ_{fct})	kN/m^2	1.0	0.1
	Internal friction (φ')*	°	μ_φ	$0.15 \cdot \mu_\varphi$
	Cohesion (c')*	kN/m^2	μ_c	$0.3 \cdot \mu_c$
EMA	Embankment height (H)	m	3.0	0.03
	Crest Width (cw)	m	2.8	0.025
	Foundation height (H_f)	m	0.5	0.075
	Reservoir level (H_w)	m	2.0	0.1
EMB	Embankment height (H)	m	5.0	0.05
	Crest Width (cw)	m	4.0	0.04
	Foundation height (H_f)	m	0.83	0.125
	Reservoir level (H_w)	m	3.0	0.15

* Negatively correlated (-0.5)

Table 4. Benchmark probabilities of failure (P_f), and associated performance levels and risk targets for structural form of failure

Target probability of failure (P_f)	Notional performance level	Slope behaviour (Management)	Risk classification (Consequence = constant)
$P_f < 0.006$	Satisfactory	Safe (stable)	Low Risk (Acceptable)
$0.07 > P_f \geq 0.006$		Slope is 'vulnerable'	Risk Reduction Required
$0.16 > P_f \geq 0.07$	Unsatisfactory		
$P_f \geq 0.16$	Hazardous	Failed	High Risk(Unacceptable)

Table 5. P_f for downstream slope failure, for EMA & EMB given different slope gradients when S_r = 57 % for Soil C1 and C2 under variable future extreme precipitation scenarios

		Probability of failure (P_f): July 2070-2099			
		Soil C1		Soil C2	
Rainfall duration		1 hr	3 hrs	1 hr	3 hrs
EMA	Downstream slope 1.0: 2.5	$2.46e^{-03}$	$2.46e^{-03}$	$1.49e^{-03}$	$1.55\ e^{-03}$
	Downstream slope 1.0: 4.0	$3.66e^{-04}$	$3.66e^{-04}$	$1.34e^{-04}$	$1.40e^{-04}$
EMB	Downstream slope 1.0: 2.5	$8.04e^{-03}$	$8.04e^{-03}$	$5.91e^{-03}$	$6.18e^{-03}$
	Downstream slope 1.0: 4.0	$2.95e^{-04}$	$2.95e^{-04}$	$9.97e^{-05}$	$2.06e^{-01}$