Back analysis of landslides to allow the design of cost-effective mitigation measures

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Abstract. For many deep-seated landslides adverse and often complex geology and hydrogeology are fundamentally important and this is illustrated through case examples. Back-analysis is the process by which the nature and development of a landslide is determined through a series of deductions. This may involve numerical simulation but need not. Developing a model that can be used to explain all aspects of the landslide is key. Failures in engineered slopes are often particularly revealing in that they demonstrate flaws in thinking, investigation and analysis from which lessons can be learned. Examples presented here include failed slopes that had been investigated using standard ground investigation and instrumentation techniques but where the true mechanism had been overlooked or missed. In terms of mitigation, it is very important that an active landslide is properly understood as a geo-mechanical model to ensure that correct and cost effective mitigation measures are adopted. Monitoring is important for assessing risk but that monitoring needs to be linked to models identified through proper investigation and analysis that can then be tested through prediction and measurement.

Keywords. Back-analysis, geological and hydrogeological models, landslides, remedial measures, Malaysia, Korea, Hong Kong

1. Introduction

Landslides often involve complex geological and hydrogeological situations. The true mechanism of a landslide is often difficult to unravel - there may be many contributing factors and the investigator needs to act as a detective, looking for evidence, developing theories and testing these through further observation, analysis and focused investigation. This whole process which may or may not include numerical simulation of the failure is termed here 'back-analysis'. One of the key questions is often why a landslide has occurred at a particular location, at a particular time (especially where there is no immediate trigger) and with a particular geometry rather than elsewhere in the same slope or in adjacent slopes. Simple attempts to remedy the situation by cutting back often do not work and can make matters worse. It is argued here that without proper, insightful investigation of landslides, remedial measures may be ineffectual or at least not cost-effective. Numerical calculation may help to establish what is or is not an acceptable solution and for the deduction to be correct, the model must certainly work mechanically at least in principle. The investigation need not be expensive or involve deep drilling to derive a realistic and workable model but it does need to involve knowledgeable and experienced personnel who can recognise geological structures and understand the implications for groundwater partitioning and shear strength. Once working models are derived that explain the features of a landslide, then that model can be tested by additional ground investigation, instrumentation and numerical simulation. Without a proper model the back analysis may be unrepresentative of true conditions and certainly open to numerous alternative explanations.

2. Benefits from Landslide Studies

The benefits from landslide studies can be considered in two categories: generic and site-specific. Aspects that need to be addressed in any slope design include geometry, geology, hydrogeology, mass strength and method of mathematical analysis. Hencher et al (1984) reviewed the then current state of knowledge in Hong Kong with respect to each of these and concluded that the poorest understood were mass strength and hydrogeology and that one of the best ways of advancing knowledge in these areas was by studying landslides. Examples were provided of how landslides studies could be used to improve knowledge in these specific areas. Progress continues to be made, particularly concerning hydrogeological models (Jiao et al., 2005; Hencher et al, 2006). Other generic benefits of systematic landslide studies in Hong Kong such as lessons regarding improved detailing of drainage of slopes are discussed by Ho & Lau (2008).

At an individual site level, it is important to understand the causes of any major landslide before attempting to apply permanent remediation or other action so that such measures can be robust and cost effective. Case examples are presented below that illustrate the need for good geological understanding, for timely investigation and to demonstrate how landslide studies can give insight into complex hydrogeological conditions and other factors, ignorance of which would limit the effectiveness of any remediation works.

3. Pos Selim Landslide: complex geological structure controlling displacement

The Pos Selim landslide is a currently active landslide in Malaysia. Some details are provided by Malone et al (2008). The landslide occurred in one of the many large and steep cut slopes along the new 35km section of the Simpang Pulai – Lojing Highway project and it is pertinent to ask the question why it occurred there rather than somewhere else?

Failure occurred early on in the cut slope and affected the natural slope above the cutting (Figure 1). Progressively the slope was then cut back in response to further failures until the works reached the ridgeline about 250m above the road (Figure 2). The slope has continued to move with huge tension cracks developing near the crest with vertical drop at the main scarp of more than 20 metres in three years.

Fig. 1 Pos Selim Landslide, August 2000

Clearly at the site there are some predisposing factors that are causing instability whereas many other equally steep slopes along the 35 km of new highway show no similar deep seated failures. The general geology of the site is schist but the main foliation actually dips into the slope at about 10 degrees so the common mode of failure associated with such metamorphic rocks of planar sliding on daylighting, adverse schistosity or on shear zones parallel to the schistosity (Deere, 1971) is not an option to explain this landslide. Following detailed face mapping by geologists, review of displacement data and examination of the various stages of failure, a model was derived that can be used to explain the nature of the failure, the vectors of movement and the fact that it has not yet failed catastrophically but is bulging at one section of the toe (Figures 3 & 4). Key aspects of the geology are frequent joints that are oriented roughly orthogonal to the schistosity, three persistent faults cutting across the failure and another major fault to the north of the landslide area. The derived model is of a mechanism of sliding on the short, impersistent joints that combine with offset sections of schistose fabric to form a shear surface. The shearing forces are largely balanced by sliding friction on joints, along the transverse faults and schistosity in one part of the toe where the failure is kicking out. Resistance is also provided by the dilating mass towards the right side toe of the slope (facing). One possible option for remediation that can be derived from this model therefore involves strengthening that toe area by anchoring or otherwise buttressing.

It is to be noted that this model is not numerical but could certainly be used as the basis for a numerical model that would, indeed work for some realistic set of parameters. Without this understanding of geological mechanism, it would be impossible even to begin to design successful remedial measures.

Fig. 2 Pos Selim Landslide, 2002

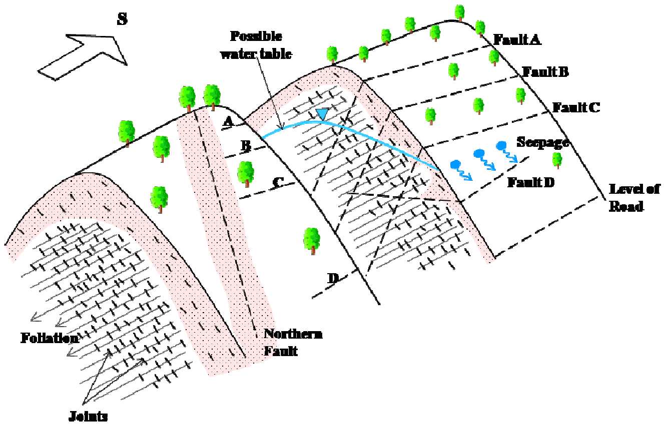

Fig. 3 Block model of main geological features

Currently there is some minor evidence that groundwater is playing a part in the failure (some seepage) and therefore it has been recommended that long, trial raking drains be installed at points of seepage in such a way that they also allow water pressures to be monitored within the slope (a cost-effective combination of ground investigation and remedial measure).

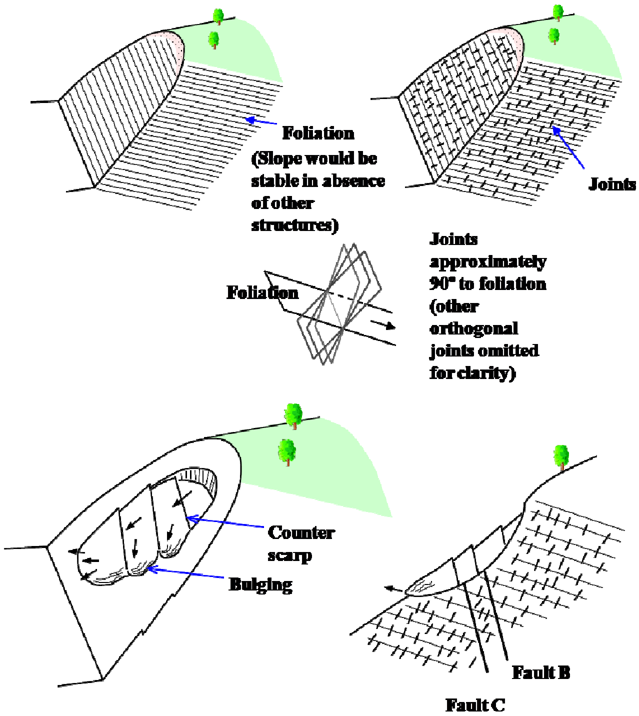

Fig.4 Schematic model for the Pos Selim landslide.

4. Kimhae agricultural complex near Busan, Korea: the need for timely and insightful investigation

The circumstances of this failure are described in detail in Lee & Hencher, 2008. In summary, the original ground investigation and design for the large slopes that were to be cut at the site, in complicated geological conditions, were

Fig.5 Large scale failure near Busan, Korea

deficient and the slope failed during construction.
The slope continued to fail progressively until it finally collapsed catastrophically in August 2002 during heavy rainfall.
During the series of retrogressive failures leading to the final collapse there were 11succesive inspections and reassessments of stability over 9 years. Various techniques were employed in turn in attempts to stabilize the slope using piles, ground anchors and soil nails. Drainage was attempted and retaining walls constructed. As a result of the repeated failures the height of the cut slope was increased from 45 m to 145 m with associated costs rising from 3.3 million to 26 million US dollars. It was not until the complexity of the geology and specifically the importance of fault control was properly identified that the slope could be finally understood. Various assessments prior to then had tried analysing the slope as a soil and one late review attributed the landslide to natural disaster (triggered by a typhoon) without acknowledging the failure of previous studies to go about the investigation in a scientific manner. This example demonstrates that without proper investigation, even after significant failure has occurred, the success or otherwise of remedial measures cannot be relied upon.

5. Ching Cheung Road Landslide, Hong Kong: complex hydrogeology

Cut slopes along Ching Cheung Road in Hong Kong have been the source of several major landslides since the road construction in the early 60's. One of the common features of these landslides has been that they are deep seated and occurred several days after heavy rainfall. The most recent large landslide occurred in 1997 in a section of slope that had

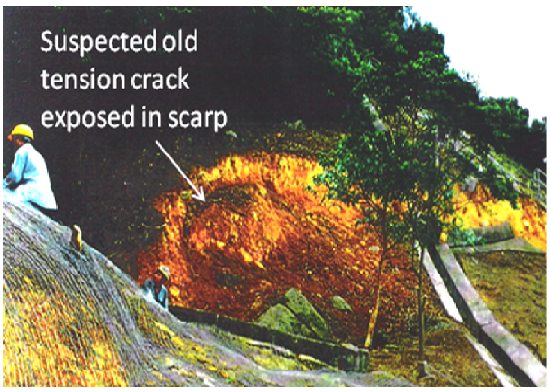

Fig.6 Evidence of previous movement in 1997 scarp

Fig. 7 Alluvial sand recovered in Mazier sample

recently been investigated and modified to try to improve its stability. This failure was also delayed in that the first major movement occurred four days after heavy rain. The slope continued to deteriorate and eventually, about a month later, collapsed during heavy rain so that the debris blocked both carriageways of this important road. Back analysis of this failure was aimed at explaining why the failure occurred as it did, at that location but also specifically to offer some explanation for the delayed response to heavy rainfall. In terms of why the failure occurred at that location, this seemed to be linked to the fact that the site was the location of previous failure dating back to the 1940's. This had been identified during investigation of a failure in a nearby slope in 1982 (Hudson & Hencher, 1984).
Signs of previous movement were found during the investigation of the 1997 landslide as illustrated in Figure 6 (HAP, 1998). Detailed mapping of trial pits showed however that the 1997 failure was not a simple reactivation of the earlier landslide but it was still suspected that the location of the 1997 failure was related to the previous distress.
Boreholes were put down specifically aimed at achieving 100% recovery using Mazier sampling with foam flush (no in-situ tests were conducted during drilling). Some boreholes were inclined upwards back into the failure scarp. All samples were examined and described. No samples were taken for strength testing because it was considered that current knowledge of the shear strength of such materials was sufficient for numerical simulation and that detailed geological examination was more important for explaining the details of this landslide.
One of the key findings from the investigation was the presence of numerous infilled natural pipes found in borehole samples. Pipe infill included single sized sand (Figure 7) and graded sands (deposited in still water) at great depth within the decomposed granite that makes up the bulk of the slope. It was clear that there was a well developed underground stream system at the landslide site. A leaf was found in one sample and this was dated using ^{14}C enrichment values as 1958 to 1960. It was concluded that the presence of the underground stream and lake system allowed an explanation of deep groundwater recharge over a period of several days and delayed failure. Delayed groundwater response was observable in some piezometers but it was recognised that such observations might be very localised depending on whether or not a particular borehole tapped into an active part of the stream system. Such variation in groundwater flow became evident during the installation of soil nails as part of the remediation works. In order to install the nails, dewatering

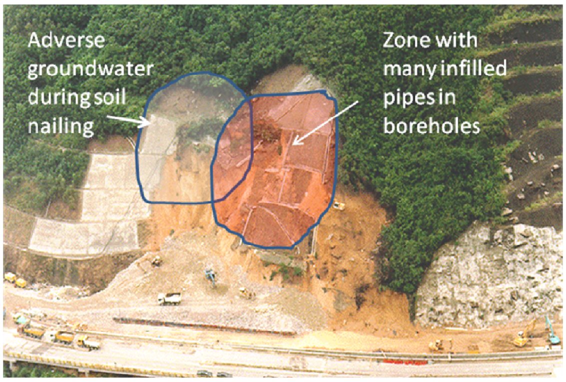

Fig. 7 Ching Cheung Road Landslide 1997.

was carried out using 14 wells which extracted 1.2 Ml during the nailing contract. One single well accounted for more than 40% of that volume (HAP, 1999). Interestingly, and totally compatible with the emerging model, in one area of the slope, despite dewatering, water flowed from soil nail holes, some holes collapsed and it was observed that there was a degree of interconnection. The area of problems during soil nailing was not the same as where the majority of sediment choked pipes were encountered during ground investigation (Figure 8). It was interpreted therefore that the underground stream system had migrated with time and was still changing continuously; the sediment filled system represented natural pipes and hollows that had clogged and collapsed during dry spells. Given later intense rainfall and infiltration, other routes for throughflow developed as an open system.

This model for the observations at Ching Cheung Road and elsewhere has ramifications, not only regarding site-specific remediation but more generally. It can be surmised that the presence of such sediment clogged pipes and other sediment infill to joints (HCL, 2002) may be evidence of a long period of deterioration and perhaps imminent collapse (Hencher, 2006). Furthermore such channel systems can be expected to evolve and migrate. Drainage measures adopted for remediation should be expected to show changing performance with time as the groundwater pattern alters and the need for upgrading should be considered periodically.

Conclusions

Landslide studies are extremely important for improving the capability of geotechnical engineers and engineering geologists to make slopes safe and to avoid disastrous failure. The lessons learned may be applicable generally to many slopes or may be used to devise cost-effective solutions for stabilising a specific slope.

The back-analysis process should result in a conceptual model that explains the features of a landslide. For most large landslides this model will involve a detailed representation of structural geology and hydrogeology. Without such understanding landslide mechanisms are likely to be misinterpreted. The model created should work mechanically in the sense that it would be feasible to analyse the failure numerically to help understand how the landslide developed. Numerical modelling may indeed be very helpful in testing the model in that the feasibility can be checked, for example for exploring the necessity or otherwise for invoking temporary adverse water pressures or other triggers. Nevertheless, numerical analysis is unlikely to provide a unique solution because of the many variable parameters and numerical back-analysis, without a proper geological understanding is not to be recommended.

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