Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 51 No. 3 September 2020 ISSN 0046-5828

Mechanical Models for Hazard and Risk Analysis of Structures in Creeping Landslides

Philipp W. Oberender [1], Dimitri V. Val [2] and Alexander M. Puzrin [1]
[1] *Institute for Geotechnical Engineering, ETH Zurich, Zurich 8093 Switzerland*
[2] *Institute for Infrastructure and Environment, Heriot Watt University, Edinburgh Scotland EH14 4AS*
E-mail: alexander.puzrin@igt.baug.ethz.ch

ABSTRACT: Inspired by John Burland's outstanding work on stabilizing the Leaning Tower of Pisa, this paper proposes a novel approach that allows risk assessment for another historic tower - the Leaning Tower of St. Moritz. The leaning of the St Moritz Tower is caused by differential displacements of the permanent landslide in which it is embedded, making its risk assessment challenging due to difficulties in predicting displacements and loads in creeping slopes. This paper proposes a methodology for hazard assessment in terms of expected displacements and ultimate loads making use of two novel approaches: (i) observation guided constitutive modelling (where visco-elastic-plastic models of the landslide are calibrated using observations) and (ii) assessment of landslide pressure via limit analysis. In order to complete the formulation for the assessment of risk, exemplary exposure models (for weather variables including the effect of climate change) and simple vulnerability functions are proposed.

KEYWORDS: Landslide, Creep, Risk analysis, Leaning tower

1. INTRODUCTION

In 1994-1995, when the third author was working at Imperial College, stabilization of the Leaning Tower of Pisa went through its most critical phase, culminating in the "black" September of 1995, when the tower acceleration raised fears of its imminent collapse. It was a great professional and life lesson to observe how Professor John Burland and Professor Michele Jamiolkowski, who lead the stabilization project, handled this enormous pressure and brought this challenging task to successful completion (Burland et al. 2003). A large part of this lesson was that one should never get involved in the stabilization of a leaning tower.

Unfortunately, as it often happens with important lessons, 10 years later it became completely forgotten, and the author got involved in stabilization of the leaning Tower of St. Moritz in Switzerland (Figure 1). The curious history of the tower and its continuous stabilization attempts has been recently described in Puzrin (2018). The peculiar nature of the tower inclination is that it is not caused by leaning instability or a lack of bearing capacity – the soil strength and stiffness are sufficiently high to prevent these types of deformation. The source of the tower inclination is largely kinematic – it is located on a creeping landslide. First attempts to understand the landslide kinematics and its effects on the evolution of the tower inclination opened a Pandora box, which the authors have been unsuccessfully trying to close over the past 15 years. Having Professor Burland as a role model, however, implies that you are not allowed to give up and this paper represents an attempt of a broader view on the hazard and risk analysis of structures in creeping landslides in general, and the Leaning Tower of St. Moritz in particular.

Creeping landslides are characterized by very slow slope movements caused by seasonal changes in environmental conditions, continuous viscous flow in the sliding soil mass and rate-dependent shear resistance on the sliding surface. In Switzerland, a total of 6% of the country's area is estimated to be affected by slope instabilities (Lateltin, 1997). Growing urbanization in mountainous areas and growing need for infrastructure lead to conflicting interaction between man-made structures and creeping (also called permanent) landslides. Examples of such conflicts are:

(i) deflection of roads or pipelines crossing a landslide;
(ii) damages to houses that have been built on a landslide;
(iii) creeping landslides along the banks of artificial reservoirs that might collapse into the basin.

These examples illustrate the need in understanding of the mechanisms governing such landslides and the landslide-structure interaction in order to

(i) judge the risks for existing structures,
(ii) allow risk estimations for development projects, and
(iii) provide guidelines for construction of new structures.

Figure 1 View of the Leaning Tower of St. Moritz.

The complexity of the problem, which includes rate dependent phenomena characterised by high levels of uncertainty, often makes the use of existing tools inefficient. Deriving models that aim to reproduce at the same time 2D or 3D geometry, time-dependent material parameters, hydro-mechanical coupling, large deformations and possibly interaction between soil and structures becomes an almost impossible task and often leads to overcomplicated models, which are inapplicable for practical needs.

Promising alternatives are given either by approaches which simplify the landslide mechanisms to a limited number of important elements and study their influence and interaction (Type I), or approaches that look at the landslide-structure interaction in terms of limit states (Type II).

Phenomenological landslide models that facilitate the Type I approaches have been presented by Puzrin and Schmid (2012, 2011) and Puzrin and Sterba (2006). These models have been integrated into a generalized methodology that allows derivation of constitutive models for creeping landslides based on observations (Oberender and Puzrin, 2016). Following this method, constitutive models even for complex landslides can be derived with reasonable effort from monitoring the landslide behaviour.

These models can be used to predict future movements of a creeping landslide and, therefore, assess its hazard in terms of potential future displacements. For landslide-structure interaction, which can be described sufficiently in terms of displacement, this method allows for determining the structure specific risk.

The Type II approaches may be used in cases when knowledge about the pressure acting on the structure due to the landslide is required. Friedli et al. (2017) and Hug et al. (2018) used limit analysis to estimate the ultimate pressure that can act on a structure embedded in a creeping landslide. These estimates can be used to assess whether a structure is in danger to be overstrained by the pressures from the landslide.

Hazard and risk analysis based upon these two types of recently developed methods are introduced in the following sections, using the case of the Brattas landslide in St. Moritz and of its most famous structure - the Leaning Tower.

2. BRATTAS LANDSLIDE, ST MORITZ

The Brattas landslide in St. Moritz is a particularly challenging landslide to model, as it exhibits varying behaviour both in space along the landslide and over time.

The landslide is overbuilt in its lower part (see situation in Figure 2a) by modern and historic structures (e.g. the leaning bell tower of the St. Mauritius church dating back to the 12th century), making it important to understand its future behaviour in order to assess potential hazards to structures and people living on the slope.

The landslide is constrained by a rock outcrop at its foot, with its velocity increasing uphill, leading to compression of structures on the landslide. Observations of the annual landslide velocities in comparison to the model predictions from Oberender and Puzrin (2016) are shown in Figure 2b.

Over the past decade the landslide behaviour has been monitored along its entire length, while in the overbuilt part at its foot, more than 40 years of displacement data has been collected. In this part, the landslide exhibited stages of de- and re-acceleration (for details see Oberender and Puzrin, 2016).

3. METHODOLOGY

This section briefly introduces recent developments for Type I and II approaches. For details readers are referred to the original papers.

3.1 Landslide model to analyse slope movements

Oberender and Puzrin (2016) developed a methodology which uses the data from the landslide monitoring to find a suitable constitutive model for simulating landslide behaviour.

Conceptually, the landslide is modelled as a sliding body that is moving over a slip surface (i.e. zone of intense shearing that separates stable and unstable soil). At the bottom and top of the sliding body different boundary conditions for constrained or unconstrained landslides can be applied. In case of the Brattas landslide, zero displacement at the foot and constant pressure at the top have been used.

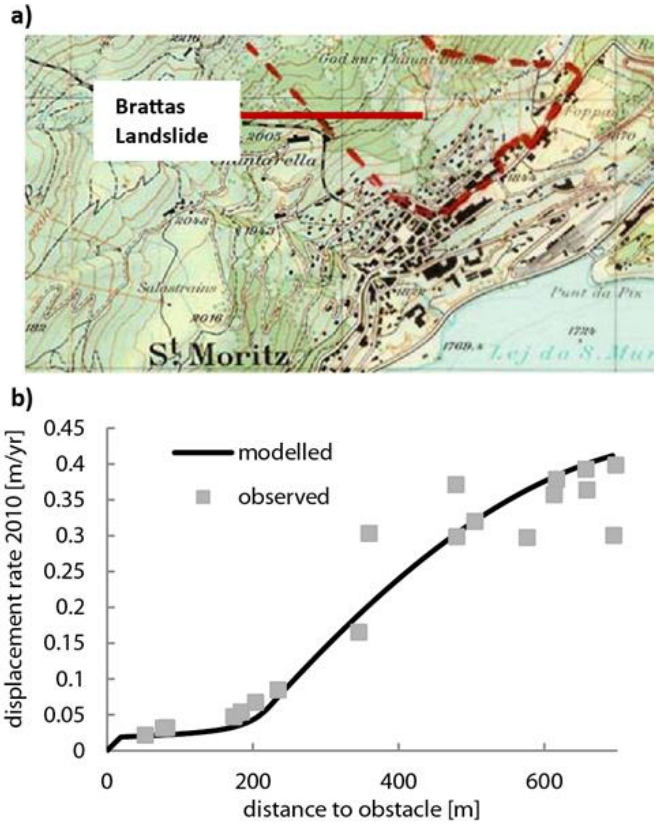


Figure 2 a) Situation showing the town of St. Moritz and the landslide; b) velocity profile along the length of the landslide.

Figure 3 shows the schematic representations of the constitutive models for slip surface and sliding body as combinations of visco-elastic-plastic elements. These are generalized models that can reproduce a number of phenomena observed in creeping landsides, such as rate dependent strength on the slip surface, creep and relaxation in the sliding body, etc. During calibration of the model, it can be simplified in such a way that only the elements that are necessary to reproduce the observed behaviour at a specific landslide location are active. In the case of St. Moritz, important observations from laboratory tests like the rate dependency along the slip surface were accounted for in the model (Figure 3a). Beyond that, observations from the field monitoring are the main source of information for the model calibration. In case of the Brattas landslide, for example, once a certain yield pressure (p_y) is reached, a change in the sliding body behaviour from visco-elastic (described by the parameters E_1, E_2, η_1, η_2 in Figure 3b) to visco-plastic (using only parameter η_3) explains the change from deceleration to reacceleration at the landslide's foot.

The landslide geometry is simplified allowing it to be modelled using a method of slices in combination with the constitutive models. Effective precipitation data is linked to fluctuations of the pore pressures along the slip surface introducing transient loading. For the Brattas landslide, a linear reservoir model linking effective precipitation to pore pressure along the slip surface has been proven to reproduce the observed pore pressure and landslide velocity fluctuations sufficiently well.

The combination of the simplified geometry with the two constitutive models (for the landslide body and the slip surface) and the simple hydrological model allowed for a reasonably accurate simulation of the landslide behaviour.

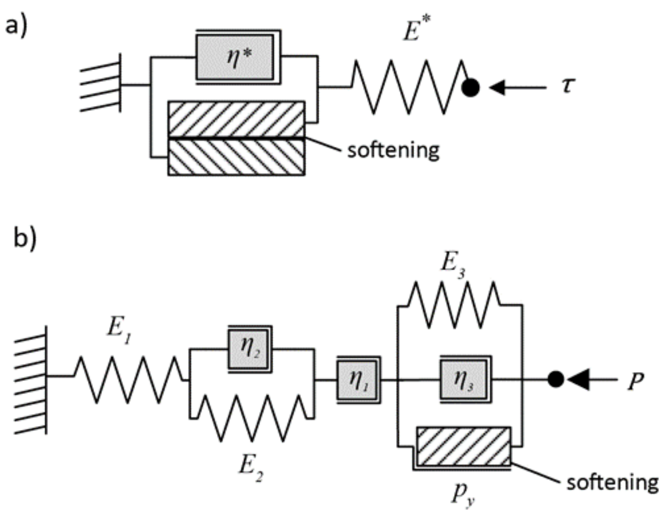


Figure 3 Conceptual visco-elastic plastic models of a) slip surface and b) sliding layer from Oberender and Puzrin (2016).

3.2 Ultimate loads on structures in creeping slopes

For structures that are embedded in creeping slopes but founded below the slip surface, e.g. retaining walls, Friedli et al. (2017) derived an exact limit analysis solution for the ultimate landslide pressure. For structures that are not founded deep enough to reach stable ground but are embedded in a compressing landslide body (Figure 4), Hug et al. (2018) used upper bound limit analysis and finite element simulations to calculate the pressure that can ultimately act on their up- and downhill facing walls.

Parameters required for the calculation of the ultimate load (F) are given in Figure 3. These are easy to determine strength parameters of soil (friction angle, ϕ', and cohesion, c'), weights (of soil, γ_{soil}, and of the structure, G_b) and geometry parameters (slope inclination, α, depth of the sliding surface, t, and embedment depths d_1 and d_2 at the up- and downhill sides of the structure):

$$F = F(\phi', c', \Theta, \gamma_{soil}, G_b, d_1, d_2, t) \tag{1}$$

The dashed lines in Figure 4 outline one potential failure mechanism. Depending on the parameters other mechanisms are also possible (see Hug et al. 2018). The analytical solutions to estimate the pressure on structures can be found in Friedli et al. (2017) and Hug et al. (2018).

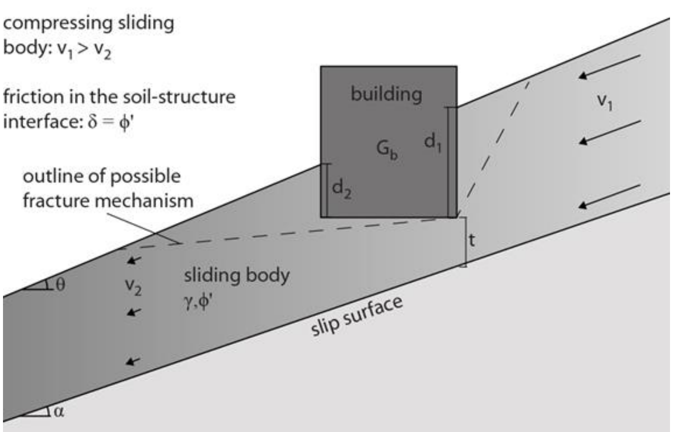


Figure 4 Structure embedded in a compressing landslide (changed from Hug et al. 2018)

3.3 Exposures

As mention in section 3.1, the landslide model requires exposure data in terms of effective precipitation. In Oberender and Puzrin (2016) effective precipitation is calculated according to Thornthwaite (1948), which requires the exposure in terms of precipitation and temperature.

Pore pressures at the depth of the slip surface in the Brattas landslide are shown in Figure 5, where the solid lines show hourly measurements and the grey diamonds monthly average values. As can be seen, the pore pressure is mainly influenced by long-term pore pressure variations that are induced by snowmelt during spring and rainy months in autumn. This pattern is only interrupted in 2015 when no autumn peak can be observed. Heavy short duration precipitation events (e.g. thunderstorms) have far smaller influence on the pore pressures than long-term fluctuations (the short-term peaks in Figure 5 are either due to malfunction of the monitoring system or drilling works near the existing piezometer).

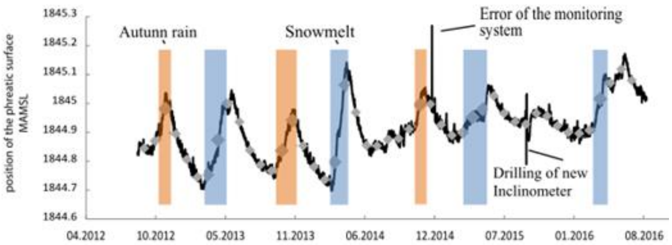


Figure 5 Piezometer readings of pore pressures on the slip surface in the Brattas landslide (Oberender, 2018)

Due to these observations it has been decided to use time steps of one month and an exposure model for long-term weather patterns for the Brattas landslide. In order to reproduce the effects of long-term weather variations, a simple weather generator has been developed. The generator allows producing monthly precipitation and average monthly temperature that can later be converted into series of effective precipitation. Since no complete weather data series for St. Moritz itself is available, 151 years of weather data from two weather stations in the vicinity of St. Moritz have been combined to complete it. In order to model the total amount of monthly precipitation ($P_{tot,i}$), different distributions have been evaluated in literature (e.g., Wilks and Wilby, 1999). The two-parameter Gamma distribution is a common choice to model daily and monthly precipitation and also is in good agreement with the observed data:

$$P_{tot,i} = G(a_i, b_i) \; with \; i = 1 \div 12 \tag{2}$$

where $G(a_i, b_i)$ is the Gamma distribution with parameters a and b derived for each month (index $i = 1$ to 12) separately.

More complex probability distributions or different distributions for each month could be applied to better represent, e.g., large rain amounts, but according to Wilks and Wilby (1999) this would have little influence on a final result. For St. Moritz, the correlation of precipitation of subsequent months is weak and, therefore, precipitation for each month will be treated independently.

An autoregressive process (AR-model) has been used to model other weather variables, such as monthly mean temperature (compare to Wilks & Wilby, 1999). In order to reflect the dependency of monthly mean temperature on the amount of precipitation, this model is extended by an explanatory variable, which is monthly precipitation, similar to Kilsby et al. (2007). This results in a so called ARX-model which is derived for each month of the year ($i = 1 \div 12$):

$$\bar{T}_i = C_{1,i}\bar{T}_{i-1} + C_{2,i}\bar{P}_i + \varepsilon_i \tag{3}$$

where ε_i is a white noise term and $C_{j,i}$ are regression constants which are calibrated for each month separately in order to reflect seasonal dependence of temperature; $\bar{T}_i$ and $\bar{P}_i$ are the standardized monthly average temperature and monthly total precipitation, respectively:

$$\bar{T}_i = \frac{T_i - \mu_{T,i}(t)}{\sigma_{T,i}}; \quad \bar{P}_i = \frac{P_i - \mu_{P,i}}{\sigma_{P,i}} \tag{4}$$

where $\mu_{T,i}(t) = K_{1,i}t + K_{2,i}$ and $\mu_{P,i}$ are the mean of the average temperature and the mean of the monthly precipitation, respectively; $\sigma_{P,i}$ and $\sigma_{T,i}$ are standard deviation of precipitation (P_i) and temperature (T_i). As can be seen from Eq. (4), the mean of the average temperature, $\mu_{T,i}(t)$, changes linearly with time (parameters $K_{1,i}$ and $K_{2,i}$), reflecting the climate change induced trend towards higher temperatures.

In order to achieve a stationary time series, the observed trend is first removed from the temperature data, and subsequently the time series is standardized by dividing it by its standard deviation. The trend is treated here as deterministic, therefore subtracting it from the data should preserve the properties of the AR-process (Yue and Pilon, 2003).

The performance of the combined precipitation/temperature generation model was assessed by simulating the 151 years of observations. Figure 6 shows the comparison between observed quantiles and quantiles for 1000 generated series of 151 years of precipitation and temperature. Both mean values and variances can be captured reasonably well.

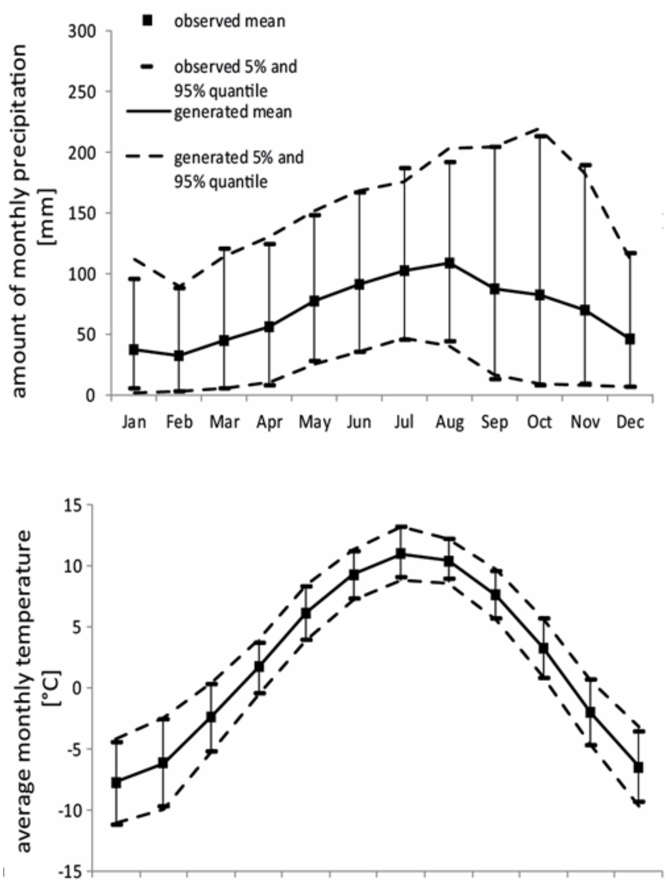


Figure 6 Comparison of observed and simulated quantiles for a) monthly precipitation and b) monthly average temperature (Oberender, 2018)

Additionally, the model allows the correlation between precipitation amount and average temperature to be preserved. Also, the first two moments of the generated annual precipitation and temperature are reproduced reasonably well, which indicates that the generated precipitation series are applicable for long-term simulations as well. Alternatively, other weather generators that produce long-term precipitation and temperature data could also be combined with the landslide model.

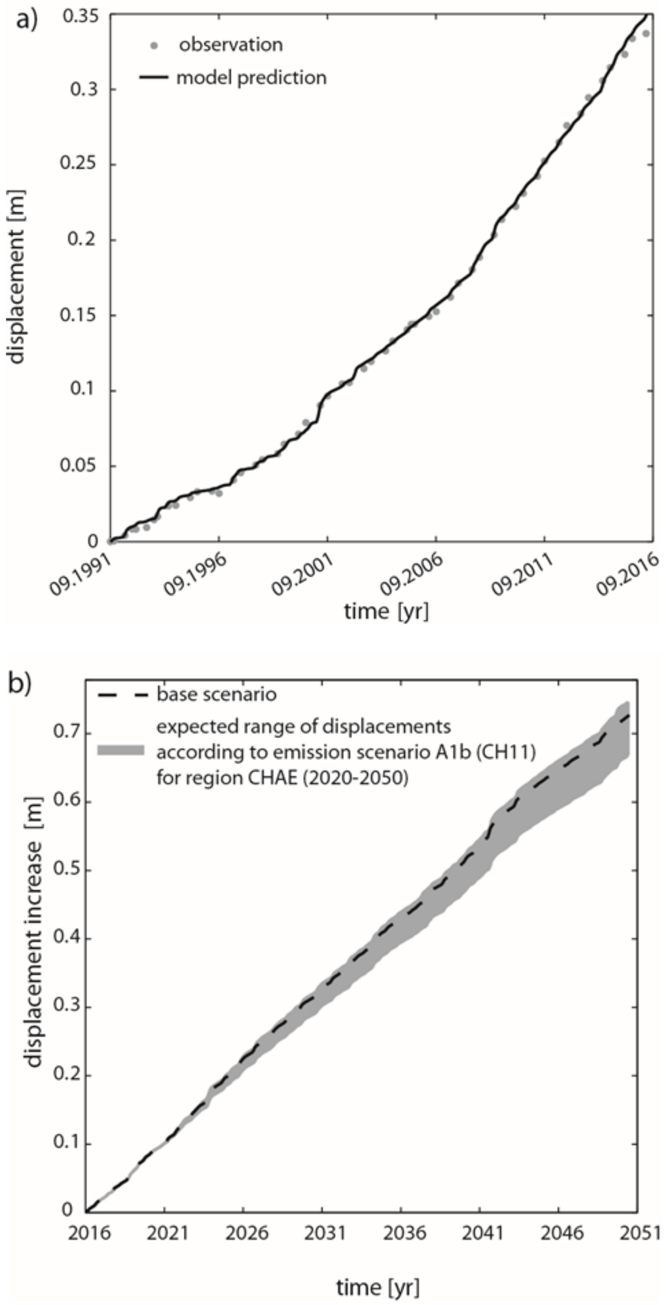
4. METHODOLOGY

4.1 Landslide model to analyse slope movements

Using the exposure model described before in combination with the landslide model (section 3.1 and Oberender and Puzrin, 2016), hazard can be calculated in the form of expected displacements for the Brattas landslide.

The generated weather data is converted to the effective precipitation input (accounting for winter and snowmelt as described in Oberender and Puzrin, 2016) and then applied to the landslide model. This allows the long-term behaviour of the landslide to be simulated and the influence of variability of precipitation patterns on the predicted displacements to be assessed. Additionally, the influence of climate change can be studied by applying synthetic precipitation and temperature from different time periods.

Figure 7a shows the comparison between observations (dots) and model prediction (solid line) for the calibration period of the landslide model from 1991 to 2016. Figure 7b shows predicted range of displacements for temperature and precipitation modified according to Swiss climate change scenarios in the vicinity of the leaning tower.



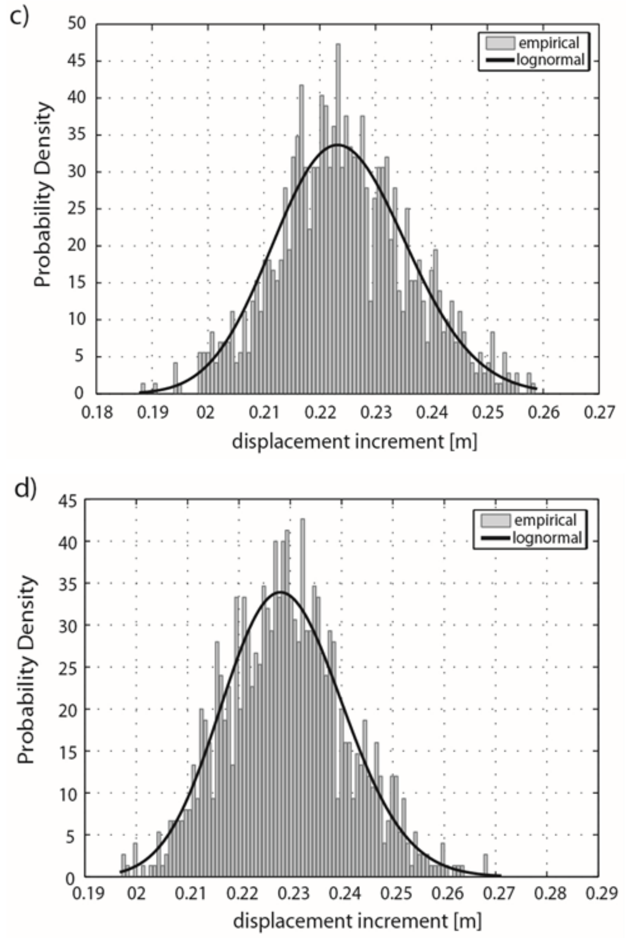


Figure 7 a) comparison between landslide model and observed displacement data in the vicinity of the leaning tower during the calibration period (1991-2016); b) predicted range of displacements for temperature and precipitation modified according to Swiss climate change scenarios (CH2011, 2011) in the vicinity of the leaning tower; Expected distribution of displacement increase near the leaning tower for 10 years; c) precipitation data generated for 2016–2026; d) precipitation data generated for 1950–1960

Figure 7c displays the expected displacement distribution at the foot of the landslide in the vicinity of the leaning tower of St. Moritz 10 years from a starting point in 2016, using weather data generated for the period from 2016 to 2026. Figure 7d shows the same prediction, but using weather data generated for the period 1950–1960. As can be seen, the predicted displacement distribution for the weather data 2016–2026 has slightly lower mean value than the one simulated with the data from 1950–1960.

This observation results from the fact that due to generally higher temperatures but constant precipitation amount, the effective precipitation decreases. Since effective precipitation is the main driver of the landslide, a drop in effective precipitation leads to a drop in pore pressures on the slip surface and, therefore, a smaller velocity of the landslide.

To compare the results generated using the probabilistic weather model, change factors for temperature and precipitation provided by the Swiss meteorological service (Meteo Swiss) have additionally been used. These seasonal change factors can be applied to monthly temperature and precipitation data for the period 1980–2009 and result in data that is representative for the period 2021–2050 (see CH2011, 2011). For the missing years between 2016 and 2021, data from the past 5 years has been used. To compare the results, the data from 1980–2009 is also applied without change factors, forming a base scenario (i.e. without further climate change).

For the different change factors according to the climate change scenarios given in CH2011 (2011), predictions show a small increase or decrease in predicted landslide displacements (grey shaded area in Figure 7b). This confirms the results of simulations with synthetic precipitation data and similar to results from other research (Comegna et al. 2013). Note that herein only climate change induced differences in the rain water balance have been taken into account. Other consequences of climate change like increased glacier melting or accelerated snowmelt in spring may have a more adverse impact on creeping landslides.

4.2 Hazard modelling: Loads on structures

In cases where the soil structure interaction cannot be expressed sufficiently accurately via displacements, loads (i.e., pressures on the structure) have to be used in risk assessment. These loads on structures are difficult to assess from observations and the only methods for reliable measurements have been developed so far for pressure changes (Schwager 2013, Schwager and Puzrin 2014) and not for absolute pressures.

However, following Hug et al. (2018), the ultimate load acting on a structure embedded in a creeping slope can be estimated and uncertainty with respect to the model parameters can be taken into account by using the analytical solutions of the upper bound limit analysis. Since the parameters with respect to geometry (d_1, d_2, t) are either known or can be found from inclinometer measurements with high certainty, they can be treated deterministically. The same is true for the slope inclination throughout the length of a potential failure mechanism (θ) and the weight of the building. In St. Moritz, building regulations require the so called weight compensation, where structures are to be built to compensate the weight of soil that they replace in the landslide.

Marchetti dilatometer tests (Marchetti et al. 2001) showed friction angles ranging from 30° to 35° for the material of the Brattas landslide. Assuming according to Lumb et al. (1978) that the angle of internal friction is normally distributed with parameters $\mu = 33.67°$ and $\sigma = 1.97$, distributions of expected normalized horizontal earth pressure (K_{creep}) can be generated. Figure 8 shows the expected distribution of the creep (earth-) pressure coefficient.

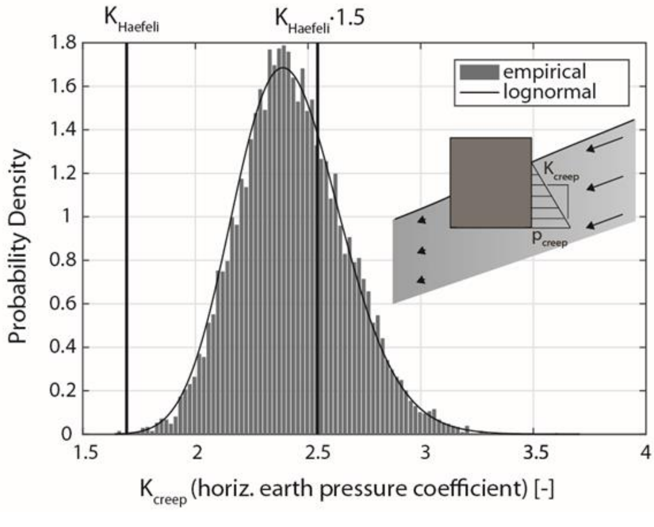


Figure 8 Predicted distribution of earth pressure coefficients in creeping slopes (n=10000 simulations) compared to the pressure coefficient calculated according to Haefeli (1946).

Although Hug et al. (2018) only considered the plane strain problem while other collapse mechanisms that might involve the structure have not been investigated, their approach allows to further develop the calculation model and reduce uncertainties. Also, finite element simulations by Hug et al. (2018) show that the ultimate load is likely to be reached within the lifetime of a typical structure, therefore using the ultimate state for assessment of structures is not overly conservative.

4.3 Risk assessment for creeping landslides

In order to assess the risk associated with creeping landslides, the consequences and vulnerability of elements at risk have to be determined. This paper only looks at the creep stage of a landslide where structures within the creeping soil mass get continuously damaged but the risk for human life is not present. Thus, it is necessary to relate movements of the landslide (hazard) to damages caused to structures. This is not an easy task, as reliable models do not yet exist, while information about the damage state and characteristics of existing structures on creeping slopes is often difficult to obtain.

In principle, three construction strategies to cope with the damage from creeping landslides can be distinguished:

(i) Isolating the structure from the landslide;
(ii) Accommodating the deformation of the structure;
(iii) Resisting the deformations of the landslide.

The following sections will briefly outline potential ways to use the previously derived hazard in terms of displacement or ultimate loads to be used in risk assessment for structures depending on the chosen construction strategy.

4.4 Risk for structures isolated from the landslide

For structures isolated from the landslide and similarly for structures that accommodate the landslide movements, the vulnerability function can simply be expressed in terms of accumulated displacements:

$$V = P\big(D|\delta_{ls}(t)\big) \tag{5}$$

where $P(D|\delta_{ls})$ is the probability of a certain damage (D) given that the structure has experienced the displacements δ_{ls} from the landslide.

In cases of isolated structures where no damage occurs before the limiting displacement (δ_{lim}) is reached, the vulnerability function can often be written in a binary form:

$$V = \begin{cases} 0 \ for \ \delta_{ls}(t) < \delta_{lim} \\ 1 \ for \ \delta_{ls}(t) \geq \delta_{lim} \end{cases} \tag{6}$$

Having formulated the vulnerability function in such a form, the risk is given as the product of the probability of the landslide displacements exceeding the limiting displacement within a certain time period and the costs thereby incurred.

4.5 Risk for structures compressed by the landslide

In landslides that are compressing like the Brattas landslide, the pressure on a structure will grow until either visco-elastic load redistribution allows the landslide velocity field to homogenize around the structure or one of four collapse scenarios occurs:

(i) failure of the soil not involving the structure (global failure of the landslide, see Friedli et al. 2017);
(ii) failure of the soil and the soil–structure interface around the structure (local failure, see Hug et al. 2018)
(iii) collapse of the structure;
(iv) combined failure of soil and structure.

During the time before one of the scenarios occurs damage accumulates. Estimating the vulnerability of structures as a function of damage vs. displacements is difficult and so far mostly empirical or semi-empirical (e.g. Palmisano et al. 2016, Uzielli et al. 2015). In contrast, the previously shown hazard in terms of ultimate loads offers an opportunity for deciding if a structure will or has already reached its limit and, therefore, requires structural strengthening, based on calculations of load and resistance.

Provided that uncertainties with respect to the bearing capacity of the structure can be quantified, the probability distribution for the resistance (R) can be calculated. With the hazard shown in section 4.2, this allows for deriving the probability of failure. Since the assessment of the structural properties may be difficult, in particular for existing structures, this evaluation can be simplified by analysis of the load assumptions made during the design of the structure.

For example, a common way to estimate the creep pressure is to use an approach proposed by Haefeli (1946). Figure 7 shows the earth pressure coefficient calculated according to Haefeli (1946) based on a mean angle of internal friction of 33.7° (from the Dilatometer tests) and the same coefficient multiplied by a global safety factor of 1.5.

As can be seen, using the coefficient based on the mean friction angle severely underestimates the pressure; using the coefficient with the safety factor still produces a load that in this case has a 29% probability of being exceeded. Combining this probability with the cost of losing the structure allows for calculating risk for this case. Note that, as shown by Friedli et al. (2017), in other situations using the Haefeli's approach may lead to even more significant underestimation of the earth pressure.

4.6 Decision making algorithm

Given that the first assessment indicates a relatively high risk of the structural resistance being exceeded, the decision maker has three options:

(i) strengthen the structure (no further investigation);
(ii) accept the risk of potential overstraining;
(iii) collect further data and/or implement the observational method.

Usually, the collection of additional data via inspection of the building will be the preferred course of action. Since the development of the creep pressure is a time dependent process, at the time of the assessment the maximum pressure may not yet be reached. Therefore, evaluation of the structural state should include the age of the structure and a monitoring period sufficiently long to observe the development of deformations and damages.

In case the ultimate pressure in the landslide around the building has already been reached without causing structural damage, no strengthening of the structure is required.

In case the pressure induced by the landslide on the structure is still increasing, the deformation of the structure and subsequently (structural) damage will also increase.

In cases where the ultimate resistance of the structure has been exhausted before the maximum possible pressure that can be mobilized in the landslide is reached, the structure or parts of it will fail. In a landslide body experiencing compression, like in the Brattas one, the building will be continuously compressed during the landslide motion. Due to viscous nature of creeping slopes, a sudden collapse of such a structure may not occur since load redistribution within the creeping slope may still be possible. However, such a state obviously cannot be tolerated, since the structure will deform with the landslide until eventually the serviceability limit state is reached or, more dangerously, the vertical load transfer cannot be guaranteed anymore. Additionally, in such state the structure has no reserves that could be mobilized in the case of an extreme loading scenario (e.g. earthquake).

It has to be noted that delaying the strengthening of the structure to collect more information may increase the cost of refurbishment as it may become more difficult and more parts of the structure may require to be strengthened.

When the decision criterion in terms of expected cost ($E[C]$) is based purely on existing information (i.e. the probability of the design load being exceeded, without monitoring the structure), it is given by:

$$E[C] = min\,\{(P) \cdot C_0; C_1\} \tag{7}$$

where P is the prior probability of structural failure; C_0 and C_1 are the costs of failure of the structure or its strengthening, respectively.

If additional information from monitoring is gathered, the expected cost can be evaluated as:

$$E[C] = min\{(P')(C_0) + C_2; (C_1 + C_{1+} + C_2)\} \tag{8}$$

where P' is the posterior probability of failure; C_{1+} is the extra cost due to delaying the strengthening; and C_2 is the cost of inspecting and monitoring the structure. The entire process is schematically given in Figure 9.

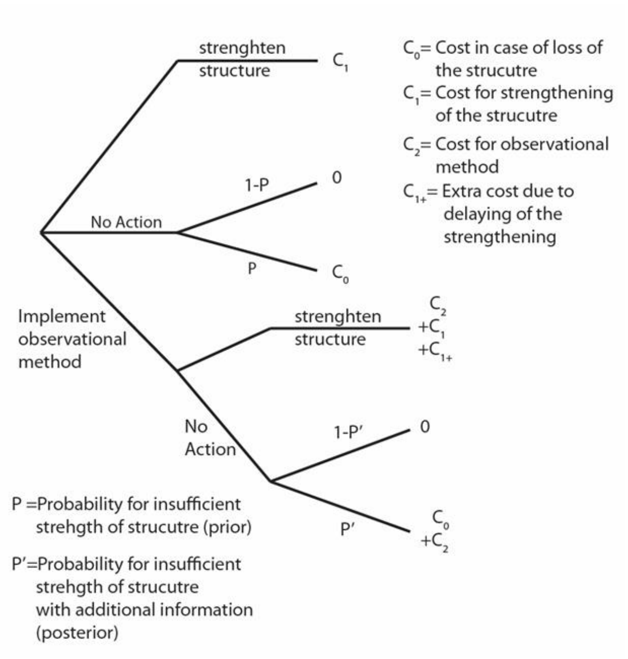


Figure 9 Schematic depiction of possible courses of action when assessing structures in creeping landslides and related costs

5. THE LEANING TOWER OF ST. MORITZ

For the leaning tower of St. Moritz (Figure 1), a strategy which can be viewed as a combination of (i) and (ii) from section 4.3 has been used since 1983: the historical structure has been lifted in 1983 from its foundation and founded on two concrete diaphragm walls via Teflon bearing pads, so that the actual historic tower is isolated from the landslide. The two foundation walls are allowed to move with the landslide; consequently, for the entire structure, the displacements due to the landslide are accommodated.

The foundation walls not only move with the landslide but also rotate causing the tower to tilt downslope. Therefore, the connection between the foundation and the historic tower has been designed such that it allows the correction of some of the tower inclination induced by the landslide movement. At the same time, the tower has been pre-stressed to allow a relatively large amount of tilt.

Thus, similar to isolated structures, whenever a certain limiting inclination, usually expressed as a limiting deflection of the tower at height of its bell chamber ($d_{\text{tower,limit}} = 2$ m), is reached, the tower has to be stabilized, i.e. the inclination has to be reduced. This stabilization is done by lifting the tower with hydraulic jacks and adjusting the height of the bearing pads.

There is correlation between the tower inclination and the landslide displacements that allows using displacements for predictions of the inclination. Stabilization works at the tower and its surrounding walls can alter the correlation between displacements and inclination; therefore, after each stabilization the correlation between tower deflection and landslide displacements has to be adjusted.

In Figure 10, the expected distribution of tower inclination for the year 2031 is shown. The results can be represented by a log-normal distribution from which the probability of exceeding the limit 2 m deflection, $P(\delta > \delta_{lim})$, can be calculated as 0.04. Using Eq. (6), the risk is given as:

$$\begin{aligned} R &= P(\delta > \delta_{lim}) \cdot V(\delta_{ls}(t) > \delta_{lim}) C_{stabilization} \\ &= 0.04 C_{stabilization} \end{aligned} \tag{9}$$

where $C_{stabilization}$ are the costs of stabilizing the leaning tower.

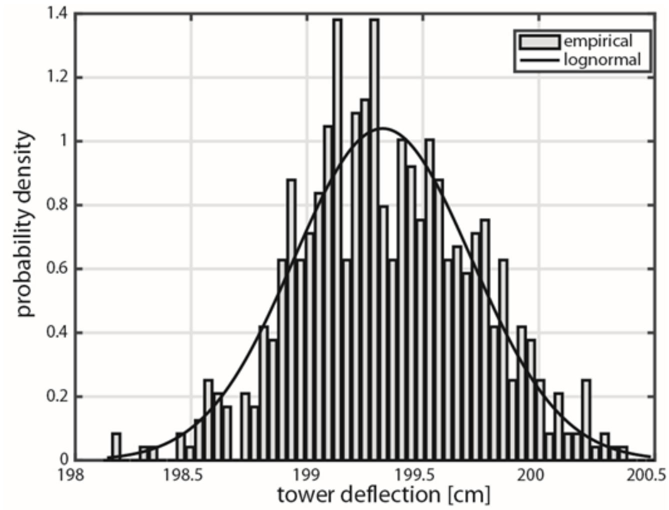


Figure 10 Predicted distribution of tower deflection in 2031 from n = 1000 simulations.

6. CONCLUSIONS

The two proposed approaches (displacements and forces) for the assessment of hazard and risk associated with creeping landslides based on simple assessment methods of landslide mechanics have been presented.

Which method is best suited for the assessment of a particular structure on a creeping landslide depends on the interaction between the structure and the landslide. For structures that are built to be isolated from the landslide movement or can simply accommodate a certain level of deformation induced by the landslide, risk can be assessed on the basis of landslide displacements (first approach). For structures that resist the landslide movement the situation is more difficult and herein it is proposed to assess the danger of collapse of the building based on ultimate limit states in the landslide (second approach).

In the first approach, the hazard and risk assessment is based on simple phenomenological landslide models that allow the derivation of expected displacements within a certain time frame. The models heavily involve observations of landslide behaviour during transient loading (i.e. influence of precipitation) what aims to increase the reliability of the models.

Application of the model required developing the methods for predicting the most important exposures (temperature and precipitation) since many existing methods for weather generation seem not yet to be suitable for the problem considered herein. Modelling of the landslide behaviour has indicated that long-term precipitation patterns have more influence on the landslide movement than short-term extremes. Therefore, applying a weather generation model that can produce long-term series with correct variations is necessary.

Similar to what has been found by other researchers, the effect of climate change causes a slight deceleration of the landslide, provided that the weather is the only influence taken into account.

Combining the generated displacement data with a vulnerability function for the structure of interest allowed to estimate the structure specific risk. The procedure was demonstrated using the case of the leaning tower of St. Moritz.

Structures, for which the ultimate limit state cannot be expressed in terms of deformations, require information about the forces they are subjected to by the landslide. Such structures can be assessed based on limit loads. In this case, loads derived from an upper bound limit analysis provide estimates for the maximum possible load generated by the landslide. This load can then be compared to the calculated resistance of the structure or to the design assumptions made with respect to loads from the landslide. Of course, this process still does not allow for predicting the damage evolution, in particular for non-structural damage, but it can serve as an additional tool (e.g. to establish a deformation-damage relationship) to decide which structures are not safe and for which additional information should be collected. Since the ultimate load on a structure depends only on relatively simple geometrical and geotechnical parameters, introduction of uncertainty via these parameters is possible.

Needless to say, the simplifications with respect to the models used in both approaches introduce unavoidable model uncertainty. The first approach, however, is strongly based on observational data, reducing the uncertainty of the model over time. For the second approach, the tools used to find the ultimate limit states (upper bound limit analysis and FEM modelling) allow for further reduction of the uncertainty with respect to the numerical model, e.g. by accounting for the 3D nature of the problem.

Overall, the assessment of structure-specific risk posed by creeping slopes remains challenging. However, the methods presented in the paper provide new tools for such an assessment by using original models based on fundamental mechanics and observations. In particular, these tools can help to assess the structure-specific risk of reaching the state where the structure is either overstrained or loses its functionality.

7. ACKNOWLEDGEMENTS

The work has been supported by the Swiss National Science Foundation, SNF Grant No. 200021_144253. The authors are grateful for the community of St Moritz for the long-term cooperation and to Dr. B. Friedli and S. Hug for data and useful discussions. The third author is grateful to Professor John Burland for his life-long support and inspiration.

8. REFERENCES

Burland, J. B., Jamiolkowski, M., and Viggiani, C. (2003) “The stabilisation of the leaning Tower of Pisa.” Soils and Foundations 43(5): pp 63-80. https://doi.org/10.3208/sandf.43.5_63

CH2011, (2011). Swiss Climate Change Scenarios CH2011 (Report). Zurich.

Comegna, L., Picarelli, L., Bucchignani, E., and Mercogliano, P. (2013) “Potential effects of incoming climate changes on the behaviour of slow active landslides in clay.” Landslides 10, pp 373–391. https://doi.org/10.1007/s10346-012-0339-3

Friedli, B., Hauswirth, D., and Puzrin, A. M. (2017) “Lateral earth pressures in constrained landslides.” Géotechnique, pp 1–16. https://doi.org/10.1680/jgeot.16.P.158

Friedli, B., Hauswirth, D., and Puzrin, A. M. (2017) “Der Kriechdruck – Erddruck auf Bauwerke im Kriechhang.” Mitteilungen der Geotechnik Schweiz 175 pp 41-48.

Haefeli, R. (1944) “Zur Erd- und Kriechdruck-Theorie.” Schweizerische Bauzeitung 124, Nr. 20, pp 256–260.

Hug, S., Friedli, B., Oberender, P., Puzrin, A.M. (2017) “Ultimate loads on buildings in landslides.” Géotechnique, pp 1–34. https://doi.org/10.1680/jgeot.17.p.134

Kilsby, C. G., Jones, P. D., Burton, A., Ford, A. C., Fowler, H. J., Harpham, C., James, P., Smith, A., and Wilby, R. L. (2007) “A daily weather generator for use in climate change studies.” Environ. Model. Softw. 22, pp 1705–1719. https://doi.org/10.1016/j.envsoft.2007.02.005

Lateltin, O. (1997). Berücksichtigung der Massenbewegungs-gefahren bei raumwirksamen Tätigkeiten.

Marchetti, S., Monaco, P., Totani, G., and Calabrese, M. (2001) “The Flat Dilatometer Test (DMT) in Soil Investigations.” A Report by the ISSMGE Committee TC16

Oberender, P. W. (2018) Creeping constrained landslides under extreme environmental and seismic conditions. ETH Zurich.

Oberender, P. W., and Puzrin, A. M. (2016) “Observation-guided constitutive modelling for creeping landslides.” Géotechnique 66, pp 232–247. https://doi.org/doi:10.1680/jgeot.15.LM.003

Palmisano, F., Vitone, C., and Cotecchia, F. (2016) “Methodology for Landslide Damage Assessment.” Procedia Eng. 161, pp 511–515. https://doi.org/10.1016/j.proeng.2016.08.679

Puzrin, A. M. (2018) “The Leaning Tower of St. Moritz: A structure on a creeping landslide.” In Geotechnics and Heritage: Historic Towers, edited by Lancellotta, Renato, Flora, Alessandro and Viggiani, Carlo, pp 123-143, Boca Raton: CRC Press.

Puzrin, A. M., and Schmid, A. (2011) “Progressive failure of a constrained creeping landslide.” Proc. R. Soc. A - Math. Phys. Eng. Sci. 467, pp 2444–2461. https://doi.org/DOI 10.1098/rspa.2011.0063

Puzrin, A. M., and Schmid, A. (2012) “Evolution of stabilised creeping landslides.” Géotechnique, 62, pp 491–501.

Puzrin, A. M., and Sterba, I. (2006) “Inverse long-term stability analysis of a constrained landslide.” Géotechnique, 56, pp 483–489.

Schwager, M. V. (2013) Development, analysis and applications of an “inclinodeformeter” device for earth pressure measurements. ETH Library. https://doi.org/10.3929/ethz-a-010183078

Schwager, M. V, and Puzrin, A. M. (2014) “Inclinodeformeter pressure measurements in creeping landslides: analytical solutions and field applications.” Géotechnique, 64, pp 447–462.

Thornthwaite, C. W. (1948) “An Approach toward a Rational Classification of Climate.” Geogr. Rev. 38, pp 55–94. https://doi.org/Doi 10.2307/210739

Uzielli, M., Catani, F., Tofani, V., and Casagli, N. (2015) “Risk analysis for the Ancona landslide—II: estimation of risk to buildings”. Landslides 12, pp 83–100. https://doi.org/10.1007/s10346-014-0477-x

Wilks, D. S., and Wilby, R. L. (1999) “The weather generation game: a review of stochastic weather models”. Prog. Phys. Geogr. 23, pp 329–357. https://doi.org/Doi 10.1177/030913339902300302

Yue, S., and Pilon, P. (2003) “Interaction between deterministic trend and autoregressive process.” Water Resour. Res. 39. https://doi.org/10.1029/2001WR001210