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A REVIEW OF SELECTED UNEXPECTED LARGE SLOPE FAILURES

Marthinus Sonnekus and *John Victor Smith

School of Engineering, RMIT University, Melbourne, Australia

*Corresponding Author, Received: 29 Nov. 2017, Revised: 21 March 2018, Accepted: 10 April 2018

ABSTRACT: Significant advancements in the application of soil and rock mechanics have been achieved in managing the risk of large-scale slope instability. In practice, however, unexpected slope failures do occur, sometimes with significant safety and economic implications for nearby communities, public infrastructure or the environment. This review focus on large slope failure case studies, considering the slope failure mechanisms and the effectiveness of the controls adopted in managing the geotechnical risk. The role of appropriate data collection and interpretation in underpinning analysis methods is investigated. The impact of levels of uncertainty of input data on different methods of analysis is addressed in the paper. In some instances, the slope failure mechanisms are not understood and can therefore not be incorporated into geotechnical models. It is also found in this review that the safety implications for communities located in the failure path were not initially evident, in some case, resulting in significant loss of life. A thorough understanding of the failure mechanism and triggers is essential for assessing slope stability conditions. In addition, reliable stability monitoring, geological and hydrogeological data are required for determining slope stability conditions. It is also evident from this review that time-dependent behavior is likely to result in shear strength reduction and should be considered for long-term slope stability.

Keywords: Slope stability, slope failure, Southern Leyte, Guinsaugon, Vaiont, Yallourn Mine

1. INTRODUCTION

Large landslides can be highly complex in terms of failure mechanisms and movement history [1]. Mountainous countries in high rainfall and earthquakes prone areas can be highly susceptible to landslides [2]. Countries such as Indonesia, China, Japan and the Philippines have a long history of devastating landslides [3]. In the Philippines, landslides are typically associated with intense rainfall from tropical weather patterns [4]. It is expected that climate change, will result in changes in these weather patterns, further complicating the risk management of landslides [5-6]. In Europe, there is also the potential for extreme climatological events that can increase the frequency of rainfall-triggered landslides [7].

The structural geology, lithology, shear strength, pore water pressure, soil, rock mass, defect characteristics and topography have a significant impact on slope stability. External factors can include earthquakes and high rainfall events [8-11].

One of the greatest flaws in slope stability assessments is the absence of reliable lithology and structural geology information. This can result in assumptions relating to the geological defects that are not correct [11-12]. The shear strength characteristics, persistence and orientation of geological structures are important in landslide studies, improving the understanding of failure mechanisms and slope deformation characteristics [13-14].

Integration of the structural geology into the slope stability assessment process has been recognized as difficult [15]. Pre-existing geological structures, with low residual shear strength, may not be evident until the failure occurs [16-17].

Excessive pore water pressure can have a significant influence on the stability of a large slope. Water can act in soil or along discontinuities of a rock mass, effectively reducing the shear strength [11]. It may be possible to install slope drainage systems to reduce pore-water pressure and in the process improving stability conditions [18].

Rainfall and pore-water pressure data can be used to develop transient groundwater models. These models can be used in assessing the reactivation of old landslides, where there is a sudden increase in pore water pressures from external sources, such as a river in flood or a significant rainfall event [19].

The triggers for deeply seated slope failures are typically high rainfall, resulting in pore-water pressure increases and regional seismicity [20]. However, the long-term stability of a slope can also be affected by creep behavior, for example, movement along a critical geological structure can result in a residual shear strength conditions and subsequent failure. Creep behavior in rock and soil slopes is the focus of ongoing research [21]. Another potential trigger for slope failure can be the filling and drawdown rates of dam reservoirs. Both filling and drawdown cycles can result in slope failure [22].

A multidisciplinary approach to landslide assessment is required. The use of geographical information systems (GIS) and other remote sensing techniques are increasingly being used to manage and assess landslide risk over a large area. Aspects such as earthquake loading, groundwater change and geotechnical properties can be incorporated into a probabilistic GIS application [23-26]. In all aspects, it will be important to calibrate these models with observed field conditions.

Reliable monitoring data is required to provide early warning of impending slope failure. Information on both surface and deep movement monitoring and pore-water pressure are required. Other benefits of monitoring include information for back analysis purposes and assessing the failure mechanisms [27]. In mining, monitoring can provide a management tool to optimize slope angles, i.e. mine slopes at steeper angles with less costly overburden removal [28].

There has been extensive development in real-time monitoring of slopes. The design of a monitoring system is dependent on the failure conditions and comprise of field sensors, field data acquisition systems and communication systems [29]. Due to advancements in technology the monitoring systems are becoming more cost-effective and reliable [30].

1.1. The significance of the selected case studies

The case studies reviewed here include a natural slope in a remote location, a natural slope near a large engineering project and a cut slope in an open pit mine. The role of geology, landforms and geotechnical conditions related to each failure are reviewed. Geotechnical issues include the failure mechanism, the role of progressive failure, geotechnical parameters, reliability and failure triggers. The lessons learned in each case, and by comparison of the cases, are identified.

The Philippines has a long history of landslides with significant environmental and social-economic implications for nearby communities [3]. With increased population growth and urbanization there is a scarcity of land for development purposes. This has resulted in the development of residential areas and infrastructure in areas that are prone to landslides [24], [31]. The Guinsaugon failure in the Philippines was considered an example of the influence of landslides on adjacent communities.

The Vaiont dam failure in Italy is important in understanding the implications of unreliable geological information, inadequate monitoring and not appreciating the consequence of failure on the village below the dam wall. The landslide is further complicated by the effect of filling and drawdown phases of the reservoir [22], [32]. The Vaiont failure is considered a good example of a slope failure near a large engineering project such as a reservoir.

The third example is the Yallourn mine failure in Victoria, Australia. The review investigates the risk of mining a slope near a river, not adequately managing the geotechnical risk and removing important controls to reduce pore-water pressure in the slopes.

2. GUINSAUGON LANDSLIDE

A large slope failure occurred on 17 February 2006 at St Bernard, Southern Leyte province in the Philippines. The failure volume is estimated at between 20 to 25 million cubic meters with a runout distance of almost four kilometers [33]. The maximum velocity of the failure was estimated at between 120 to 130 m/s [34]. The failure resulted in the destruction of the Guinsaugon village with more than 1,000 people being killed and much more displaced.

2.1. Geology

Leyte Island is in the central part of Philippine islands. The archipelago is in one of the most active geological settings on earth. The Philippine Fault Zone, NW-SE orientated 1,200km long fault system traverses the Leyte Island. The fault is actively moving with a mean slip rate of 26±10mm/year at an azimuth of about N130°E [35].

The Geological Map of the Philippines indicates that the landslide developed in a succession of Upper Miocene-Pliocene interbedded sedimentary, volcanic and volcaniclastic rocks [36]. Field mapping undertaken in the Guinsaugon landslide area consist of sandstone, breccias and mudstones with faults and defect infill comprising smectite clay [37].

2.2. Natural Landform

The failure is bound at the crest of the 780 m above sea-level Mount Can-a bag. This ridge is approximately 30 km long and is a geomorphic expression of the active Philippine Fault Zone. The pre-landslide topography was characterized by steeply dipping slopes that formed a wedge geometry. The slope release area is approximately 780 to 400 m above sea-level on the eastern slope of Mount Can-bag [34].

2.3. **Geotechnical**

2.3.1. Failure mechanism

The Guinsaugon failure mechanism was structurally controlled with failure on defects that were continuous, slickensided and weathered with a smectite clay infill. The Philippine Fault Zone resulted in the weakening of the rock mass strength. The kinematic analysis suggests a wedge failure mechanism with a plunge towards the east [38].

It was proposed by [33] that the Philippine fault zone may have acted as a release surface i.e. the failure was initiated along the fault zone. It is expected that high porewater pressure would have developed in the rock mass and along the defects due to heavy rainfall. It was found in a study by [34] that increasing pore water pressure significantly affected the calculated Factor of Safety (FoS) of the slope.

At the base of the slope, the landslide debris spread out almost 3 km^2 over flooded paddy fields. The extensive spread is the result of reduced frictional resistance at the base of the debris mass sliding on the flat flooded rice paddies [33].

Fig. 1 Scar of the Guinsaugon landslide above intensively farmed plains (photograph by Christian Arnhardt, 2010)

2.3.2. *Progressive failure*

Post-landslide studies indicate that there is no slope movement and groundwater level monitoring data. There are also no records of inspections to identify cracks or other signs of slope instability. In addition, it would have been difficult to locate tension crack due to the dense tropical vegetation and difficult terrain. The absence of monitoring data makes it difficult to determine the progressive failure mechanism and to calibrate stability models.

If movement and piezometric data were available, it may have indicated the onset of the landslide. Residents observed small failures a few months and days before the landslide. Other indications include cracking and muddy water flow of the Aliho Creek that flows down the mountain [33].

2.3.3. *Geotechnical parameters and reliability*

There is very limited laboratory testing data available for the Guinsaugon landslide. Intact cored samples were obtained for Uniaxial Compressive Strength (UCS) testing with results ranging from 17.9 to 23 MPa [34]. The number of tests, rock type and reliability of test work are not known.

The calculated rock mass (and defect) cohesion range between 0.45 and 0.78 MPa and the angle of friction between 22.9° and 32.2° [34].

The shear strength of the clay infill is not known.

2.3.4. *Failure triggers*

No direct triggers for the Guinsaugon landslide could be identified [33], [36], [38]. Heavy rainfall preceded the landslide and two minor earthquakes occurred the day of the failure.

The Leyte island is characterized by a total annual rainfall of approximately 3,640 mm. This has resulted in deep tropical weathering profiles [36]. During February 2006, 970.8 mm rainfall was recorded at the Otikon rainfall station. This was significantly more than the average rainfall of 275 mm for February. The heaviest recorded rainfall of 687.8 mm occurred from 8 to 16 February [33]. This rainfall would have resulted in significant pore water pressure buildup in the rock mass and along defects. There would have been relatively limited time for drainage.

Two minor earthquakes were recorded in Southern Leyte Island on the day of the landslide. There is uncertainty if the earthquakes induced the landslide. Some authors believe the magnitudes are well below the threshold that would be required to induce the landslide. It is also possible that the landslide itself could have caused the ground tremors [33], [36], [38]. It is possible that the occurrence of the earthquakes may not have any relationship with the Guinsaugon landslide.

2.4. Lessons Learned

Practical monitoring methods such as the identification of tension cracks, changes in slope geometry, changes in creek flows and the reporting of small failures to authorities should be encouraged.

Slope movement and hydrogeological data are important in the development and calibration of stability models. In the case of the Guinsaugon landslide, this data doesn't exist. There is also very limited geological, geotechnical and hydrogeological information available. Most of the data were only collected after the landslide and this makes geotechnical back analysis work difficult.

In landslide-prone areas, geotechnical mapping and drilling can be highly beneficial in understanding geotechnical conditions and obtaining samples for geotechnical testing purposes. With technological advancements, it is possible to set up a very cost effective and accurate slope monitoring system. Groundwater levels can be monitored by drilling observation bores and installing piezometers.

Geological mapping of the pre-historic landslides in the Guinsaugon area will aid in the understanding of failure mechanisms, volumes, triggers and perhaps even the frequency of landslides. Authorities should continue to develop and implement a Landslide Risk Management Plan with alert levels for monitoring and evacuation of villages.

3. VAIONT LANDSLIDE

The Vaiont valley is situated in the Italian Alps, approximately 90 km north of the city of Venice.

The Vaiont landslide occurred on 9 October 1963 with approximately 270 to 280 million cubic meters of material suddenly sliding from the northern slope of Mt. Toc into the Vaiont reservoir. The failure resulted in a 245 m high wave that overtopped the 260 m high double curved arced dam. The flood wave destroyed Longarone and nearby villages. It is estimated that more than 2,000 people were killed in the disaster [39-40].

3.1. Geology

The Vaiont valley slopes comprise of middle Jurassic limestone and overlain by upper Jurassic limestone with clay and Cretaceous limestone [40]. Multiple clay layers occur near the base of lower Cretaceous stratigraphic units [41].

3.2. Natural Landform

The 300 m deep valley was formed by glacial and fluvial action in an asymmetric syncline [40]. The deep and narrow gorge made it ideal for dam construction. The dam is located just above the junction of the Vaiont and Piave rivers.

There is evidence of the existence of an old landslide on the northern slope of Mt. Toc. Air photo studies identified evidence of the landslide that includes drainage pattern changes, bulges and depressions in the slope geometry [41].

3.3. Geotechnical

3.3.1. Failure mechanism

Although numerous geotechnical studies have been published since the Vaiont landslide there is still uncertainty on the failure mechanism.

The re-activation of an ancient landslide would have resulted in very low shear strength along the pre-existing sliding surface. The low shear resistance could have contributed to the high failure velocity of 20 to 30 m/s [42]. A residual friction angle as low as 5° may even be possible [43].

The presence and influence of clay beds in the landslide have been widely discussed. Some authors dismiss the presence of any clay beds while others have described the presence of these layers in the stratigraphy and even conducted laboratory testing on the clay beds [41], [44].

Some authors propose that sliding occurred along 5 to 15 cm thick bands of clay 100 to 200 m deep within the limestone mass. The clay layers are sub-horizontal near the gorge and further out dip at 35° towards the valley [40]. It is possible that persistent rainfall and raising the reservoir level resulted in increased pore water pressure [40-41].

If a clay sliding surface is at sufficient depth, then the clay may exhibit brittle type behavior due to the formation of microscopic cracking. This may also explain the rapid failure that occurred [40].

Another recent study described a 30 to 60 m thick shear zone at the base of the landslide [39].

3.3.2. Hydrogeology

Two aquifers are present in the northern slope of Mount Toc. The upper aquifer was mainly influenced by the reservoir level and the lower aquifer by both the reservoir and rainfall. The two aquifers may be separated by a continuous clay layer [43].

Limited groundwater level data was obtained from three boreholes with open standpipes. The standpipes only recorded the average groundwater levels for the different hydrogeological units encountered. In addition, the piezometers did not reach down to the sliding surface. The reliability of groundwater data is one of the biggest obstacles in understanding the effect the reservoir levels may have had on slope movements [43].

There is also evidence of karstic conditions at Mt. Toc, suggesting transmission of high groundwater pressures along a possible clay sliding surface [41].

3.3.3. Progressive failure

Three cycles of raising and lowering of the reservoir water commenced in February 1960 until the landslide occurred. During the first cycles, a small failure occurred on March 1960 and a 2 km long tension crack opened up. The second failure of 700,000 m^3 occurred on 4 November 1960. Displacement rates of up to 3.5 cm/day were recorded. During the third cycle movement velocities continuously increased with rates of up to 20 cm/day [43].

3.3.4. Geotechnical parameters and reliability

Direct shear test results on the clay material ranged between 5° and 22°. Back analyzed effective friction angle values calculated by various authors ranged between 17° to 39°. The back analyzed values are considerably higher than the direct shear results. The back analysis was complicated by not having reliable groundwater data [41].

3.3.5. Failure triggers

It is possible that rainfall and raising and lowering of the reservoir levels could have acted as triggers for the landslide [43]. It was difficult to correlate the piezometric levels with the rainfall and water level of the reservoir [42].

Seismic events were recorded from May 1960 until the landslide occurred. However, the seismic events could not be located with confidence as there was only one seismometer installed at the Vaiont dam [40].

3.4. Lessons Learned

It is very important to incorporate the correct failure mechanism into slope failure models. In the Vaiont landslide, there still appears uncertainty on the failure mechanism and hydrogeological conditions that could have contributed to the landslide.

An adequately designed slope monitoring system can provide valuable insight into the failure mechanism and early warning of an impending landslide. Instrumentation such as borehole extensometers can be used to locate deep-seated sliding surfaces.

Groundwater observation bores should be drilled to the correct depths and equipped to ensure reliable and representative readings are obtained for each hydrogeological unit. Modern grouting techniques have simplified the installation of vibrating wire piezometers.

Geological and geotechnical field investigation may include comprehensive mapping, drilling and laboratory testing programs. It is important that experienced geologists, hydrogeologists and geotechnical engineers manage these programs.

4. YALLOURN LANDSLIDE

A review and discussion of some of the key findings of the Mining Warden Yallourn Mine Batter Failure Inquiry [45] are provided. The authors of this paper are also familiar with the geotechnical aspects of the Latrobe Valley brown coal mines.

The Yallourn Mine is in the Latrobe Valley, approximately 150 km east of Melbourne in the state of Victoria, Australia. The Latrobe Valley forms part of the Gippsland Basin that holds significant brown coal deposits [46]. The coal is used for power generation at the Yallourn Power Station.

On 14 November 2007, a large landslide occurred on the approximately 80 m high North-East slope of the Yallourn East Field Mine. The failure volume was estimated at approximately 6 million cubic meters. The landslide was sudden with a runout distance of approximately 250 m [45]. The Latrobe River that is behind the North-East slope flooded the mine after the landslide. The landslide resulted in significant damage to the environment and mine infrastructure. Fortunately, there was no loss of life.

4.1. Geology

The brown coals of the Gippsland Basin were deposited during the Eocene to Late Miocene. The coal forms part of a sequence of non-marine sands, clays and coals, comprising the Latrobe Valley Group. The Yallourn seam is mined at the Yallourn Mine. Pliocene sandy clays, sands and gravels form part of the Haunted Hill Formation. [46].

The Haunted Hill overburden thickness may range from 10 to 44 m overlying 50 to 88 m of the Yallourn brown coal seam. Below the Yallourn seam, there are clay, sand and other coal seams [47].

4.2. Natural Landform

The Yallourn Mine is in a relatively flat area. The Morwell river is west of the Yallourn East Field Mine and flows into the Latrobe river. The Latrobe river is north of the North-East slope. The Eastern Highlands is north of the mine and the South Gippsland Highlands towards the south [48].

4.3. Geotechnical

4.3.1. Failure mechanism

The Yallourn coal seam is highly jointed with continuous sub-vertical joints. The dominant joint set is striking west-northwest to east-southeast and forms an acute angle with the North-East mine slope [45].

Due to the low density of the brown coal, the coal slopes are prone to movement and can fail if there is a sufficient increase in the slope groundwater levels. The Yallourn landslide is a typical horizontal block sliding mechanism. The high groundwater pressure in joints that connected to the Latrobe river and along the inter-seam resulted in the failure. The planned buffer distance between the pit slope and the Latrobe river was only 150 m [45].

4.3.2. Hydrogeology

A phreatic groundwater level is present in the Yallourn coal seam. This groundwater level can be affected by rivers or rainfall runoff into open joints.

Horizontal drain holes have historically been used at the Yallourn Mine to dewater and reduce the groundwater level in the coal slopes. A decision was made around 2003 to stop the drilling of horizontal drainholes [45].

Confined aquifers are present below most of the slopes for the Latrobe Valley Mines. These aquifers can be very extensive [49]. Deep aquifer dewatering has historically been required at the Yallourn Mine to manage the risk of floor heave. After various studies, it was decided in 2004 to switch off the deep aquifer dewatering bores. Unfortunately, high porewater pressures remained in the interseam clays under the North-East slope [45].

4.3.3. Progressive failure

The movement monitoring survey pins on the North-East slope indicated accelerated movement for years before the landslide occurred.

In general, the piezometer levels on the North-East slope reduced over time. However, a few months before the failure there was a significant increase in some of the bore levels. This sudden increase may indicate hydrogeological connectivity being established between the joints that formed the failure surface and the Latrobe river [45].

In the months before the failure large cracks started forming between the pit crest and the Latrobe river. This was followed by significant inflows of water from the Latrobe river until the failure occurred. There was also significant displacement of the conveyers and other infrastructure on the North-East slope the days and weeks before the failure.

4.3.4. Geotechnical parameters and reliability

Movement of the North-East slope in the months and years before the failure would have resulted in residual shear strength conditions in the interseam clays below the base of the coal. A residual friction angle of 16° was used in back analysis/validation modeling by [45]. Based on experience in the Latrobe Valley mines the residual friction angle can be significantly lower than 16°.

4.3.5. Failure triggers

Various factors contributed to the Yallourn landslide as previously discussed. It is possible that a rainfall event on 4 November 2007 could have acted as a trigger for the landslide to occur.

4.4. Lessons Learned

There is a long history of the block sliding failure mechanism in the Latrobe Valley brown coal mines [45]. The use of horizontal drain holes and deep aquifer dewatering is required to reduce groundwater pressure in both the coal joints and along the inter-seam clays [45]. Removing these controls, and mining very close to the Latrobe river, resulted in a significant increase in the risk of slope instability.

Table 1 Summary of the context and processes involved in the slope failure case studies

Case	Context	Deterioration or Disturbance event(s)
Vaiont landslide, Italy, 1963 (also written as Vajont)	Natural slope during reservoir filling	Reservoir filling and drawdown. Groundwater and stress conditions.
Guinsaugon landslide, Philippines, 2006	Natural slope	Rock mass strength deterioration inferred. Peak to residual strength during failure. Earthquake and rainfall association.
Yallourn landslide, Victoria, Australia, 2007	Open cast coal mine near a river	Mining approaching the river, reducing buffer to groundwater pressure. Relaxation of rock mass during mining. Inter-seam layer low residual strength.

5. CONCLUSION

The three large slope failures reviewed share the following features [1]. The failure mechanisms are complex and have required significant detailed investigation [33]. No single trigger event could be identified as the ‘cause’ of the landslide [34]. Movement on pre-existing bedrock structures was involved thus generating the large volumes involved in the landslides [35]. Water movement and related water pressure was part of the problematic conditions associated with the failures.

Risk management planning is needed in excavations, engineering projects and for communities near slopes. In the case of excavations such as mining, every slope requires a management plan to assess stability. All engineering projects including dams, transport corridors and building construction also require assessment of slopes in the vicinity. In remote areas, it may not be reasonable to assess and monitor the stability of every natural slope. However, every community should be aware of slopes that represent a potential hazard. Risk factors such as heavy rain periods and observations such as ground cracking or anomalous surface water behavior together with associated action plans should be known by residents.

Significant advances have been made in regional assessments of susceptibility to shallow landslides [19] but the potential for larger, deeper landslides to occur remains difficult to assess on a regional scale.

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