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ORIGINAL PAPER

The 2014 Hans Cloos lecture: Engineering Geology—some feedback regarding the practice of a scientific and technical discipline

Conférence Hans Cloos 2014: Géologie de l'ingénieur – quelques retours d'expérience relatifs à la pratique d'une discipline scientifique et technique

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Abstract This Hans Cloos lecture paper develops general reflections inspired by Ian McHarg's (1969) book, "Design with Nature" and concerning engineering geology. Three case studies are illustrated: landslides in reservoirs, gallery excavation in a shield volcano, large rockslides and rock avalanches. For these three case studies, the potential and limits of conceptual and numerical models are discussed.

Keywords Engineering geology · "Design with Nature" · Reservoirs · Gallery excavation · Rockslides and rock avalanches

Résumé Cet article reprenant la Conférence Hans Cloos développe des réflexions générales sur la géologie de l'ingénieur, inspirées par le livre de Ian McHarg «Design with Nature». Trois cas d'étude sont illustrés: glissements dans les retenues de barrage, creusement d'une galerie dans un volcan bouclier, grands éboulements rocheux et avalanches rocheuses. Pour ces trois cas d'étude, les potentialités et les limites des modèles conceptuels et numériques sont discutées.

Mots clés Géologie de l'ingénieur · "Design with Nature" · Retenues de barrage · Creusement de galerie · Eboulements rocheux et avalanches rocheuses

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Introduction

This paper is a transcription of the Hans Cloos lecture given during the IAEG XII Congress in Torino, on the 15th of September, 2014.

It is necessary to begin by thanking the people who have supported this candidacy submitted by the French National Group of the IAEG. There are many who would have been eligible for such an award, with excellent professional references. The IAEG XII Congress was held in memory of Marcel Arnould, as IAEG Honorary President. I was one of his students and then collaborators (Cojean and Audiguier 2011). So, in this context, it is a particular great honour for me to receive the Hans Cloos medal.

Here, I want to explain that Marcel Arnould opened my eyes to the geological world, the Earth, our common home and the actions of humans, sometimes so invasive. Thanks to Marcel Arnould (1969, 2009), I was quickly convinced by the precepts set forth in the book of Ian McHarg (1969), under the title *"Design with Nature"*. Ian McHarg was an architect and town planner. In fact, the book goes beyond purely technical concepts of environmental planning and the key to this book is in the title. Ian McHarg promoted the concept of ecological planning, which implies global analyses of climate, hydrology, geology, hydrogeology for a given site where designers intend to develop land use planning projects. In addition, Ian McHarg set his thinking in opposition to domination and destruction of "Nature" and developed ethical discussions related to land use planning with his students. I think that "Design with Nature" could be the key phrase of the IAEG: man or humanity is behind the word "Design". All environmental issues are related to the word "Nature" and "Nature" as a true partner. *We have to continually learn from "Nature" and respect "Nature".*

During the preparation of this Hans Cloos lecture, I decided to focus on several technical or scientific topics I encountered during my professional life. And I thought that perhaps, from these technical and scientific topics, it would then be possible to highlight basic concepts of engineering geology. It was a very ambitious objective! Finally, more modestly, I decided to choose the following title: “Engineering geology: some feedback regarding the practice of a scientific and technical discipline”. The main idea of this lecture consists in developing general thinking about Engineering Geology that is in agreement with the “*Design with Nature*”, focusing on the question of the evaluation of the distance between modeling and reality. Then three case histories have been chosen to illustrate this question.

First part: observations, conceptual models and numerical simulations, decisions

In this first part, general thinking about Engineering Geology is proposed.

In the application of engineering geology, it is usual to distinguish, on the one hand, geological materials and structures: soils and rocks, soil masses and rock masses, aquifers and groundwater, and on the other hand, geological processes and mechanisms such as: weathering and hydrothermal alterations, surface and underground erosion, gravitational movements of all kinds: subsidence, landslides and rock falls, and also volcanism and seismic activity, climatic change and so on.

In each situation, our challenge is to implement a global approach and to be able:

- First, *to observe “Nature”* and analyze geological materials and structures and geological processes.
- Second, *to build conceptual models* related to “Nature” and interactions between “Nature” and engineering works, and then, to perform numerical simulations.
- Third, *to take appropriate decisions* concerning land use planning issues, for example, or the design of engineering works, following the precepts of “Design with Nature”.

It is possible to describe these three stages of this global approach:

1. First stage: to observe “Nature”, but at what scales?

(a) The *geometrical scales*. Different scales have to be considered: the scale of minerals and microstructures in soils and rocks. The scale of soil or rock samples in the laboratory. The scale of the outcrop, the soil mass or the rock mass, with structural characteristics, heterogeneities and anisotropies. The scale of large geological structures: mountain ranges or subsiding basins.

(b) The *time scales*. Different scales have to be analyzed: the microsecond or the second for earthquake events or for failures of rock bridges in an unstable rock slope. The scale of years for hydrological cycles. The scale of a year, a century or a thousand years for climatic changes or for rheological aging of materials. The scale of a century, thousands of years and millions of years for geoprospective issues such as variations of sea-levels or creeping of materials with applications related, for example, to the storage of radioactive waste.

(c) Different scales, geometrical and time scales: and then specific scientific questions, concerning the *validity of physical laws depending on scale effects*, such as Darcy’s Law for materials of very low permeability in argillites or clayey formations, and the Coulomb friction law for gravitational movements of huge landslides or rock avalanches. Also, scientific questions arise concerning the choice of design parameters, such as creeping thresholds in materials as a function of the considered time scale.

In addition, the necessity of making measurements in the laboratory or in the field with appropriate instruments is obvious. Also monitoring is necessary to investigate geological materials and structures and the geological processes in the deepest way.

2. Second stage: to build conceptual models.

Modeling consists not only of numerical modeling and numerical simulations. Modeling is, firstly, appropriate synthesis of data. So, appropriate data are necessary! Sometimes this can be forgotten! Synthesis of data has to be done by reference to a global geological knowledge and also geomechanical and hydrogeological knowledge. This question of conceptual models has to be shared with our colleagues in the corresponding specialties of soil and rock mechanics and hydrogeology.

The conceptual models have to deal with different challenges:

- How to represent “Nature” objectively as a complex system.
- How to deal with the multi-physical couplings, when physical, mechanical, thermal, hydraulic and chemical processes are involved together.
- How to manage uncertainties in the model.

- How to prepare the necessary simplifications of "Nature" so that the conceptual model can be transformed into a geometrical and geomechanical model, then a numerical model.
- How to measure or appreciate the difference between a numerical model and reality.
- As a consequence, how to implement *appropriate monitoring systems* to control the real behaviour of soil and rock masses or engineering works. And, how to be ready for actions in case of some discrepancies between model and reality.

The numerical models have to be able to perform quick parametric analyses to investigate the whole range of natural possibilities concerning characteristics of geological materials. With humility, we have also to concede that numerical simulations can show or reveal processes or mechanisms that "Nature" had not yet revealed to our mind, or that our imagination had not yet considered.

Because of these challenges, the issue of paramount importance is: the assessment of the *distance between the model and the geological reality*. So, Engineering Geology must take ownership of all geological, geomechanical and hydrogeological components of this global approach. Of course, this approach has to be shared with other scientific and technical disciplines in friendly cooperation.

3. Third stage: To take appropriate decisions, to design with "Nature".

"Design with Nature" is not to cope with "Nature". "Design with Nature" is not to come to a compromise with "Nature". It is really *to design in harmony with "Nature"*, "Nature" being a true partner. To implement the concept of "Design with Nature", the engineering geologist has to take advantage of numerical simulations, but also has to rely on past events and take advantage of feedback analyses.

"Design with Nature" is also to forecast the realistic behaviour of the soil or rock mass. That means a monitoring system has to be installed so that instrumental data allow for the checking of the behaviour of the soil or rock masses and the engineering works. Then, decisions can be taken according to *an observation method* where the behaviours of the soil or rock masses are continuously verified. Decisions can be taken quickly according to pre-calculated scenarios of behaviours.

Now, I move to a few examples related to engineering geological subjects encountered during my professional life. Three examples have been selected to enable discussion of conceptual models and numerical simulations, trying to illustrate what can be good practice of the *"Design with Nature"* concept.

Second part: three examples related to engineering geological subjects

Landslides in reservoirs. Contribution of conceptual and numerical models to the design of stabilization techniques

The theme of landslides in reservoirs is a part of our common history for engineering geology specialists. I became interested in this subject many years ago with my colleague Jean-Alain Fleurisson. We published a general paper on the subject of the influence of geological structures on the stability of slopes gradually submerged by the rise of water in a reservoir. This paper was published for the Sixth International IAEG Congress in 1990 (Cojean and Fleurisson 1990). Of course, many other papers could be mentioned about this question.

In this paper, we were interested in highlighting the role of the morphology of the slope, as well as the role of the form of a potential sliding surface in the evolution of the factor of safety as a consequence of the rise of the water level in the reservoir, or as a consequence of a more-or-less rapid drawdown. A series of 50 case histories were investigated.

The following figures provide an understanding of the evolution of the factor of safety (F) (on the *y*-axis) as a function of the reservoir water level Hw1 (on the *x*-axis). The form of the corresponding blue curve (Fig. 1) has to be noted down for the particular type of slope morphology that is presented, with a clearly decreasing evolution of the factor of safety, at the beginning of the impoundment, as a function of the rising water level in the reservoir. Then, for a given water level Hw1 (point Ai on the blue curve), when a rapid drawdown is achieved (Fig. 2), Hw1 is decreasing and the evolution of the factor of safety is described by the red curve. And in case of a slow drawdown (Fig. 3), intermediate between the rapid drawdown and the perfect drawdown, the evolution of the factor of safety is described by the orange curve.

Thus, for any type of unstable slope, it is possible to draw this set of curves and then analyze the behaviour of reservoir slopes as a consequence of variations in water levels in the reservoir, for different conditions. This was done, in particular, for the Vaïont landslide (Fig. 4) to obtain a better understanding of the cause of the failure that occurred in 1969. The historical conditions of variations of water level in the reservoir are presented on the left part of the diagram. The corresponding evolution of the factor of safety can be observed until failure.

The results obtained were later further researched by Yaojun Caï in his PhD Thesis (Caï 2000) when I became

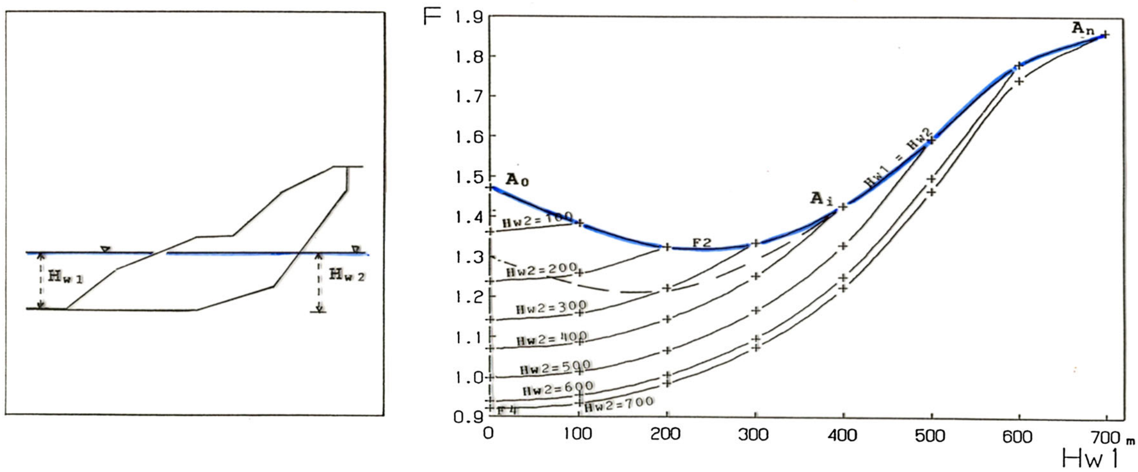

Fig. 1 First impounding of the reservoir. Slope factor of safety as a function of the reservoir Hw1 water level (*blue upper curve*), with conditions of a slow impoundment of the reservoir or a slow lowering of the water level associated to a perfect drainage of the slope (Hw1 = Hw2). After Cojean and Fleurisson (1990)

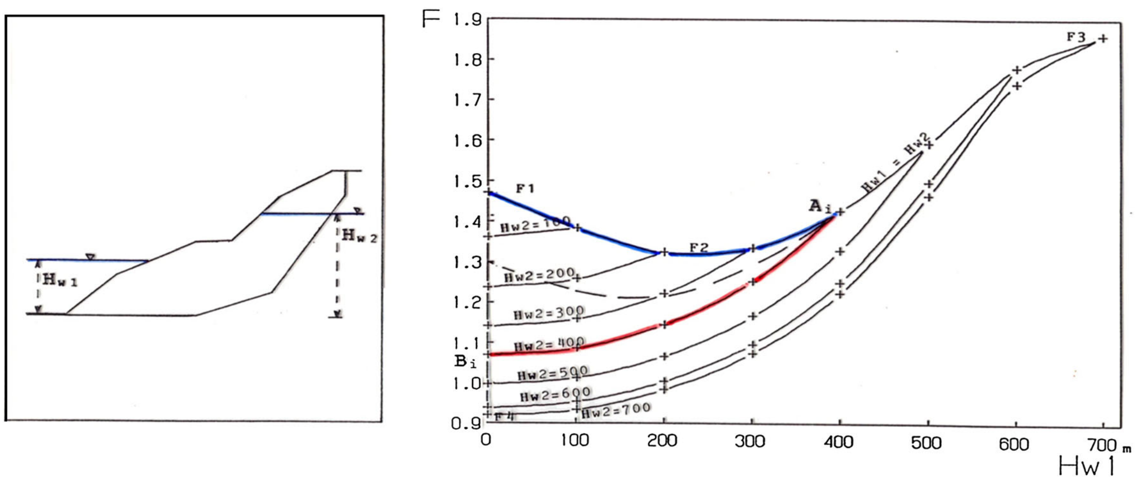

Fig. 2 Rapid drawdown of water in the reservoir. Slope factor of safety evolution as a function of the lowering of the reservoir Hw1 water level (*red curve*), with rapid drawdown conditions in the reservoir and the corresponding no drainage conditions in the slope. The water lowering in the reservoir begins at point Ai in the diagram. After Cojean and Fleurisson (1990)

interested in the Three-Gorges dam located on the Yangtze River in Hubei Province, China (Fig. 5).

At that time, a lot of data was available about the analysis of landslide hazards in the reservoir, including, in particular, an atlas of slope movements identified along the Yangtze River (Fig. 6) (Chinese Ministry of Geology, 1993).

Field trips with Chinese colleagues (Fig. 7) allowed selection of three particular sectors of the Yangtze River where geological investigations were performed and numerical simulations carried out, following the approach presented above and also implementing finite element analyses.

General results are given concerning the landslide of Huangtupo (Fig. 8), in Triassic formations, near the town of Badong, with the water level elevations of: 65 m for the Yangtze River, then after the impoundment, 145 and 175 m for the reservoir, for low and high levels during the year, respectively. The formations forming the slope consist, in alternating layers, of claystone, siltstone and limestone, dipping towards the river. However, the unstable mass corresponds to an ancient landslide of about 50–80 m in thickness and 40 millions of cubic metres in volume, consisting of disturbed and reworked materials. A complex groundwater system was identified with several natural drainage paths through the slope.

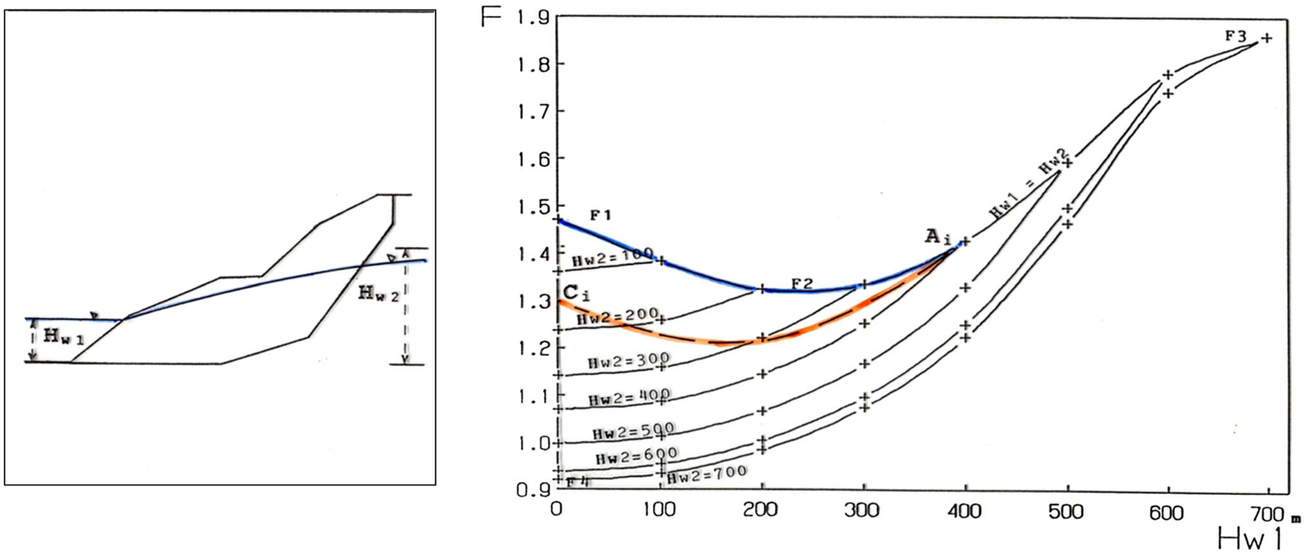

Fig. 3 Low drawdown of water in the reservoir and intermediate drainage conditions in the slope. Slope factor of safety evolution as a function of the regular lowering of the reservoir Hw1 water level (*orange curve*), with intermediate drainage conditions in the slope. The water lowering in the reservoir begins at point Ai in the diagram. After Cojean and Fleurisson (1990)

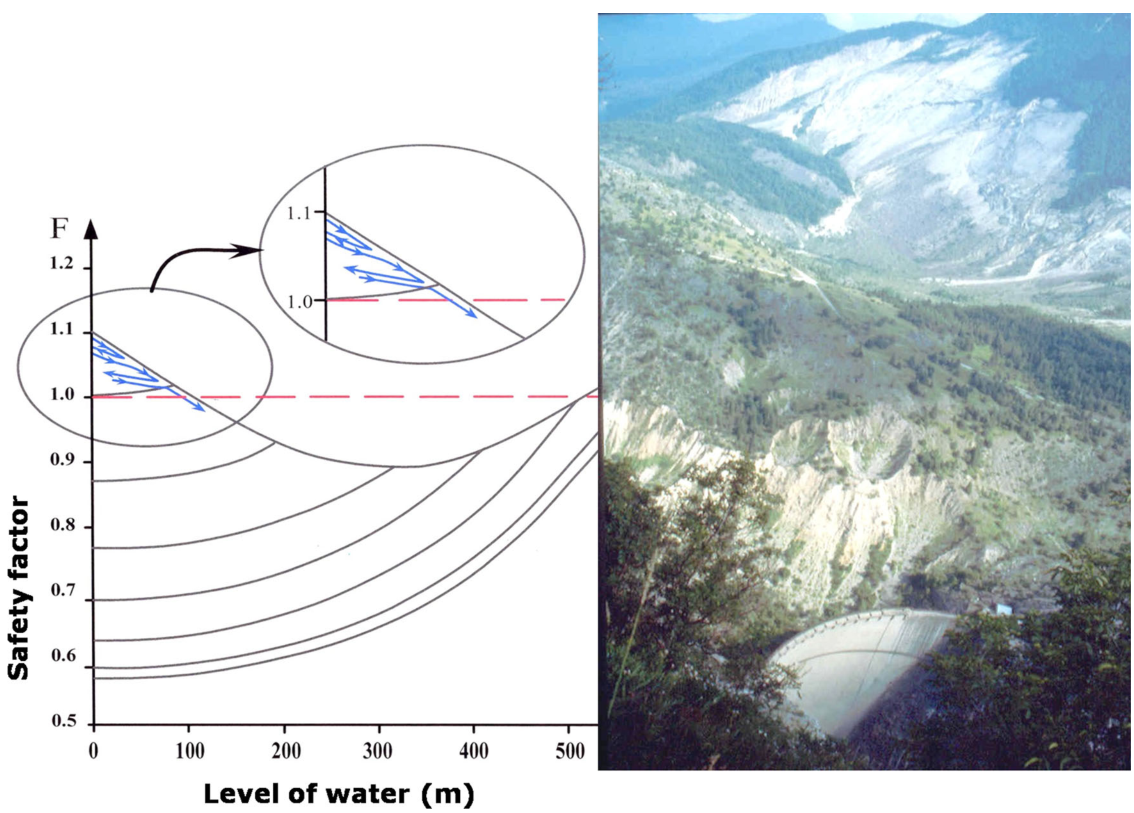

Fig. 4 The Vaïont landslide and the corresponding set of curves before failure, on the *left* part of the diagram. After Cojean and Fleurisson (1990)

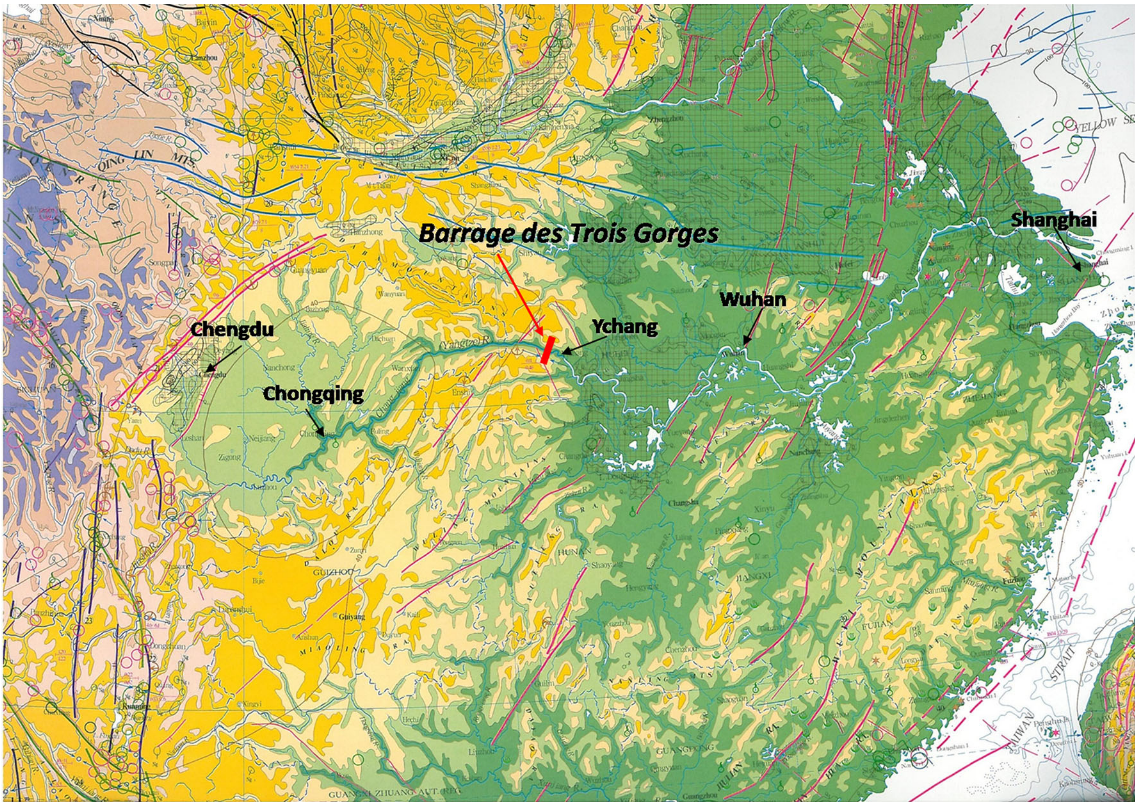

Fig. 5 The Three Gorges dam (China) located on the Neotectonic map of China (extract), original scale: 1/5 000,000, after Chinese Academy of Geological Sciences (1996)

Fig. 6 Front cover of the Atlas of slope movements along the Yangtze River, with maps and geological sections, after the Chinese Ministry of Geology (1993)

Thanks to the numerical simulations (Fig. 9), it was possible to highlight the critical situation of a water level at the elevation level of 108 m concerning the toe of the slope, potential failure being revealed by a continuous line of plasticity indicators corresponding to local numerical failures at particular mesh nodes. This water level was at the lowest point of the previously presented blue curve with the minimum factor of safety. For water levels lower or higher than this elevation, the factors of safety for the slope were higher.

Then, relying on these numerical simulations, it was possible to adapt the stabilization techniques to this situation (Fig. 10), with mechanical reinforcements and drainage patterns especially designed at the toe of the slope. As a conclusion of the work of Caï (2000), a scheme of drainage and reinforcement of the slope was proposed. A few details are given in Fig. 10. However, the question remains of how to evaluate the difference between, on one hand, the conceptual and numerical models and, on the other hand, the geological and geomechanical reality. A monitoring system for the slope was proposed and an observation method recommended (Caï 2000). In this case, the *"Design with Nature"* consists of implementing numerical simulations adapted to the geological context and checking the real behaviour of "Nature", thanks to appropriate monitoring devices.

Figure 11 presents an overview of the site at the end of the engineering works.

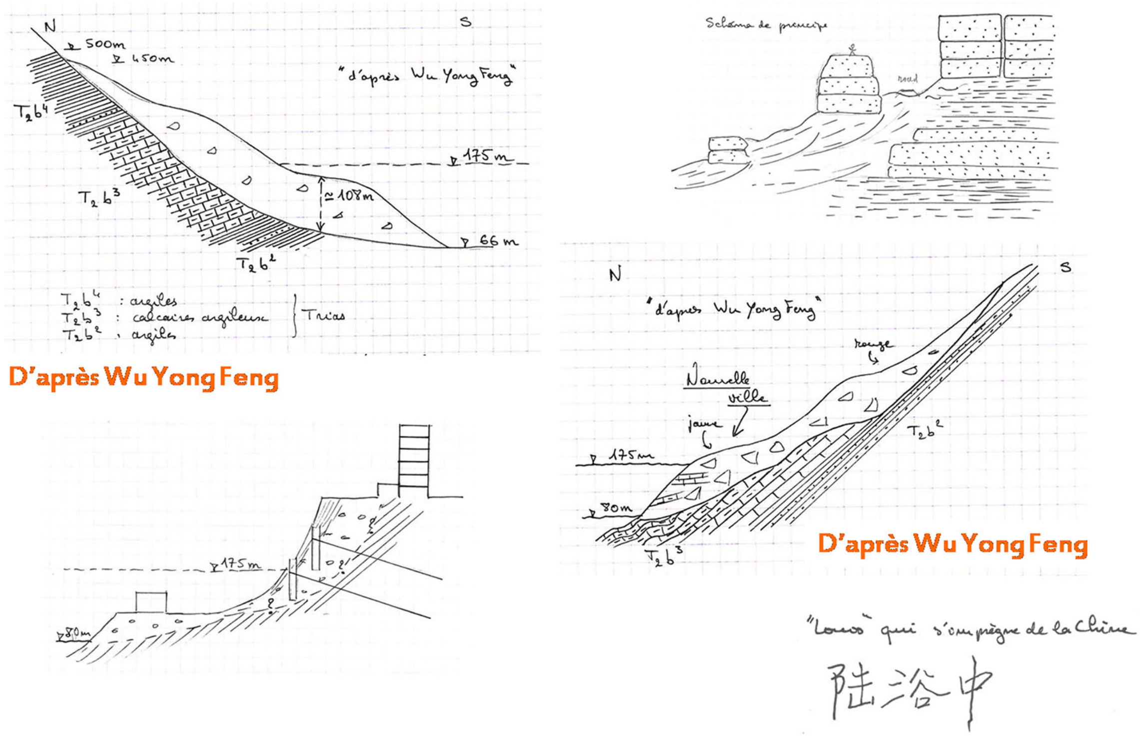

Fig. 7 Chinese field notebook: along the Yangtze River (Chang Jiang), after Cojean (1996)

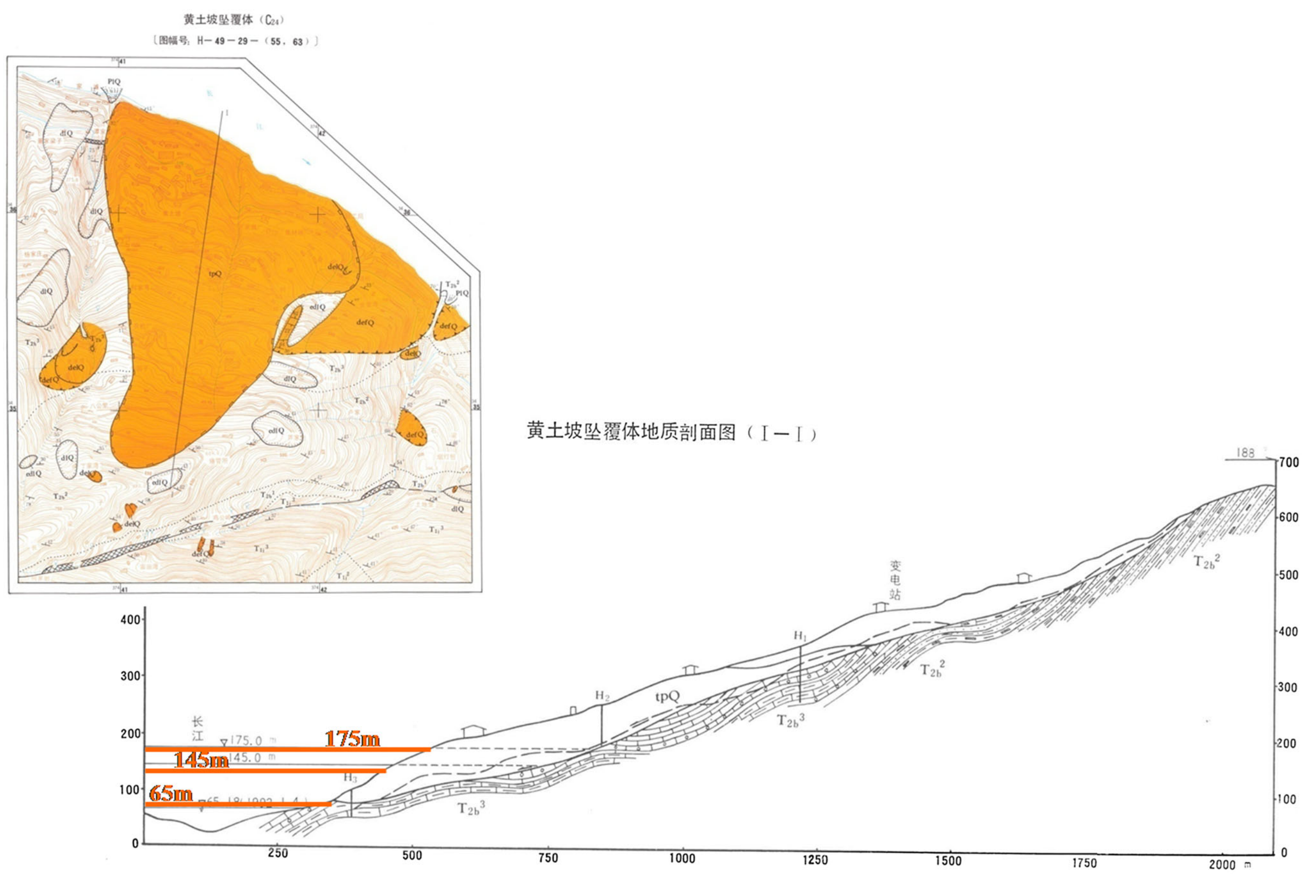

Fig. 8 Geological map and cross-section of the Huangtupo landslide, after Chang Jiang Water Research Commission (China) documents

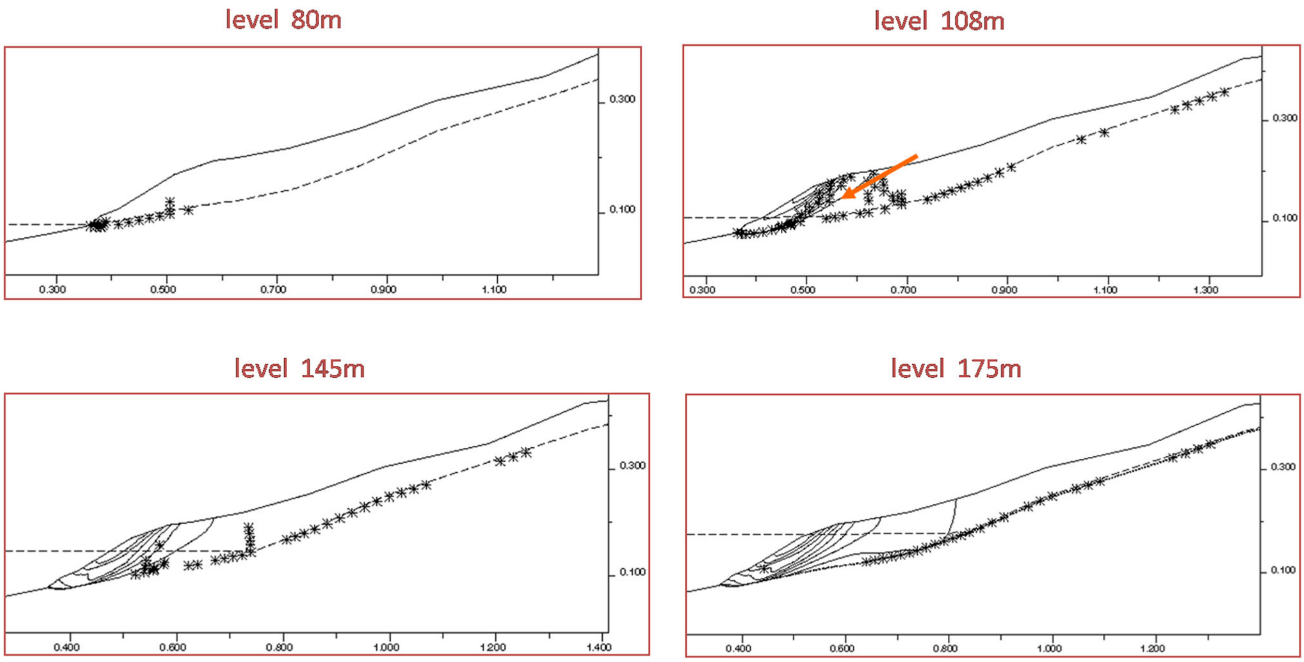

Fig. 9 Impounding of the Three Gorges reservoir from the level 80 m to the level 175 m: plasticity indicators (*symbols**) and iso-value curves of displacement vectors (cm) account for progressive deformation, after Caï (2000)

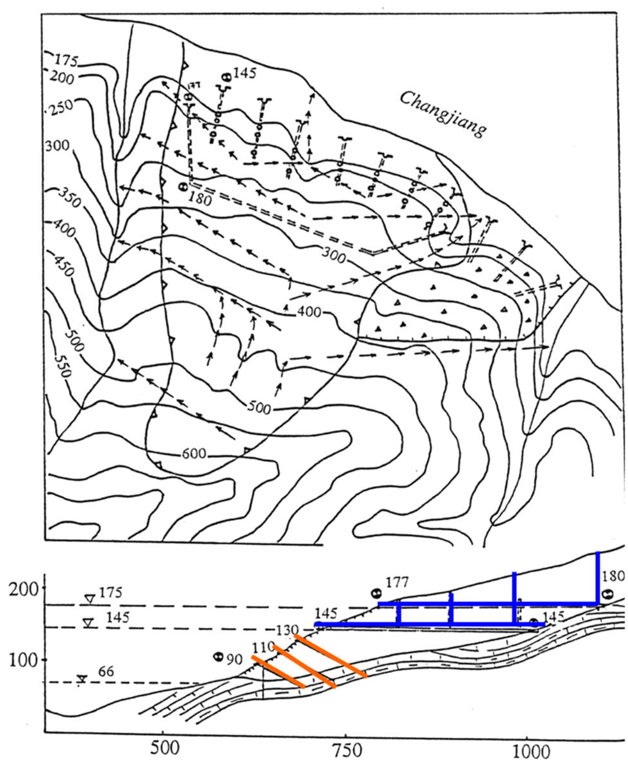

Fig. 10 Scheme of the drainage and reinforcement project for the Huangtupo landslide proposed by Caï (2000). Drainage ditches network on the whole slope, rainwater and waste water collected in sewers, drainage galleries at the toe of the slope to prevent rapid drawdown conditions, mechanical reinforcements with tensioned rock bolts at the toe of the slope, superficial reinforcements (nailed soils, surface protections: small girders and geotextiles) at the toe of the slope, monitoring system

Fig. 11 Overview of final situation at the site of Badong. Courtesy of Chang Jiang Water Research Commission, China

The Piton des Neiges (La Réunion, France) and the excavation of the Salazie Amont gallery: is a conceptual hydrogeological model conceivable in this case?

This is an insight into a controversial subject concerning the question of groundwater conceptual models in volcanic islands. The island of La Réunion, in the Indian Ocean, is the subject of this analysis. The geological map is presented (Fig. 12) with the Piton des Neiges in the northwest part of the island and the active volcano of La Fournaise in the southeast part.

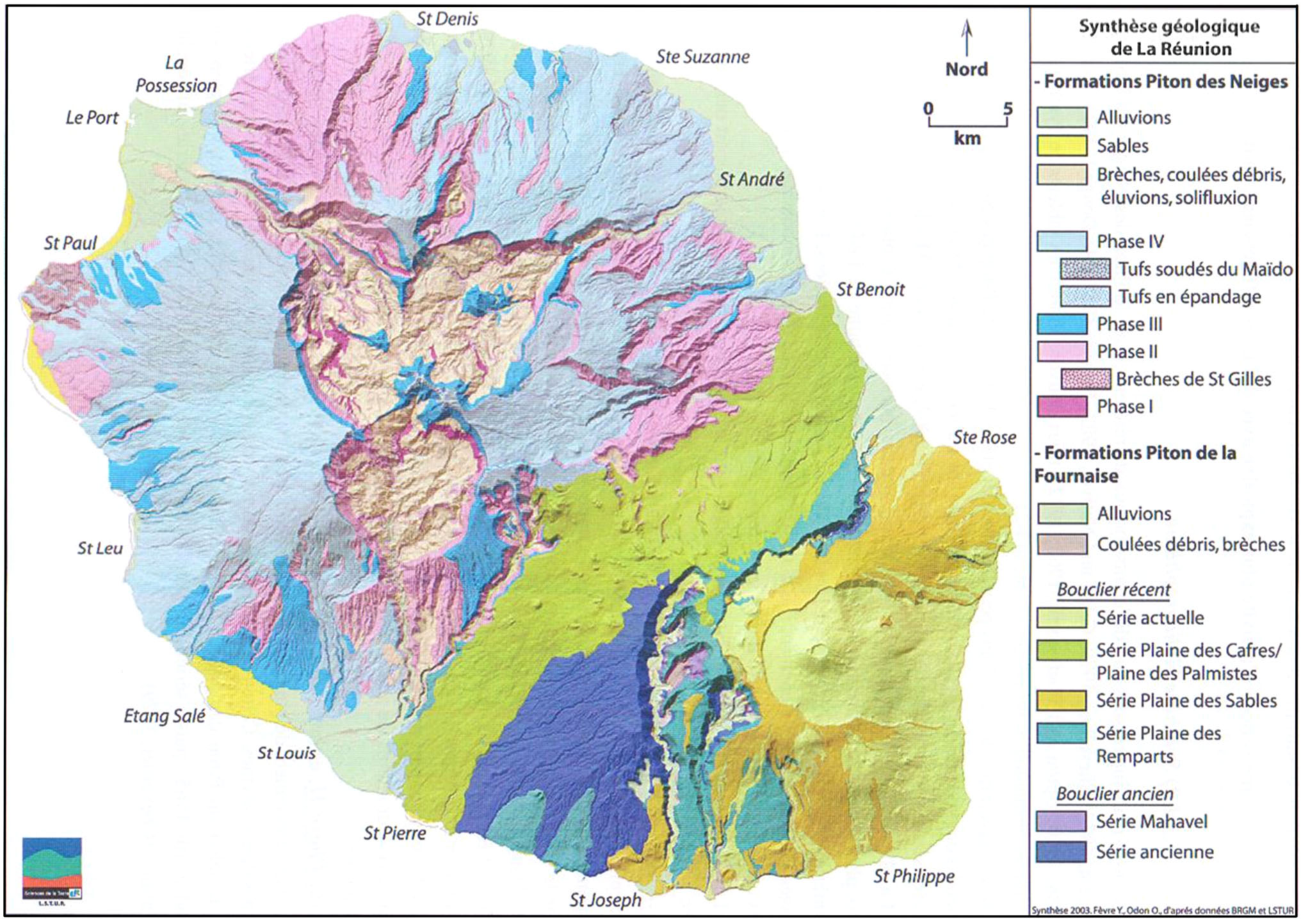

Fig. 12 Geological synthesis of La Réunion island, proposed by Fèvre (2005), after Bret (2002)

The Piton des Neiges is deeply eroded by three erosional basins: Salazie, Cilaos, and Mafate. Particular features of the Salazie erosion basin can be seen in Figs. 13 and 14.

I will just focus on two hydrogeological conceptual models usually put forward for islands formed by shield volcanoes, lava flow deposits alternating with pyroclastic deposits: the Hawaiian conceptual model and the Canarian conceptual model (Fig. 15). The following questions then arise: do high water levels in the landscape result from perched aquifers or dyke-confined aquifers (as in the Hawaiian type)? Or, is there a kind of central groundwater dome that could be explained by altered old volcanic terrains in the basal central part of the shield volcano (as in the Canarian type)?

These questions are important, with consequences about water pressure distributions within the volcano and interactions with the excavation of tunnels or galleries and problems of water pressures and water inflows in the galleries. With my colleague Benoît Deffontaines, I had the opportunity to investigate this subject in 2010 for the excavation of the Salazie Amont gallery for the East–West Water Transfer project on the island (Cojean and Deffontaines 2010).

Fig. 13 Salazie erosion basin (La Reunion island), with very steep slopes or “remparts” (walls). Photo: R Cojean

High water levels can be observed in the landscape, such as the bridal veil (Fig. 16), probably resulting from perched aquifers in this case. Complex generations of dykes,

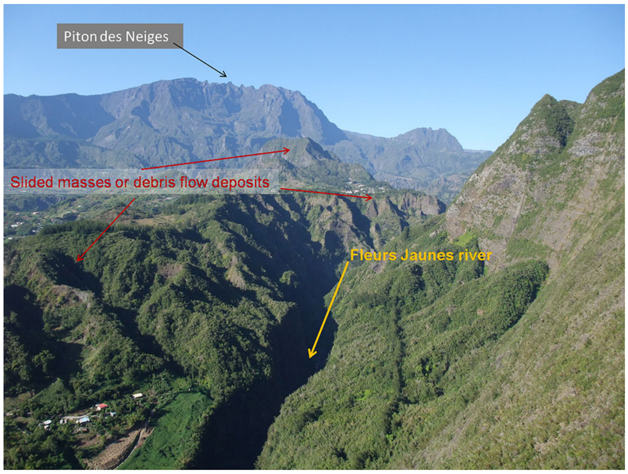

Fig. 14 Salazie erosion basin, with the Piton des Neiges in the background, the large slipped masses and debris flow deposits and the Fleurs Jaunes River in the foreground. Photo: R Cojean

usually vertical, are usual in the Fleurs Jaunes River (Fig. 17), with a deep incision through layers of lava flows and pyroclastic deposits (Fig. 18). The very steep slopes of the banks of this river exhibit vertical dykes of very large vertical extension with the possibility of delimiting confined aquifers between them. Hydrothermal alterations are observed in the lower part of the slope, with clay minerals and zeolites in basalts (Fig. 19).

These observations were made around the site of the Salazie Amont gallery that was under excavation in 2010. The Salazie Amont gallery project was represented by a gallery with a total length of 8.5 km, a diameter of 4 m, with overburden of about 1000 m (Figs. 20, 21).

The Tunnel Boring Machine (TBM) that was used was not adapted to the excavation work with very high water pressures and water inflows. At PM 1238, the blocking of the TBM occurred after very large water inflows of 400 l/s at the heading face. Water pressures of 3 MPa were measured. At that point, the overburden was about 1000 m thick. There was concern that a sudden flood with out-wash of altered materials might occur ahead of the gallery face. A by-pass gallery was excavated (Fig. 22) and excavation continued with the traditional method, until it was possible to excavate again with the TBM after important exploratory borings and drainage works.

Observations in the gallery were difficult (Fig. 23). The objective of the observations, with the help of water

Fig. 15 Conceptual models for hydrogeological systems in volcanic islands corresponding to shield volcanoes (after Join et al. 2005)

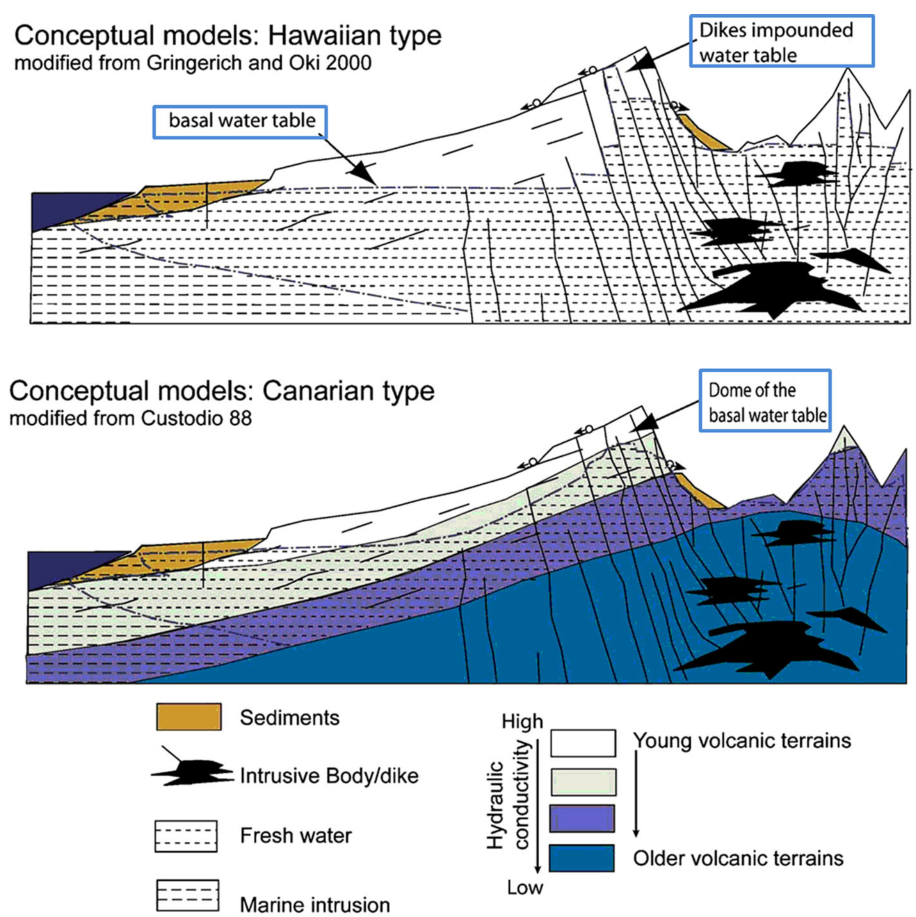

Fig. 16 The bridal veil, corresponding to high water levels in the landscape. Photo: R Cojean

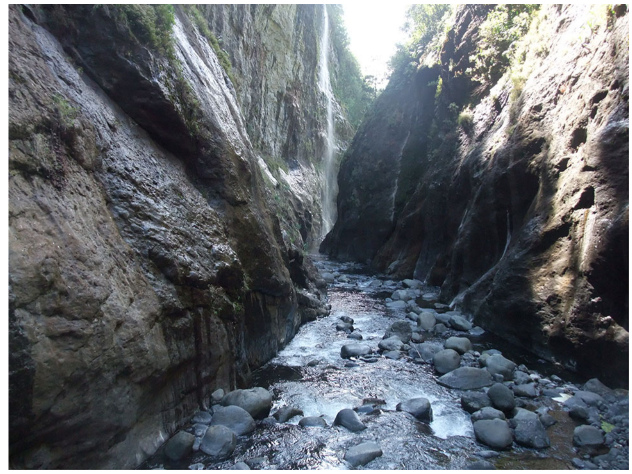

Fig. 18 Deep gorges in the Fleurs Jaunes River where vertical dykes of very large extension can be observed. Photo: R. Cojean

Fig. 17 Vertical or oblique dykes of different generations intersecting lava flows. Photo: B. Deffontaines

Fig. 19 Basalts altered by hydrothermalism with clayey minerals and zeolites at the basis of the banks in the Fleurs Jaunes River. Photo: R. Cojean

pressure and water discharge measurements, was to clarify the conceptual hydrogeological model and to help in the definition of drainage works in advance of the excavation of the gallery.

Two long boreholes of 400 and 800 m in length, parallel to the gallery, had allowed identification of critical zones with high water pressures. Different drainage systems were studied with different advantages or disadvantages. Finally, an observation method led to a drainage device adapted to the field conditions (Fig. 24).

Pressures, temperatures and the acidity of water were very surprising. For example, in the gallery under excavation, it was possible to register differences in temperature of about 10 °C over a distance of two metres! Finally, it was impossible to choose between the Hawaiian and the Canarian volcano models. The hypothesis of a nested system governed by lava flows alternating with pyroclastic deposits and subdivided by vertical dykes was proposed, complicated by a front of argillization and zeolitization in the lower part of the volcano (Cojean and Deffontaines 2010). However, no practical consequence or decision for the excavation and drainage of the gallery (Fig. 25) was possible, thanks to the new proposed conceptual model. The reason is that the model can be described as a conceptual model and it was not possible to improve it to obtain an operational tool that would have been useful for the designer. After 12 years, because of many difficulties due to water inflows, the TBM arrived at the end of the excavation with a very good precision. For the most critical situation, the total discharge of water had reached the value of 2000 l/s.

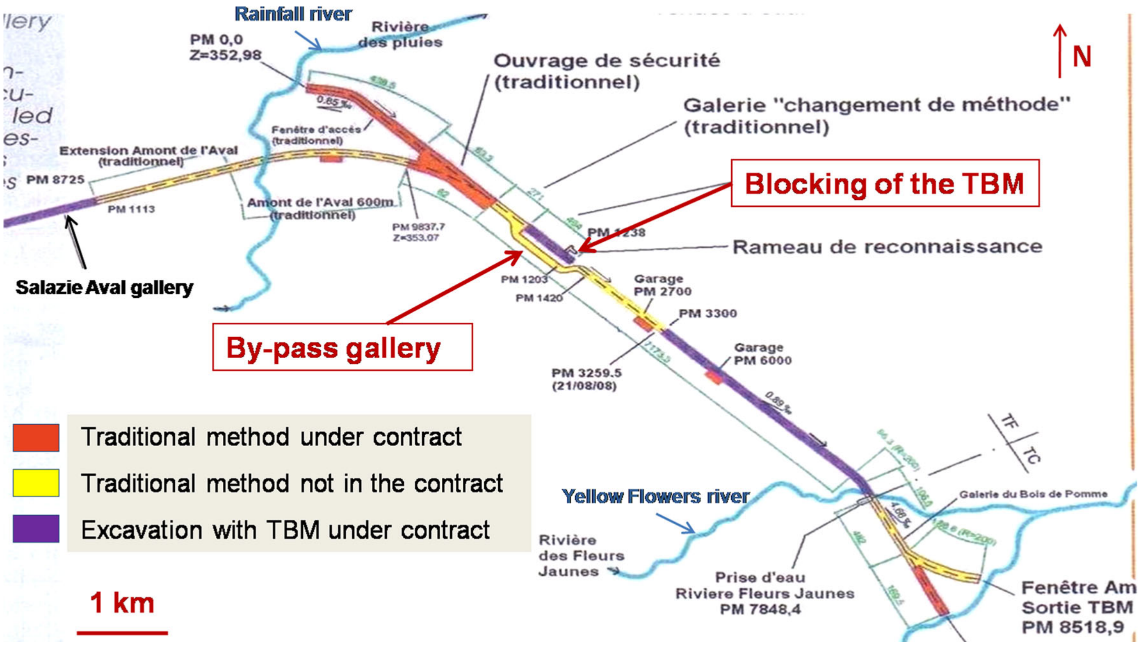

Fig. 20 Salazie Amont gallery. General scheme and important water inflow at PM 1238 and blocking of the Tunnel Boring Machine, after Département de La Réunion (2007) and GIE (Groupement d'intérêt économique) Rivière des Pluies (2008) documents

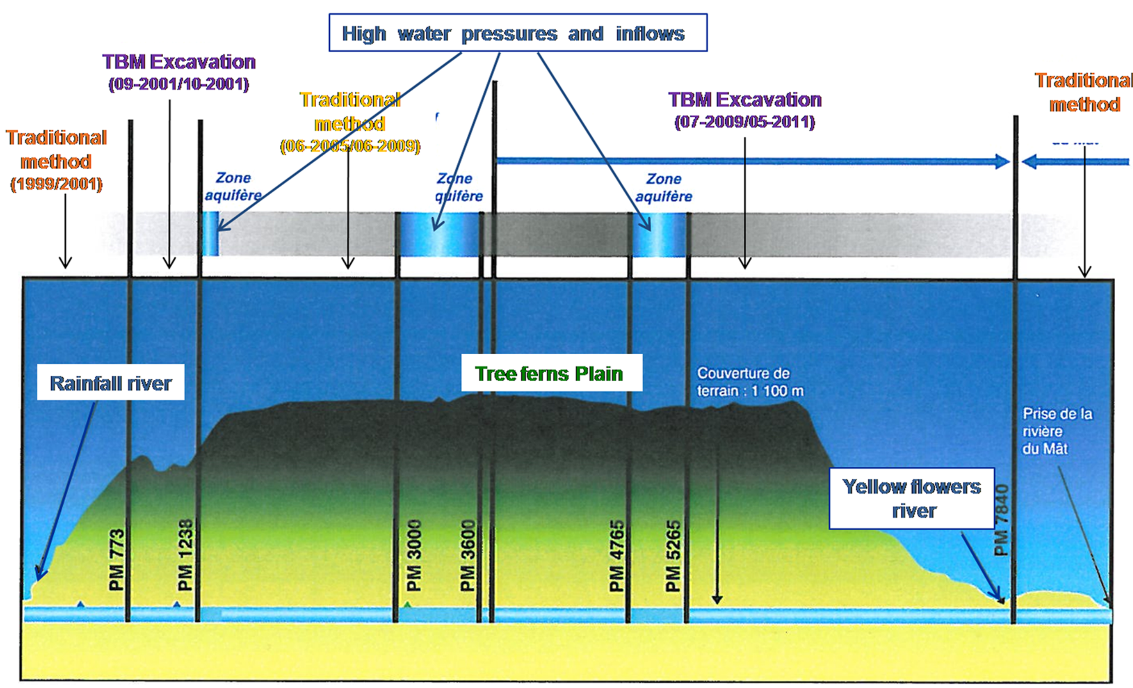

Fig. 21 Cross section of Salazie Amont gallery, excavation methods, zones of high water pressures and inflows, after GIE Rivière des Pluies Documents (2009)

Sometimes, we have to accept that the natural system is so complex that the only way to take decisions is to observe and measure in a continuous manner and to adapt progressive decisions to these observations and measurements. This conclusion is also in accordance with the principles of the *"Design with Nature"*.

Fig. 22 Salazie Amont gallery. Disengagement of the TBM at PM 1238. Courtesy of Département de La Réunion

Fig. 24 Salazie Amont gallery. Drainage aureoles at PM 3100 (eight drains 50–60 m long). Courtesy of Département de La Réunion

Fig. 23 Water inflows at PM 3050, in a section excavated using the traditional method. Courtesy of Département de La Réunion

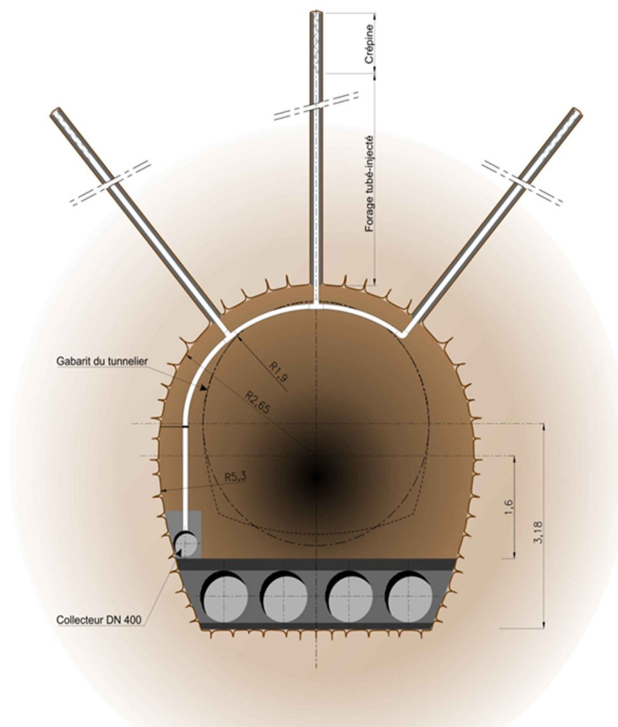

Fig. 25 Salazie Amont gallery. Final drainage system of the gallery. Courtesy of Département de La Réunion

Rockslides and rock avalanches: contribution of detailed observations to the definition of a conceptual geomechanical model

As an example, I would like to focus on large rockslides and rock avalanches and the role of detailed observations in the definition of a conceptual model.

It is not possible to describe in detail each of these three huge rockslides or rock avalanches, which were chosen as a basis for the PhD Thesis of Nicolas Pollet (2004): Koëfels in Austria (Fig. 26), Flims in Switzerland (Fig. 27) and La Madeleine in France (Fig. 28). They have in common consisting of anisotropic geological structures, such as sedimentary, or schistose and foliated metamorphic rock masses, with an orientation parallel to the slope and a dip angle lower or equal to the slope angle. In these three cases, the deposits were deeply incised and partly eroded by a river so that it was possible to obtain detailed observations in the inner part of the deposits, as well as in the distal parts.

The large complex rockslide at Koëfels (Austria) developed in gneissic rocks, the slip occurring along a

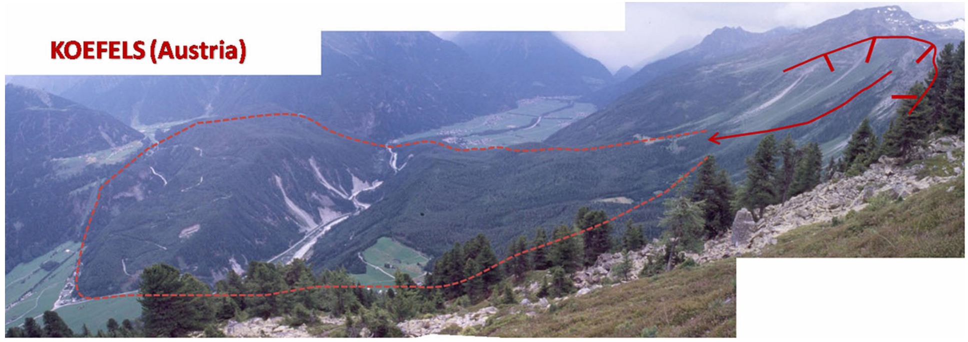

Fig. 26 Large complex rockslide at Koëfels (Austria) in hard gneissic rocks. Sliding along a basal foliation surface. Volume: 3 km^3. $H = 600$ m, $L = 2.4$ km, $H/L = 0.25$. Dating: 9800 ± 100 years BP cal (Kubik et al. 1998)

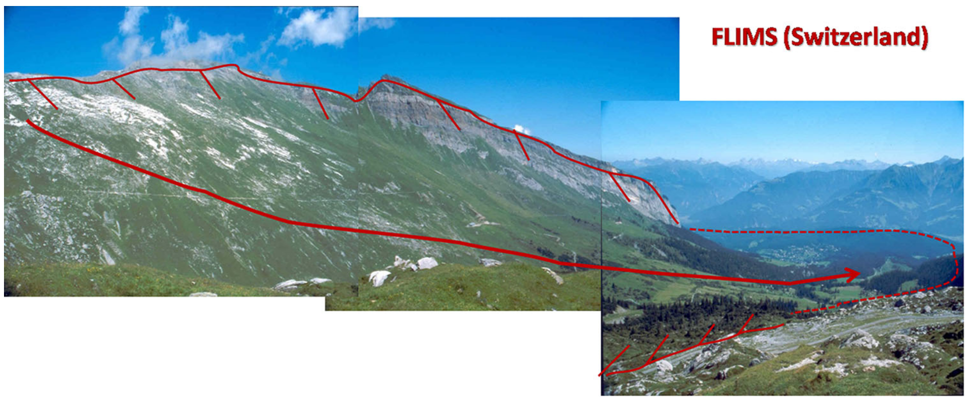

Fig. 27 Large multi-layered rockslide at Flims (Switzerland) that has turned into an immature rock avalanche. Marmorean limestones with bedding planes oriented parallel to the slope. Multi-slab shearings along bedding planes. In the inner parts of the deposit, structures are similar to the in situ rock mass, with a shattering aspect. Large structures are preserved due to the confining pressure. Large intact rock masses are present in the outer parts of the deposit. Volume: 12 km^3. $H = 2080$ m, $L = 16.5$ km, $H/L = 0.13$. Dating: 9487 ± 85 years BP (Schneider et al. 2001)

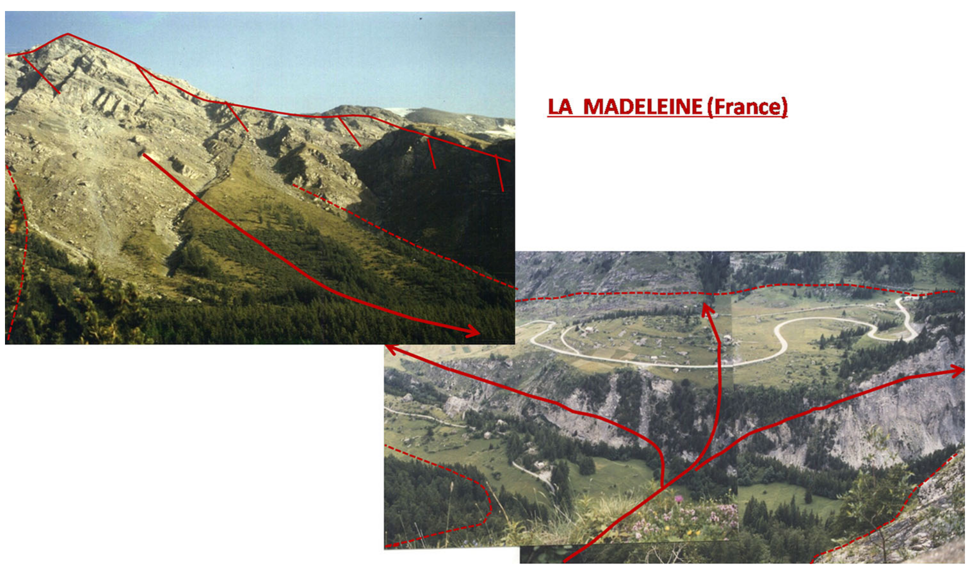

Fig. 28 Large multi-layered rockslide at La Madeleine (France) that has turned into a rock avalanche. Calcschists with foliation parallel to the slope. Sliding along numerous schistosity surfaces and high and rapid grain size reduction along the course. Volume: 0.1 km^3, $H = 1300$ m, $L = 4.7$ km, $H/L = 0.28$. Dating: 7625 ± 65 years BP (Couture et al. 1997)

basal foliation surface. The estimated volume is about 3 km^3. The source area exhibits gneissic rocks of high mechanical strength, with the foliation surface favourably oriented regarding the hazard of failure. The deposits consist of a coarse rock mass, similar to in situ materials. It can be seen that low dilatancy has occurred. Closed cracks

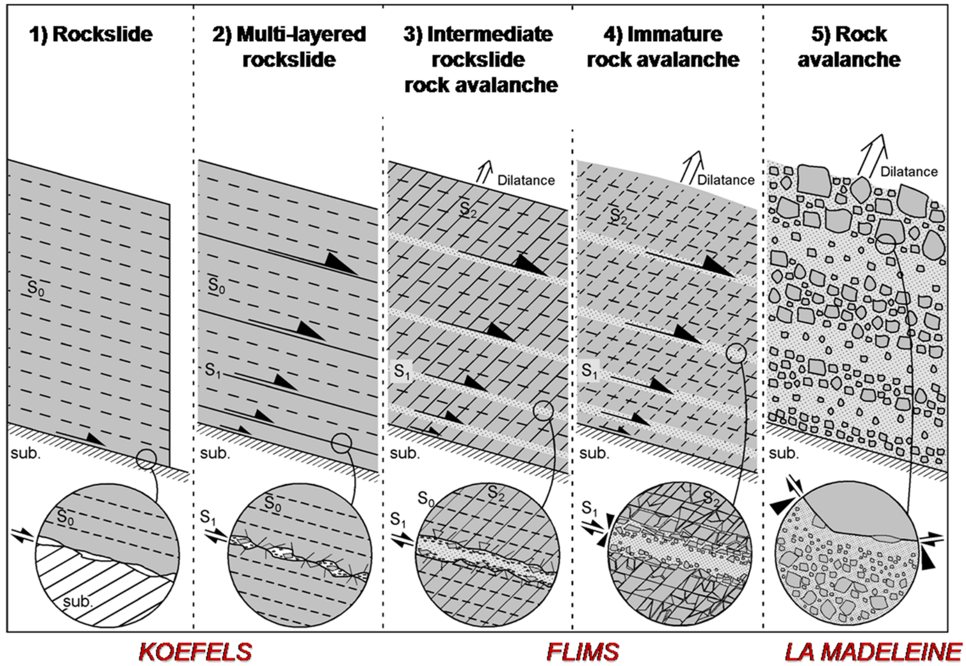

Fig. 29 Synthetic diagram related to the slab-on-slab model, after Pollet (2004)

and 'jigsaw' structures can be observed in the deposits. The model of transport can be described as sliding along a basal foliation surface, with secondary internal sliding surfaces. Finally, Koëfels (Fig. 26) can be described as a complex rockslide with a basal fractured layer and a top blocky level.

The large multi-layered rockslide at Flims (Switzerland) developed in limestone. The estimated volume is about 12 km^3. The source area exhibits marmorean limestone with bedding planes oriented parallel to the slope. The deposits consist, for the inner parts, of structures similar to the in situ rock mass, with a shattered aspect. Large shearing zones with shattered rocks and a silty-sandy matrix separate the above structures and can be seen in the deposits. Dilatancy has occurred mainly along these zones. In the outer parts of the deposit, large intact rock masses are present. The model of transport can be described as multi-slab shearing along bedding planes, with internal shattering of the rock mass. Large structures are preserved in the inner parts of the deposits, due to the confining pressure. Finally, Flims (Fig. 27) can be described as a multi-layered rockslide that has turned into an immature rock avalanche.

The large multi-layered rockslide at La Madeleine (France) developed in calcschists. The estimated volume is 0.1 km^3. The source area exhibits calcschists with well-developed schistosity. Several faults are perpendicular to the foliation. The deposits consist of a granular mass with some large blocks in an abundant matrix. High dilatancy has occurred in the deposits. In some places, rare 'jigsaw' structures can be observed. The model of transport can be described as sliding along numerous schistosity surfaces, with high and rapid granulometric reduction occurring along the course, associated with granular flows along some trajectories. Finally, La Madeleine (Fig. 28) can be described as a multi-layered rockslide that has turned into a rock avalanche.

Thus, observations have corresponded to deposits that had experienced different levels of confining pressure during the transport process. Confining pressure is a parameter of paramount importance for understanding the transport and deposition processes, and especially the mechanisms of grain-size reduction and bulking of materials.

Additional details can be found in the publications of Pollet (2004), Pollet et al. (2005) and Cojean and Pollet (2005). Finally, it was possible to design a conceptual geomechanical model (Fig. 29) that was named the slab-on-slab model.

This model can account for different contexts of rapid gravitational movements of large rock masses, evolving from rockslides to multi-layered rockslides, then intermediate rockslide/rock avalanches, immature rock avalanches and finally rock avalanches. It takes into account the rock strength of the rock material, the cohesion of the rock mass structure along potential shearing planes, the grain-size reduction during the transport process and the allowable transport distance before deposition with respect to the morphological context of the valley. The three cases that were investigated, Kofëls, Flims and La Madeleine, fitted in this proposed classification, as it is possible to see in Fig. 29.

I want to underline that a significant effort was developed in this thesis, on the basis of field observations and mechanical thinking, in order to elaborate this conceptual model before any design of a numerical model. Of course, this is a conceptual model that cannot provide practical arguments to designers. However, this model relies on precise field observations and consists of an essential result before any numerical modeling of rockslide and rock avalanche events. This conclusion is also in accordance with "*Design with Nature*".

Conclusion

I would like to underline the following thinking:
"Design with Nature" has to rely on:

(a) Observations and measurements;
(b) Conceptual geological, geomechanical and hydrogeological models and then numerical models;
(c) Monitoring of engineering works and natural sites.

The presented case histories provide illustrations of the necessity for observations and measurements before any modeling approach. Sometimes, only a conceptual model can be established that is generally insufficient for the designer to take operational decisions. In any case, we have to analyze the distance between the model and reality using appropriate monitoring devices and performing continuous observations and measurements to adapt progressive decisions to these data. This general position is in agreement with the basic principles of *"Design with Nature"* and is completely relevant to Engineering Geology.

With students or young engineers, engineering geologists have a great responsibility: helping them to observe, measure, synthesize, discover engineering geology *in the field.* For that I recommend to practice the precepts of maieutics taught by Socrates: in this case, maieutics is the art of giving birth to ideas, or how to help the students and young engineers to be the architects of their own knowledge, with the help of teachers or experienced engineering geologists.

When applying the precepts of *"Design with Nature"* that are completely in line with the basic concepts of Engineering Geology, we observe that this position can be shared all over the world with no influence of geological contexts or personal or national cultures. That is the reason why, finally, I want to highlight the *universality of Geology and Engineering Geology* that I have personally experienced. I remember my first discovery of China in a professional context, about 35 years ago, with the friendly support of Professor Wang Sijing and several Chinese colleagues. I was in the early part of my professional life and it was a kind of revelation: engineering geologists discussing together in the field about landslides, facing "Nature" together. No more nationalities. No more differences in cultures. Engineering geology was the best way to meet together and work together.

References

Arnould M (1969) Cours de Géologie de l'Ingénieur. Presses de l'Ecole Nationale des Ponts et Chaussées

Arnould M (2009) Préface de l'ouvrage: Géologie, bases pour l'ingénieur, de Parriaux A, PPUR Lausanne

Bret L (2002) Minéralogie et géochimie des séries anciennes du Piton des Neiges : modélisation et implications hydrogéologiques. Thèse doctorat, université de La Réunion

Caï Y (2000) Analyse et modélisation de mouvements de versants déclenchés par le plan d'eau d'une retenue de barrage. Application au barrage des Trois-Gorges (Chine). Analysis and modeling of slope movement triggered by the water of a dam reservoir. Application to the Three Gorges Dam (China). PhD Thesis under the supervision of R Cojean. Thèse doctorat, Ecole des Mines de Paris

Chinese Academy of Geological Sciences (1996) Neotectonic map of China. 1/5,000,000

Chinese Ministry of Geology (1993) Atlas of slope movements along the Yangtze River, with maps and geological sections, p 230

Cojean R (1996) Chinese field notebook: along the Yangtze River (Chang Yang). Unpublished personal document

Cojean R, Audiguier M (2011) Géologie de l'ingénieur/Engineering geology. Hommage à la mémoire de Marcel Arnould. Presses des Mines, collection sciences de la Terre et de l'environnement, Paris

Cojean R, Deffontaines B (2010) Expertise scientifique et technique des zones de venues d'eau souterraine, rencontrées lors du creusement de la galerie Salazie Amont (La Réunion). Scientific and technical report related to water inflows encountered during excavation of the Salazie Amont gallery (La Réunion, France). Rapport final Armines, Paris

Cojean R, Fleurisson JA (1990) Influence of geological structures on the stability of slopes gradually submerged by the rise of water level. In: Price DG (ed) Proceedings of the 6th International congress of the international association of engineering geology, Amsterdam, August 1990, A. A. Balkema, Rotterdam. 3, pp 2113–2132

Cojean R, Pollet N (2005) The slab-on-slab model as a key model to hazard assessment related to large slope instabilities. EGU Congress, Nice, 29 April 2005. Published in Geophysical Research Abstracts, vol 7

Couture R, Antoine P, Locat J, Hadgigeorgiou J, Evans SG, Brugnot G (1997) Quatre cas d'avalanches rocheuses dans les Alpes françaises. Can Geotech J 34:102–119

Département de La Réunion (2007) Projet d'irrigation du Littoral Ouest. Ile de La Réunion (France). Actualisation de l'étude d'impact. Rapport d'évaluation des incidences sur l'environnement. Saint-Denis de La Réunion

Fèvre Y (2005) Mécanismes et vitesses d'érosion à l'échelle géologique sur une île volcanique jeune à relief élevé—La Réunion (Océan Indien). Thèse de doctorat, université de La Réunion

GIE Rivière des Pluies (2008) Irrigation du Littoral Ouest. Transfert de Salazie. Galerie de Salazie Amont. Rapport de synthèse. Saint-Denis de La Réunion

GIE Rivière des Pluies (2009) Note de synthèse des éléments géologiques. Saint-Denis de La Réunion

Join JL, Folio J, Robineau B (2005) Aquifers and groundwater within active shield volcanoes. Evolution of conceptual models in the

Piton de la Fournaise volcano. J Volcanol Geotherm Res 147(1–2):187–201

Kubik PW, Ivy-Ochs S, Masarik J, Frank M, Schlüchter C (1998) ^{10}Be and ^{26}Al production rates deduced from an instantaneous event within the dendro-calibration curve, the landslide of Köfels, Ötz Valley, Austria. Earth Planet Sci Lett 161:231–241

McHarg IL (1969) Design with nature. Wiley, New Jersey

Pollet N (2004) Mouvements gravitaires rapides de grandes masses rocheuses (sturzstroms). Apports des observations de terrain à la compréhension des processus de propagation et dépôt. Application aux cas de La Madeleine (Savoie, France), Flims (Grisons, Suisse) et Köfels (Tyrol, Autriche). Rapid gravitational movements of large rock masses (sturzstroms). Contribution of field observations to the understanding of the processes of propagation and deposition. Application to the case of La Madeleine (Savoie, France), Flims (Graubünden, Switzerland) and Köfels (Tyrol, Austria)]. Thèse doctorat, Ecole des Mines de Paris

Pollet N, Cojean R, Couture R, Schneider JL, Strom AL, Voirin C, Wassmer P (2005) A slab-on-slab model for the Flims rockslide (Swiss Alps). Can Geotech J 42(2):587–600

Schneider JL, Wassmer P, Pollet N, Voirin-Schmitter C, Chapron E, Wessels M (2001) Un exemple de processus sédimentaire extrême en milieu continental : le sturzstrom holocène de Flims (Grisons, Alpes suisses). 36ème Congrès de l'Association des Sédimentologistes Français, Orléans, p 2