Porenwasserdruckänderungen aufgrund von Regen und Schneeschmelze in einer tiefgreifenden Massenbewegung

Rainfall and snowmelt forcing of pore pressure in a deep-seated landslide (Aggenalm landslide, Bavaria)

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Zusammenfassung

Tiefgreifende Massenbewegungen sind eine wichtige Naturgefahr in Bayern, aufgrund Ihrer weitreichenden Auswirkungen auf die Infrastruktur. Um die Unsicherheiten, die mir der Reaktivierung der tiefgreifenden Massenbewegungen verbunden sind, zu reduzieren, könnte das Verständnis der Porenwasserdruckänderungen eine wichtige Rolle spielen (vgl. z. B. Singer et al 2009 & Thuro et al 2010). Bisher wird die Beziehung von Niederschlag und Porenwasserdruck meist mit einfachen statistischen Methoden analysiert, z.B. durch ein direkte Korrelation der Zeitreihen. Allerdings könnten diese Methoden systematische Fehler beeinhalten, beispielsweise verursachen Schneeakkumulation und Schneeschmelze Zeitverzögerungen zwischen Niederschlag und Infiltration. Mit der Einbindung eines an die örtlichen Gegebenheiten angepassten Schneeschmelzmodells (Herrmann, 1978: 119-122), bekommen wir ein genaueres Modell während des Zeitraums der Schneeschmelze. In dem aktuellen Projekt versuchen wir Reaktionszeiten und quantitative Beziehungen zwischen Regen/Schneeschmelz und Porendruck zu entschlüsseln, um ein Modell zu entwickeln, das Porenwasserdruck in Abhängigkeit von Niederschlag und Schneeschmelze ausdrücken kann. Dieses Modell kann tägliche Porenwasserdruckveränderungen grob simulieren, die durch Regen und Schneeschmelze induziert werden, besonders bei starken Regenfällen und in der Schneeschmelze.

Schlüsselworte: Regen / Schneeschmelze, Aggenalm Erdrutsch, Herrmann-Modell, Täglicher Porendruck

Abstract

Deep-seated landslides are an important natural hazard in Bavaria, Germany with respect to their widespread impact on infrastructure. To reduce the uncertainty associated with the reactivation of deep-seated landslides, understanding changes of pore pressure could play a key role (see e.g. Singer et al 2009 & Thuro et al 2010). So far, the relationship of pore pressure with precipitation is mostly analyzed using simple statistical methods such as a direct correlation of time series. However, these methods might include systematical errors such as time lags between precipitation and infiltration caused by snow accumulation and snowmelt. By including a snowmelt model adapted to local conditions (Herrmann, 1978: 119-122), we got a more accurate model for snow period. In the current project we try to decipher response times and quantitative relationships between rainfall/snowmelt and pore pressure for finally designing a model that relates pore pressure to both, rainfall and snowmelt. This model can roughly simulate daily changes of pore pressure induced by rainfall/snowmelt especially after rainfall and in the snowmelt season.

Keywords: Rainfall/snowmelt, Aggenalm landslide, Herrmann model, Daily change of pore pressure

1 Introduction

In Bavaria, Germany the deep-seated landslides impose a certain hazard for people and infrastructure. Pore pressure always plays a key role in landslide activation. Rainfall and snowmelt events (referred to as "RS") infiltrate into the ground and raise the groundwater table, which penetrates soil and fractured rock and is finally discharged. In the process, the pressure from water that fills the void spaces among soil particles rises as the amount of water infiltrating into the ground increases. A rise in pore pressure causes a drop in effective stress and, thus, the understanding of changes of pore pressure is of great significance. Recently, different geotechnical and geodetic monitoring systems have been developed for deep-seated landslides. Examples include landslides in moraine materials on bedrock of the Werfen marls (Angeli et al., 1988), in highly-fissured mud shales (Higaki et al., 1991 and Simoni et al., 2004), in crystalline schists (Hong et al., 2005), and in a clay deposit (Thomson and Mekechuk, 1982 and Okamoto et al., 2004). These studies have revealed pore pressure relative to rainfall and snowmelt. However, the relationship is less accurate and further studies are still necessary especially considering the snowmelt forcing of pore pressure.

The Aggenalm Landslide is situated in the Bavarian Alps in the Sudelfeld region near Bayrischzell. In 1935, after being triggered by heavy rainfall, the Aggenalm Landslide destroyed three bridges and the road to the Sudelfeld skiing area. After extreme precipitation in 1997, a new debris flow originated from the landslide area and blocked the road. Since 2001, the landslide has been surveyed periodically twice a year by the Bavarian Environment Agency (Bayerisches Landesamt für Umwelt), showing average movement rates of about two centimeters per year. (Thuro et al 2010) In last three years, the interdisciplinary research project "alpEWAS" (development and testing of a continuous 3D early warning system for alpine instable slopes; www.alpewas.de) played a key role in this context (Singer et al 2009 and Thuro et al 2010). The data we used in the paper is indicated as a red (Piezometer) and yellow (central station offered the rainfall and snowfall data) circle in Fig. 1.

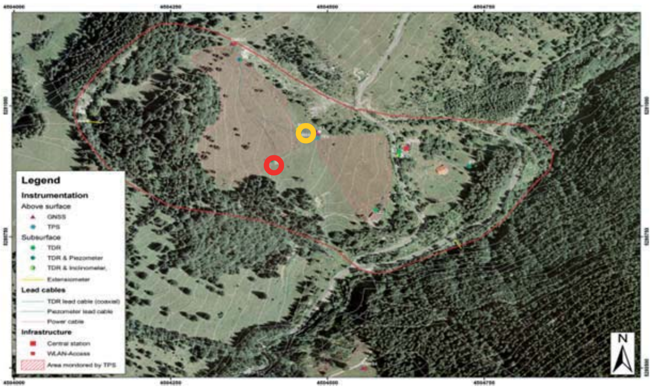


Abb. 1: Orthophoto des Aggenalm Landslides mit dem eigentlichen Ausrüstung des alpEWAS geo-Sensor Netzwerks(Singer et al 2009).

Fig. 1: Orthophoto of the Aggenalm Landslide with the actual instrumentation setup of the alpEWAS geo sensor network (Singer et al 2009).

The empirical relationship between rainfall intensity (amount of daily rainfall) and slope instability has been thoroughly documented in many places such as Japan (Kobashi and Suzuki 1987) and southern California (Campbell 1975) and several attempts were made to estimate the threshold range. They usually take the absolute pore pressure as the index. Sumio Matsuura et al (2008) studied the correlation between fluctuation ranges of pore pressure and IRS (intensity of RS).

The results show that IRS had little effect on the fluctuation range of absolute pore pressure. In our case, we studied DP (daily changes of pore pressure) and analyzed the relationship with IRS. Okunishi and Okimura (1987) argued that the (daily) change in pore pressure (in our study is "DP") is often a more effective index to anticipate failure than the absolute pore pressure ("AP"). In the Alps and Prealps the annual snowmelt brings potential drive to deep-seated landslides in the spring. Thus it is important to estimate the timing and intensity of snowmelt for better calculating pore pressure. The Herrmann (1978) snowmelt model is a good choice for estimating snowmelt. In this paper we try to design a model that forecasts daily changes in pore pressure induced by rainfall and snowmelt.

2 Method

2.1 Rainfall forcing of pore pressure without snow melt

2.1.1 Response time and higgest correlation

We studied the AP (absolute pore pressure), RP (fluctuation range of pore pressure) and DP (daily changes of pore pressure) at each RS (rainfall and snowmelt events) event. We performed a correlation analysis with IRS (daily intensity of RS) to calculate the highest correlation in every month considering response time from 0 day to 4 day respectively.

2.1.2 Relationship between IRS and DP

According to monitoring experiences in the past, rainfall and pore pressure usually have a linear or exponential relationships (Matsuura, 2000), which we adopted for this study. We divided IRS into several intervals whose increment is 2 mm, for instance 0 mm, [0-2 mm], [2-4 mm], [4-6 mm]…We related them to the respective mean daily changes in pore pressure (DP). For example: 0 mm leads to a mean DP of -0.21 KPa; 8-10 mm lead to a mean DP of 0.25 KPa.

2.2 Traditional Herrmann model considering snowmelt

In the snow period, we have to consider that snow accumulation offsets the rainfall–pore pressure response. In history, a number of landslides were triggered by rapid snowmelt and the assessment of snowmelt impacting landslide is an important geological topic (Saeki Kawagoe et al 2009 and Cardinali M et al 2000). Herrmann's (1978) snowmelt model which is suitable for the Bavarian Prealps and low Alps estimate the daily snowmelt *Abl*

$Abl = 3.51 + 2.75\ T$

where 3.51 and 2.75 are empirical initial parameter and coefficients and *T* is the mean daily temperature.

2.3 Modified Herrmann model

We modified Herrmann's snowmelt model around temperatures of 0°C to reduce the snowmelt for day with small sensitive thermal energy transfer. Here ablation is

$Abl=(3.51+2.75T)/3$, for $-1<T<1°C$;

$Abl=(3.51+2.75T)/2$,for $1<T<2°C$;

$Abl=3.51+2.75T$ for $T>2\ °C$.

3 Results

3.1 Rainfall forcing of pore pressure without snow melt

3.1.1 Response time and highest correlation

We split the data set into 18 months (excluding snowmelt and data losses months) to evaluate the correlation coefficients. The IRS/AP correlation coefficient is usually smaller than the IRS/DP correlation coefficient by 0.2-0.3. There is almost no correlation (IRS/RP) and it was roughly lower than that (IRS/AP) at about 0.2-0.25. Table 1 and Table 2 showed the parts in heavy rainfall period (07, 2009 & 08, 2009) of results.

Tab. 1: Korrelation mit IRS , Hangbewegung Aggenalm, Juli 2009.

Tab. 1: Correlation with IRS for the Aggenalm Landslide, Juli 2009.

Response time	0 day	1 day	2 days	3 days	4 days
Correlation(AP)	-0.3863	0.0841	0.4157	0.4519	0.3256
Correlation(RP)	0.2072	0.0291	0.0268	0.1933	0.0615
Correlation(DP)	0.0234	0.7296	0.5095	0.0092	-0.1373

Tab. 2: Korrelation mit IRS respektive für August 2009.

Tab. 2: Correlation with IRS respective for August 2009

Response time	0 day	1 day	2 days	3 days	4 days
Correlation(AP)	-0.1787	0.3334	0.4962	0.4190	0.3705
Correlation(RP)	0.0065	0.0666	0.1386	0.2047	0.1391
Correlation(DP)	0.0531	0.7427	0.3644	0.1937	-0.1787

1-2 days response time (IRS/DP) based on all the monitoring data has a higher correlation coefficient of about 0.6-0.75 than shorter or longer response times. For monthly RS over 85 mm the response time is more likely 1 day (highest correlation coefficient); The correlation coefficient arrived peak with 2 days response time if monthly RS between 20mm and 85mm; RS less than 20 mm would delay the response time to 3 days for highest correlation coefficient.

3.1.2 Relationship between IRS and DP

As Fig. 2 shows there is similar linear relationship between DP and IRS (response time is 1day). If the 2 days was response time correlation coefficients would be 0.8507 and similar linear function be y=0.0415x-0.1704.

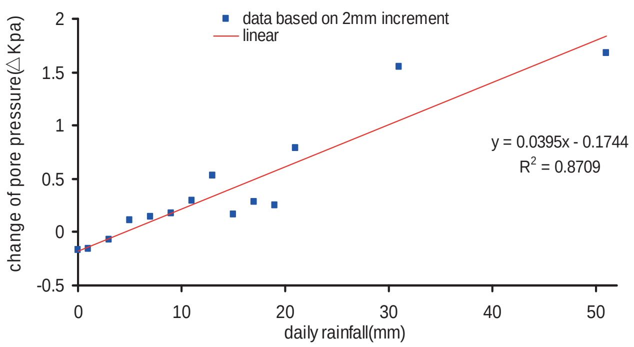
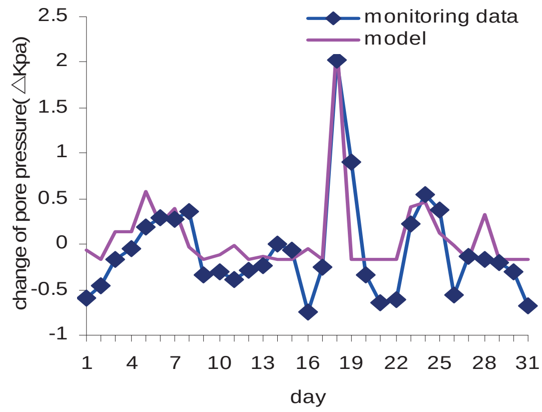


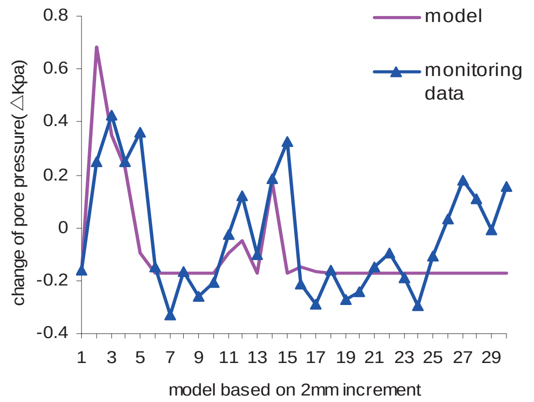
Abb. 2: Lineare Beziehung von IRS und DP (1 Tag Responszeit)

Fig. 2: Linear relationship of IRS and DP (1 day response time)

Therefore, it is seems to be possible to anticipate the change in pore pressure one (Fig. 3a) or two days (Fig. 3b) in advance using rainfall and estimated snowmelt as input.



(a) 07. 2009 (1day)



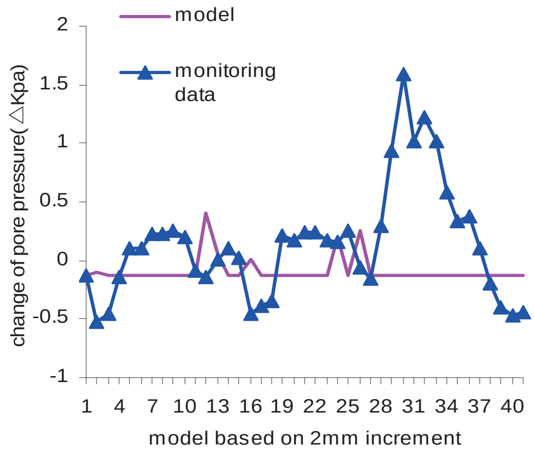
(b) 09. 2009 (2 days)

Abb. 3: Schätzung der DP basierend auf IRS mit einer Responszeit von 1 (Fig. 3a) oder 2 (Fig. 3b) Tagen Responszeit.

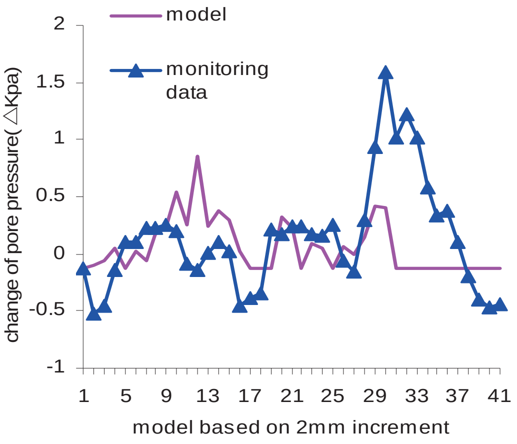
Fig. 3: Estimation of DP based on IRS with 1 (Fig. 3a) or 2 (Fig. 3b) days response time.

3.2 Traditional Herrmann model considering snowmelt

We integrated the snowmelt *AbI* into a linear function for DP. Fig. 4 showed original Herrmann model estimating snowmelt forcing pore pressure.



(a) considering no snowmelt



(b) based on original Herrmann model

Abb. 4: Modelliertes DP mit (a) und ohne (b) Schneeschmelze (04, 03, 2009-14, 04, 2009)

Fig. 4: Modelled DP with (a) and without (b) snowmelt (04, 03, 2009-14, 04, 2009)

3.3 Modified Herrmann model considering snowmelt

In Fig. 5 we demonstrate the modified Herrmann model.

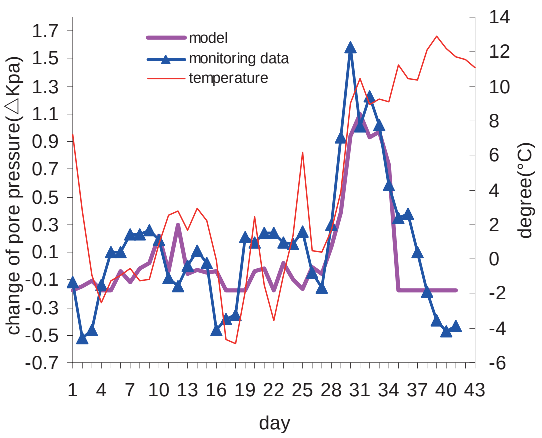


Abb. 5: Modelliertes DP im modifizierten Herrmann Modell (04, 03, 2009-14, 04, 2009)

Fig. 5: Modelled DP in the modified Herrmann Model (04, 03, 2009-14, 04, 2009)

4 Discussion

4.1 DP as the index estimated

On the basis of three years of monitoring of the rainfall, temperatures and pore pressures at a reactivated landslide in Bavaria, we analyzed the relationships between IRS and DP. We found a method to estimate the DP by IRS which is also valid in rainstorms and for intensive snowmelt. Most previous attempts are based on the relationship of IRS and AP. Our investigation of DP by IRS indicated they had a better linear correlation compare to AP and RP. Every landslide has a lowest water table (LWT). If we take the AP, actually AP=LWT+DP, the sensitivity of denominator by molecule IRS/(IWT+DP) is worse than (IRS/DP); While the RP (accumulation of DP), as time goes by, the sensitivity will reduce. For example the third day IRS_3/RP_3 $(DP_1+DP_2+DP_3)$ is not so good as IRS_3/DP_3. (IRS_i means the intensity of $_i$th day's RS; RP_i and DP_i are the $_i$th day's values). When considering drainage process, DP is definitely an effective index. For instance, subsequent to a big RS event, the pore pressure is rising. Without new RS events in the next days, the AP may still rise but at a lower velocity or may even drop because of drainage. The same is true if a recurrent RS event appears while AP declines within the response time of RS. Therefore, the index AP is perhaps not so clear even producing variance because of the bigger denominator and impact from early days' DP_i. It should be noted that this study has examined only one in situ project which could be affected by other factors outside. Maybe for the landslide itself in drainage or absorb stage, calculation of DP is not so precise. But we believe using DP can indeed reduce the impact from the problems mentioned above. And actually the concept of the Antecedent Precipitation Index (API) (Chow, 1964) is for estimating the water content of the ground. For reduce continues RS impact. Cumulative API calculation method with weights of day units (Suzuki and Kobashi, 1981 and Matsuura et al., 2003) can be used. And the effective RS has the similar results with IRS/DP. However calculation of API is complex and time consuming compared to deriving an empirical IRS/DP linear relationship at a certain site.

4.2 Response time

On the other hand, response time seems to depend on the monthly RS. Increasing monthly amounts of RS can cause shorter response time possibly due to enhanced infiltration. Firstly, the heavier IRS will increase the water content faster in the same time especially in the beginning stage. So the response time is shorter facing bigger RS. Secondly, higher monthly amount of RS keeps the water table always in a higher level. And pores of soil are less and easily show the according positive pore pressure. Adversely, if the water table was very low, soil would absorb water for filling in its pores firstly not showing the positive pressure. From the Fig. 3, part (a) seems to be more accurate than part (b). We still cannot explain why the accuracy of IRS/DP (response time is 1 day) is higher than that (response time are two and more days). Maybe for longer time frames the non-considered evaporation and drainage add increasing noise.

4.3 Herrmann snowmelt model

The Herrmann snowmelt model has been established in very similar geographical conditions nearby. But the monitoring data in our case tell us variance of temperature during one day may leads to the invalidation around zero degree sometimes. For example when T is one degree there are perhaps two situations: All hourly temperatures in one day, although fluctuation, are totally above zero and average T is one degree. The daily snowmelt by the equation should be (3.51+2.75*1) 6.26mm. Another case, usually like this in reality: on night some hourly temperatures keep under zero degree about average minus one; on daytime some keep above zero degree (average two degree). The daily snowmelt is [(3.51+2.75*2)/2]4.505mm. Therefore, the snowmelt can be lower around zero degree. And we also have to point out that latent and sensible heats are types of energy released or absorbed in the atmosphere. Latent heat is related to changes in phase between liquids, gases, and solids. Sensible heat is related to changes in temperature of a gas or object with no change in phase. (Adkins, C.J., 1975 and Maxwell, J.C., 1872) So we inferred that around zero degree snowmelt perhaps would slow down. Thus, making some modifications for the snowmelt equation considering the deviation is presumably reasonable. Fig. 4 clearly tell us when considering no rainfall (a) there almost have no DP because of less rainfall events in snow period; Part (b) and demonstrate original Herrmann model take no 'zero degree effect' into consideration and thus in early days around zero degree snowmelt be enlarged and later days there is no enough snow to melt. However, modified model can overcome the problem (Fig.5).

5 Conclusion

In this paper, we have compared absolute pore pressure (AP) and changes in pore pressure (DP) with rainfall and snowmelt infiltration. For this, we have used the Herrmann snowmelt model, which was calibrated over 10 years in a similar prealpine / low-alpine environment and calculates snowmelt as a function of temperature (degree*days). Here we confirm that the change in pore pressure (DP) can be better approximated on the basis of rainfall and snowmelt (RS) that the absolute pore pressure ("AP") itself. We also tested a modified Herrmann's snowmelt model where melting at temperature around 0°C is reduced. We achieved the highest accuracy for RS/DP with a response time of one day. However, response times of two and three days also reveal reasonable correlations. Pore pressure is one the important dynamic factors in slope destabilization; a modified version of the rainfall/snowmelt driven model for changes in pore pressure could help to anticipate critical states of stability one or two days in advance.

Acknowledge

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