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Predicting Rainfall-induced Movements of Slides in Stiff Clays

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Predicting rainfall-induced movements of slides in stiff clays

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Abstract

A physically-based numerical method is presented for displacements hazard analyses, at large-scale, in the case of landslides characterized by movements along pre-existing slip surfaces induced by rainfall-triggered pore pressure fluctuations. The method comprises a transient seepage finite element analysis and a kinematic model. With reference to the latter, the rates of displacement are assumed to be of the viscous type and are related to the factors of safety along the slip surface computed performing time-dependent limit equilibrium analyses. Monitoring data from an active slide in Central Italy are then used both for calibrating the models, by means of an inverse analysis procedure that minimizes the errors between numerically computed results and available observations, and for validating the results of the calibrated models. Subsequently, the calibrated and validated models are used to predict the response of the slope to different rainfall scenarios. The proposed method has been named "R-u-F-v prediction."

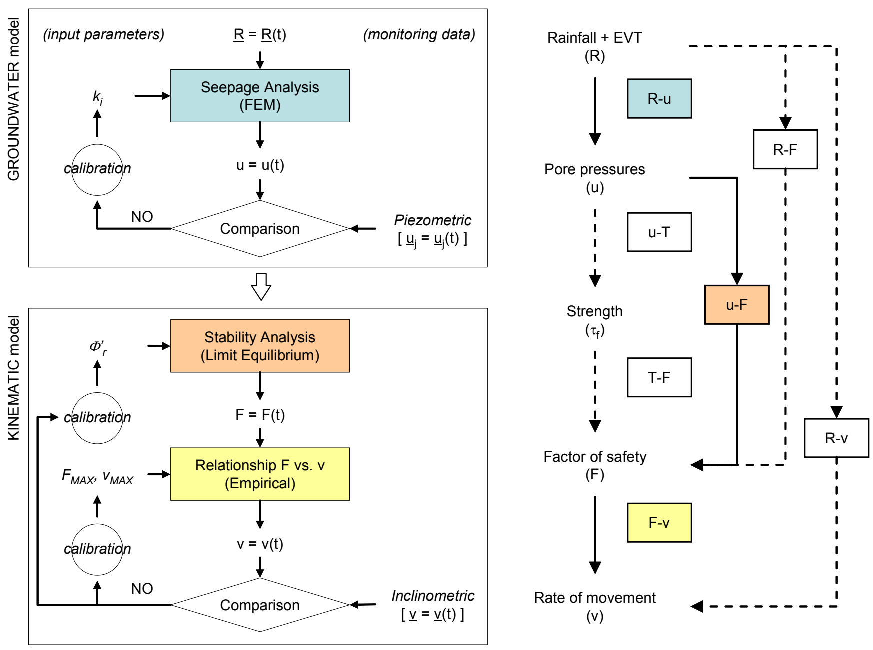
Introduction

Hazard analyses at large scale of landslide movements in clayey soils are generally performed using black-box models, i.e. phenomenological relationships, probabilistic approaches and/or artificial neural networks (Voight 1988, Mayoraz and Vulliet 2002, and others). Only rarely, geotechnical models providing physically-based predictions are used (Vulliet 1999). Within the general framework proposed by Leroueil et al. (1996) for the geotechnical characterization of slope movements, the paper will focus on physically-based models with reference to "reactivated slides in stiff clay or clay shale." These slides are generally characterized by: slope movements localized along a shear zone with essentially rigid blocks sliding over an essentially rigid base; residual shear strength at the sliding surface; low rate of displacements related to the stress level at the sliding surface; increase in pore pressures in the vicinity of shear surfaces. This study analyzes the landslides whose state of activity is related to the transient regime of a single variable, rainfall, governing both the pore pressure regime in the slope and the rate of the displacements along the sliding surface, which can be often considered of the viscous type. Rainfall effects are here modelled by setting time-dependent flow conditions at the ground surface boundary of a bi-dimensional section of the slope.

Numerical procedure to compute displacements along a pre-existing slip surface

For landslides moving along pre-existing slip surfaces, limit equilibrium analyses are commonly used to evaluate the stability of the slope. These analyses assume that soil behaves in a rigid-perfectly plastic manner, thus they only provide information about general failure and don't predict any movements before failure. However, experience shows that translational slides in stiff clays are often characterized by long-lasting intermittent movements related to the seasonal fluctuations of pore pressure values and, consequently, of the shear stress levels along the slip surface. According to many authors the nature of such movements is viscous (among others Vulliet and Hutter, 1998).

In this work, it is assumed that viscous type movements not yielding to general failure may occur for values of the average shear stress along the slip surface lower than the average residual shear strength of the soil on that surface (i.e. movements along a slip surface may occur even when limit equilibrium analyses yield values of the factor of safety higher than 1.0). By employing this assumption, one can relate the evolution with time of factors of safety along a slip surface, computed performing time-dependent limit equilibrium analyses, to the rate of displacement of the slide. In these analyses, the values of the pore pressures on the slip surface are a result of a rainfall governed transient seepage analysis of the entire slope. The flowchart of the proposed numerical procedure is presented in Figure 1(a). Figure 1(b) shows the various approaches which can be used to take into account the complexity of the soil response to rainfall (Leroueil 2001). Consistently with this scheme, the proposed method has been named "R-u-F-v prediction".



(a) (b)

Figure 1. Predicting rainfall-induced movements of slides: (a) "R-u-F-v prediction" numerical procedure, (b) (modified after Leroueil 2001) from hydrologic conditions to rates of displacement.

The method comprises two models: a groundwater model and a kinematic model. In the first model, monthly rainfall data, R(t), are used as flow boundary conditions at the surface of a 2D transient seepage analysis to compute pore pressure variations in the slope, u(t). In the second model, the evolution with time of the factor of safety, F(t), is computed by running a number of limit equilibrium stability analyses equal to the time steps defined in the transient seepage analysis and by using, at each time step, the related computed pore pressures. An empirical relationship between factor of safety, F, and rate of displacement, v, is also defined to determine the evolution with time of the displacement rate along the slip surface, v(t). The relationship assumes a threshold value of factor of safety, F_{max}, above which the displacement is null, and a maximum value of velocity, v_{max}, corresponding to a factor of safety of 1.0 (i.e. slope failure). It is important to note that an accurate evaluation of the relationship between rainfall and pore pressure variations within the slope is essential for a reliable prediction of factors of safety and, consequently, of the rate of movements along the slip surface. Thus, particularly important is the calibration of the groundwater model based on recorded pore pressure values. Herein, the calibration of both models is attained by means of an inverse analysis procedure that minimizes the errors between numerically computed results, respectively u(t) and v(t), and available monitoring data. The schematic of the inverse analysis is shown in Figure 2. The algorithm used is UCODE (Poeter and Hill 1998), in which the parameter estimation problem is solved by means of a non-linear regression analysis performed using a modified Gauss–Newton method algorithm. Details on the advantages of using such a procedure for calibrating geotechnical models can be found in Calvello (2002).

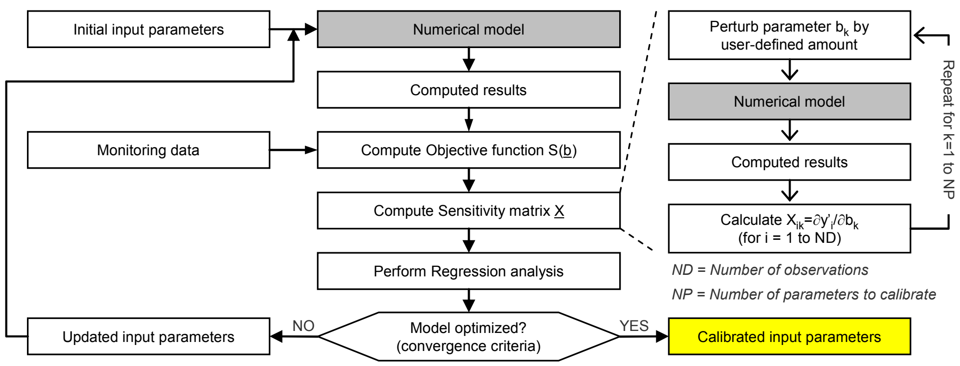


Figure 2. Calibrating numerical models by inverse analysis (modified after Finno and Calvello 2005)

In the inverse analysis, computed results are compared with monitoring data using an objective function, S(b), which represents a quantitative measure of the accuracy of the predictions. The weighted least-squares objective function is expressed as:

$$S(\underline{b}) = [\underline{y} - \underline{y}'(\underline{b})]^T \underline{\omega} \, [\underline{y} - \underline{y}'(\underline{b})] = \underline{e}^T \underline{\omega} \, \underline{e} \quad \text{(1)}$$

where b is the vector of the parameters being estimated; y is the vector of the observations being matched by the regression; y′(b) is the vector of the corresponding computed values; ω is the weight matrix, wherein every observation's weight is taken as the inverse of its error variance; and e is the vector of residuals.

The values of S(b) can be seen as a measure of the ability of the numerical procedure to correctly represent the physical process (i.e. rainfall induced movements of slides). However, S(b) does not take into account the number of observations used during the calibration of the model, nor the accuracy of the parameters' estimates. To quantify the "goodness" of the calibration, two more useful indicators can be used:

$$s^2 = S(\underline{b})/ND \quad \text{.........} (2)$$

$$CoV_j = \sigma_j / \mu_j \quad \text{.........} (3)$$

where s^2 is the model error variance, S(b) is the weighted objective function, ND is the number of observations used for the calibration, CoV_j (for j = 1, NP) is the coefficient of variation of the j^{th} input parameters, NP is the number of parameters, μ_j is the estimate of the j^{th} parameter, and σ_j is the standard deviation of the estimate.

The model error variance is a measure of the consistency between the fit achieved by the calibrated model and the accuracy of the data as reflected in the weighting (significant deviations of s^2 from 1.0 indicate that the fit is inconsistent with the weighting). The coefficients of variation of the input parameters are a measure of the relative accuracy of the parameters' estimates during the calibration stage.

The calibration, validation and prediction phases

The procedure described in Figure 1 has been applied to an active slide in Central Italy, characterized by very slow movements occurring within a narrow stratum of weathered bedrock overlaid by a clayey silt colluvial cover in which the sliding mass moves essentially as a rigid body (Bertini et al. 1984). The authors thoroughly report measures relative to a 4.5-years long monitoring period (from February 1980 to June 1984) with observations from 1 pluviometric station, 12 electropneumatic piezometric cells and 1 inclinometer, all installed along the critical section of the slope. Figure 3 shows the schematic of the slope with an indication of the location of the installed instruments.

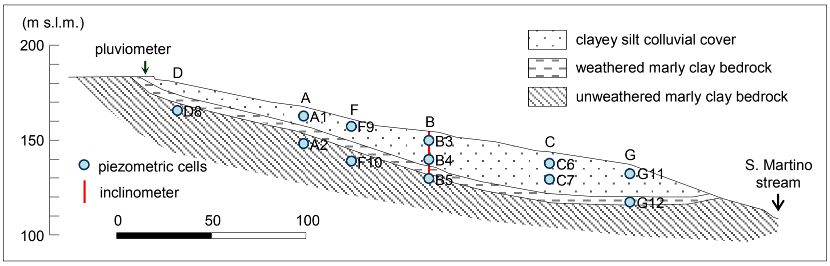


Figure 3. Schematic of the monitored slope (modified after Bertini et al. 1984)

Monitoring data from the case study are used both for calibrating the input parameters of the models according to the procedure described in Figure 2, and for validating the results of the calibrated models. Subsequently, the calibrated and validated models are used to predict the response of the slope to different rainfall scenarios. The three phases of the analysis are schematically shown in Figure 4.

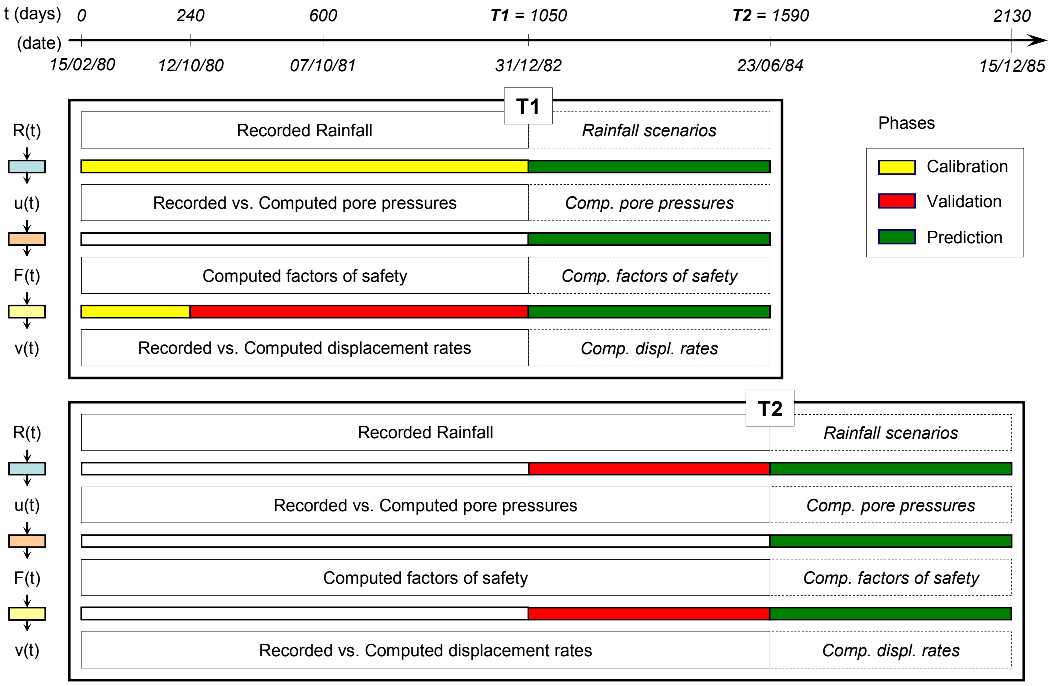


Figure 4. The calibration, validation and prediction phases at “analysis times” T1 and T2.

Two different “analysis times” are considered in this work: T1 and T2, respectively equal to 1050 and 1590 days. The first analysis does not use of all the available measures, the second one does. Evidently, at each “analysis time” the reliability of the numerical predictions depends on the availability of reliable rainfall scenarios. Thus, the need of running two analyses at different times to evaluate the reliability of the considered rainfall scenarios by comparing the predicted displacement rates, between T1 and T2 (analysis time = T1), against the displacement rates in the same period computed using the recorded rainfall (analysis time = T2). The rainfall scenarios used in the analysis are shown in Figure 5. They refer to two stationary conditions, representing reasonable upper and lower bounds, and a upper bound (thus conservative) transient distribution. The first two are computed using the maximum and the average recorded (up to the analysis time) monthly rainfall. The last one is computed using, at each month, the maximum recorded monthly rainfall data relative to the same month of the year. It is worth noting that, when detailed historical series of daily rainfall data are available, a return period can also be assigned to rainfall scenarios generated from curves relating cumulative rainfall in N consecutive days to N (Cascini and Versace 1986).

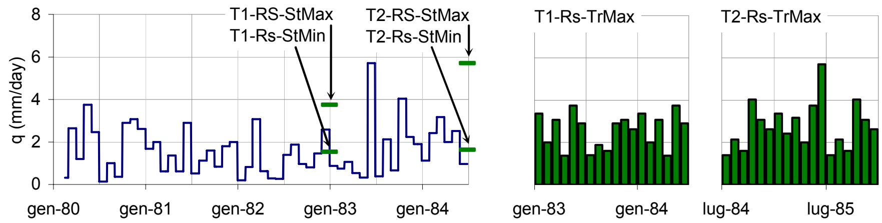


Figure 5. Recorded rainfall and rainfall scenarios considered in the analyses

The numerical results

Figure 6 shows the results of the calibrated and validated models at “analysis time” T1. The results of the transient seepage analysis clearly indicate that the model is able to reproduce the water levels in almost all piezometers as well as the magnitude of their variation with time and the time-occurrence of their peaks. This leads to the belief that the real transient water flow in the slope is satisfactorily modelled by the calibrated analysis. The results of the time-dependent stability analysis show that the average factor of safety is quite far from the limit equilibrium value (i.e. F=1.0) and that the factor of safety does not vary significantly with time. This is due to the relatively small variation with time of the pore water pressures along the slip surface, consistently with the piezometric measures which do not show significant differences between the maximum and minimum water levels. Yet, given that non-negligible intermittent movements are recorded along the slip surface, it is assumed that even small pressure variations along the slip surface, and consequently small changes of factor of safety, can be sufficient to mobilise the landslide. Two relationships are used that relate factors of safety and rates of displacement along the slip surface. Both assume the existence of: a threshold value of factor of safety above which the displacement rate is null, and a maximum value of velocity corresponding to a factor of safety of 1.0. The comparison between the rate of displacement along the slip surface and the numerical results indicates an extremely good fit for both relationships. It is worth noting that, as shown in Figure 4, this last model is calibrated using only the monitoring data corresponding to the first surge of movements, while the rest are used to validate it (i.e. evaluating the predictive ability of the model). Details about the definition of the models and about the values of the initial and calibrated input parameters used can be found in Calvello et al. (2006).

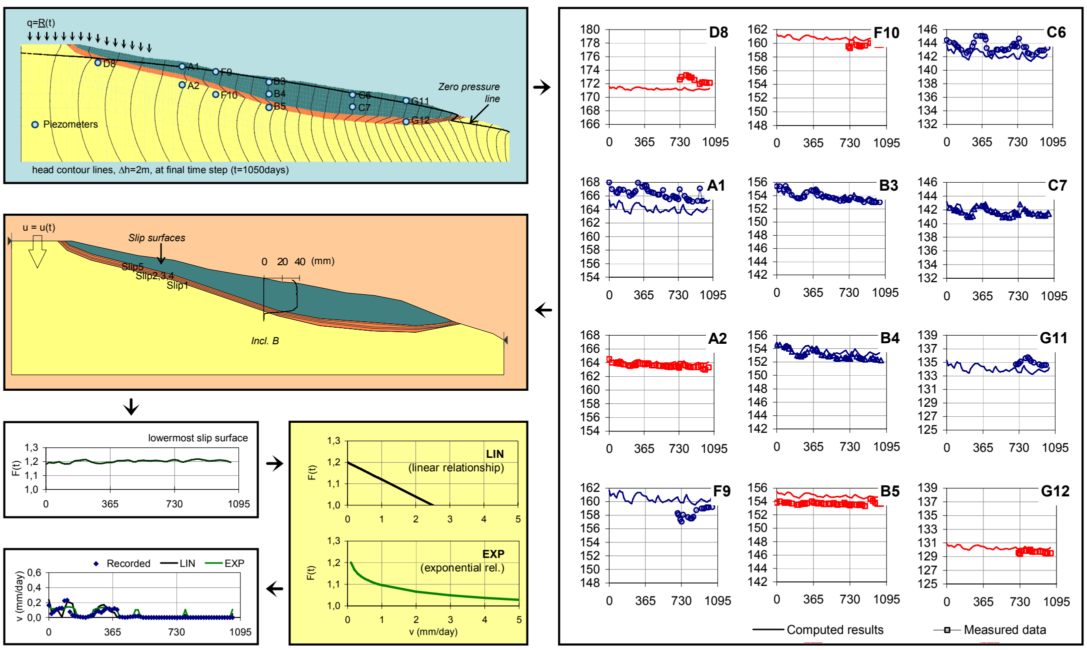


Figure 6. Results of the calibrated and validated model at “analysis time” T1

Figure 7 shows the comparison between predicted displacement rates at analysis time T1 (using different rainfall scenarios) and the displacement rates of the calibrated and validated model at analysis time T2 (using the recorded rainfall). For clarity, only the results relative to the linear relationship between factors of safety and rates of displacement are reported (the other relationship yields similar results). The results are encouraging because, despite the simplicity of the considered rainfall scenarios, the upper and lower boundaries of the rates of displacement are properly identified. In particular, the maximum displacement rates predicted by the transient rainfall scenarios (T1-Rs-TrMax) match the maximum displacement rates computed at T2. Figure 7, however, also shows that at analysis time T2 (when recorded rainfall data are used), the model overestimates the recorded displacement rates of the last surge of movements, thus prompting for further analyses. Considering that the latest recorded displacement rates seem to have "memory" of the low rainfall regime of the previous years, an option is to reformulate the transient seepage analysis. Since not enough information on the pore pressure regime is available to refine the groundwater model by means of additional details, a second option is a recalibration of the kinematic model. The results of pursuing this last option are showed in Figure 8, where recorded and computed displacement rates of the model, recalibrated at analysis time T2, are compared. The calibrated model certainly better reproduces the latest surge of movements, while only slightly underestimating the previous ones.

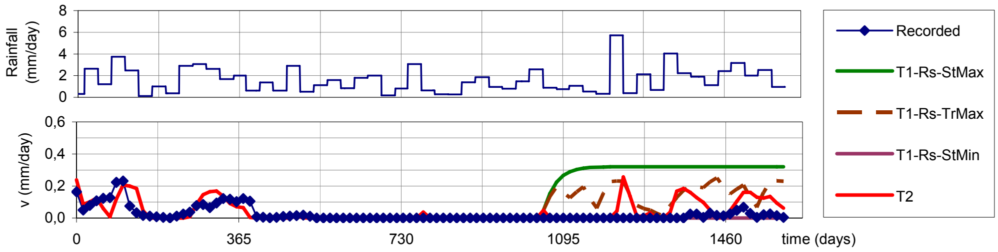


Figure 7. Comparison among recorded displacement rates, predicted rates at analysis time T1 (for the different rainfall scenarios) and rates of the validated model at analysis time T2.

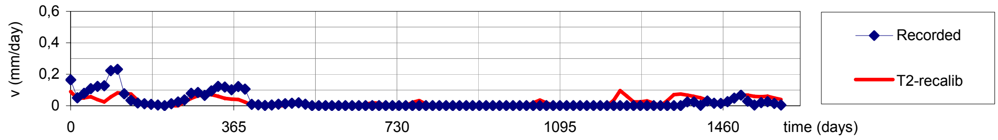


Figure 8. Comparison between recorded and computed displacement rates for the model recalibrated at analysis time T2.

Tables 1 and 2 show the values of the indicators defined in Equations 2 and 3 for three different models during their calibration and validation phases. Table 1 shows that most of the values of s^2 are close to or lower than 1.0, indicating that the model error is consistent with the accuracy of the recorded data, as reflected in the weights assigned to the observations for the inverse analysis. In this case, a standard deviation of 1 m has been considered for the pore pressure data and a standard deviation of 0.05 mm/day for the rate of displacement data. Table 2 indicates that all the input parameters are estimated with a reasonable accuracy (note that recalibration at T2 only involved the input parameters of the F-v relationship).

Table 1. Indicators of the model "error" for 3 different analyses

Analysis	Time (days)	Seepage model				F-v relationship (LIN)			
		ND	S(b)	s^2		ND	S(b)	s^2	
T1	0-240	347	570,0	1,64	1,64	17	30,8	1,81	0,66
	241-1050					54	15,9	0,29	
T2	0-1050	347	570,0	1,64	2,03	71	46,7	0,66	1,44
	1051-1590	204	545,8	2,68		36	107,0	2,97	
T2-recalib	0-1590	347	570,0	1,64	2,03	71	45,16	0,64	0,58
	1051-1590	204	545,8	2,68		36	17,16	0,48	

Table 2. Indicators of the accuracy of the estimates of the input parameters for 3 different analyses

	Analysis	Seepage model				F-v relationship (LIN)	
		H	k1	k2	k3	Fmax	vmax
Value of input parameter, μ (in red when calibrated)	T1	176 m	1 m/d	0,01 m/d	0,2 m/d	1,2	2,5 mm/d
	T2	176 m	1 m/d	0,01 m/d	0,2 m/d	1,2	2,5 mm/d
	T2-recalib	176 m	1 m/d	0,01 m/d	0,2 m/d	1,2058	1,21 mm/d
CoV (%) = σ / μ	T1	0,2	28,9	25,0	17,5	0,1	12,9
	T2	0,1	20,9	16,9	12,8	0,1	13,8
	T2-recalib	0,1	20,9	16,9	12,8	0,2	14,5

Conclusions

The numerical method presented herein has been effectively used for the hazard analysis, at large-scale, of an active slide in stiff clays characterized by movements along a slip surface induced by rainfall-triggered pore pressure fluctuations. The comparison between recorded data and numerical results, computed at different "analysis times," highlights the issue that, as time passes and more monitoring data are available, a better understanding of the mechanisms behind the activity of the slide is possible and, when needed, a recalibration or a reformulation of the numerical models must be carried out. Performing one or the other depends on the amount and quality of the monitoring data available.

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