Prevention and management of the crumblings risks
on the difficult relief roads
The case of the trunk roads of Reunion Island

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1. INTRODUCTION

The Reunion Island is a French department located in the Indian Ocean, at the East of Madagascar. With Mauritius and Rodrigues islands, it forms part of the Mascareignes archipelago. Its settlement is recent.

Figure 1 - Position of the Reunion Island in the Indian Ocean

The first colonists settled there in second half of the 17th century. Its population of 250 000 inhabitants in 1950 is currently 730 000 inhabitants. One envisages 1 million inhabitants in 2025. This important demographic development is generating of an increasing request in the fields of housing, infrastructures, displacements and transports.

Because of the mountainous topography of the island, the urbanization primarily developed on the littoral. The island is equipped with 2 international airports; the most important, Roland-Garros airport, in the north, is the main tourist vector of the island, which accomodates 500 000 tourists per annum.

Port-Reunion ensures a total traffic of about 3 200 000 tons and imports 27 000 vehicles per annum. There is no maritime coastal traffic in Reunion Island.

Created in 1882, the Reunion island railroad, connecting Saint-Benoît to Saint-Pierre, was abandoned in 1963 with the profit of the road, which constitutes today the only interior mean of communication. The road grid remains very limited (1 000 km of principal roads).

The construction of the roads is recent and was primarily carried out in the 2nd part of the 20th century, demanding, for some of them, important earthworks with side of ramparts.

The department has got a structuring national road network, which girdles the island (R.N. 1 in the West and the R.N. 2 in the East) and a diagonal (the R.N. 3), which borrows the plains between two masses – the 'Piton des Neiges' and the 'Piton de la Fournaise'.

Other ways – national main roads (R.N. 5 towards Cilaos), secondary roads (R.D. 48 towards Salazie) or communal roads – serve the circuses and the tops of the island.

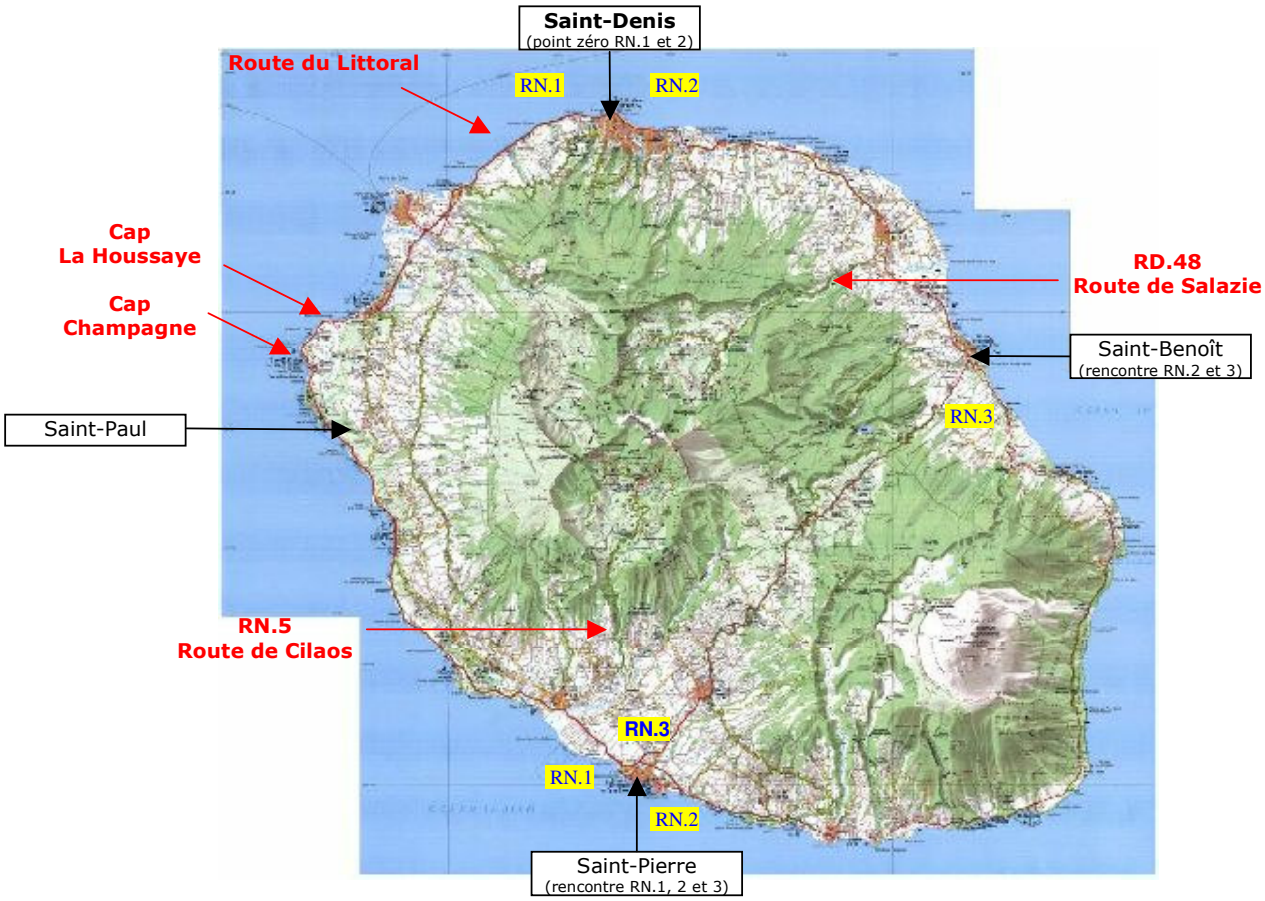

Figure 2 - Physical chart of the island

The departmental direction of the Equipment, local antenna of Equipment, Transport, Housing, Tourism and Sea French ministry, ensures the management, the maintenance and the exploitation of the 400 km of main national roads.

The 2x2 ways linear, 97 km, supports traffics from 40 to 60 000 vehicles per day. Some of these ways are located under great height ramparts. It is the case of the following sections of roads:

- The R.N. 1 known as 'road of the littoral', on a linear of 11,500 km (road point 1+500 to road point 13+000), supports a traffic of 48 000 vehicles per day (in 2002)

- The R.N. 1 between R.P. 29+000 to R.P. 34+000 road points, curves with the foot of the courses 'Cap Marianne', 'Cap La Houssaye' and 'Cap Champagne' and supports a traffic of 36 000 vehicles per day (2002)

- The R.N. 5, serves Cilaos, town of 6 000 inhabitants. Between the 6+000 and the 35+000 road points, it is located on a linear of 29 km at side of ramparts which reach several hundred meters height.

2. NATURAL RISKS IN REUNION ISLAND

2.1. Physical environment

Geology :
Reunion Island represents the emerged part (3% or 18 M km^3) of a much larger volcanic edifice resting on the bottom of the oceanic floor.

It is composed of two volcanoes i.e. the older dormant Piton des Neiges (3 Ma - 0.02 Ma) and the active Piton de la Fournaise.

The history of the Piton des Neiges is characterised by long period of volcanic building separated by shorter periods of eruptive rest. The longest and oldest of these periods, Oceanites series ranges from 2.1 Ma to 0.43 Ma.

The activity of the Piton de la Fournaise started some 530 000 years ago on the SE flank of the Piton des Neiges.

Although the overall geomorphological features of the island are relatively simple, the detail is otherwise and very reaches high degree of complexity. Volcanic phases alternating with period of erosion have resulted in an intricated and heterogeneous terrain. The same outcrop can display various rock masses with different mechanical properties : 10 m to 100 m thick massive lava flows, pyroclastic deposits, heterogeneous scoriaceous beds, breccias and alluviums; dykes and sills are numerous, cutting trough the volcanic pile.

Figure 3 - Air sight of the road of the littoral

Climate :
The Reunion Island is subjected to a mode of trade winds from South-East, directed by the anticyclone of the Indian Ocean. During the southern winter (from May to November), the current of trade wind is generally stable, inducing a relatively fresh and dry weather. During the southern summer (from December to April), the distance of the anticyclone towards the South and the lowering of the zone of low inter-tropical pressures, the trade winds weaken and give a hot, wet and rainy weather. Annual average precipitations lie between 1 000 mm on the West coast (coast "under the wind") and more than 5 500 mm on the eastern reliefs (coast "with the wind").

It is during the summer season that can create the tropical cyclones. One of the resultants of this situation is the exceptional intensity of precipitations: The Reunion Island holds world records for durations ranging between 12 hours (1 170 mm) and 15 days (6 083 mm). These pouring rains push natural balances with their limit and generate many movements of ground.

Relief :
The island is elliptical in shape (70 km x 50 km). It covers 2500 km², with a total of 207 km coastline including 40 km of beaches. Its flanks are slopping 10° to 18 ° towards the ocean and are incised by deep and steep valleys responsible for abrupt escarpments.

The erosion of Piton des Neiges has led to the formation of 3 subcircular large morphological depressions called the Cirques, some 10 km² each.

Along the coast, marine erosion has facetted a littoral cliff. The actual rising of the sea level is responsible for accrued coastal erosion line.

Coastal cliffs are either eroded at the base, either protected by a line of pebbles and sand. Littoral escarpments are also founded away from the coastline; these are called ‘non active cliffs’. The formation of which dates back to older marine transgression. They can reach 200 km in height (cliff along the littoral road between Saint-Denis and La Possession).

The escarpments can have a tectonic origin (caldera rim). Escarpments exceeding thousand meters high are common, sometimes reaching 1 500 m.

Coastal cliffs and escarpments are inaccessible and unsuitable for road tracing. Some of the abrupt relieves are for a large part man induced. In early days of road building, major workings were necessary in order to cross ravines and other major topographic relief. Nowadays, these cliffs are overgrown and display natural aspect.

2.2. The dangerous natural phenomena

In Reunion Island, the most frequent movements of ground are the falls of stones and blocks (elements of lava or slags). Stackings of scoriaceous layers and of lava flows with metric thickness, are geological grounds very favourable with the release of falls of blocks.

The scoriaceous layer, consisted by the sole and the roof of friable lava flows, erodes easily. The blocks of lava flows overlying are found in overhang and rock in the vacuum. The size of the gravitationally released blocks varies from a few cm^3 to several m^3.

Figure 4 - Fall of blocks on the road of the littoral

If the volume exceeds 10 m^3, it's possible to talk about crumbling. Another mechanism of rupture is at the origin of the crumblings of cliffs and ramparts : the chipping of the walls. Metric thickness panels delimited by cracks parallel with the wall are detached from the rampart or cliff

Volumes brought into play go from a few tens of m^3 to several hundreds of thousands of m^3.

3. THE MANAGEMENT OF ROADS SCRUMBLING RISKS

3.1. Monitoring and follow-up

- The alarm procedures :

The State services, under the authority of the Prefect, got a cyclonic alarm system including 4 phases: the cyclonic vigilance when a disturbance is on zone; the orange alarm when the trajectory of the depression is likely to threaten the island; the red alarm when the tropical depression or cyclone is in a ray of approximately 300 km from the island; the phase of prudence after the passage of the event.

During the red alert, the economic activity is stopped, the inhabitants have prohibition to leave their residence and the roads are closed. These last are again open only after evaluation of the damage and re-establishment of viability.

- The patrolling of vigilance :

A reinforced patrolling of vigilance was set up on the roads subjected to the risks. For example, the road of the littoral is the subject of an uninterrupted patrolling of vigilance, 24 hours a day, 7 days a week at a rate of one rotation per hour. In addition to their traditional tasks (information, interventions on accidents, small maintenance), these patrols count the falls of blocks precisely (date, place, weight, number of impacts). This information in particular makes it possible to draw up a correlation between the rainy events and the crumblings, which will in the future make it possible to refine the levels of risks. They also bring a legal safety complementary to the operator.

- The monitoring missions and safety devices about cliffs and ramparts

At least twice per annum, before and after the cyclonic season, like after the important rainy events or cliff fires, systematic visits of the ramparts are carried out by the operator.
These visits make it possible to draw up an inventory of fixtures of the cliff (state of the vegetation and its evolution), to locate the important cracks and resurgences and to control the passive devices of reserve of blocks installed on the walls. They give place to a detailed report and to a recommendation of preventive measures. At the time of the inspections, potentially unstable zones are sometimes located.

The most frequent case is the delimiting location of open cracks of the rock compartments several hundreds even of several thousands of m^3. These sites are then put in observation and followed to know the activity of the crack and to apprehend the risk. With this intention, measurements of the relative displacement of the rock masses are taken starting from fixed reference marks.

Figure 5 - Extensometer in peak of the ‘Cap Champagne’

On significant sites (P.R. 5+200 of the road of the littoral and Cap Champagne), displacement is controlled several times per day by extensometers. Measurements of displacement are stored in a power station of acquisition, connected or not to a modem for consultation from the offices of the Equipment departmental direction. In addition, each crumbling gives place to an in situ recognition in order to identify the starting zone and to assess the secondary risks. If necessary, a visit of the cliff is carried out by helicopter, even a recognition by cordists.

The conclusions of these visits can justify cleanings or purgings of the cliff, organized immediately – the management of the traffic is then done by micro-cuts of the way – or differed at the hours from less traffic, with total cuts of the way.

These purgings are carried out manually by cordists equipped with canes, hydraulic actuating cylinders or cushions inflated with compressed air. The explosive is very seldom used, in order to avoid secondary disorders in the solid mass.
Two companies of helicopter are present on the island and five local companies can mobilize 12 to 25 cordists quickly.

Before the implementation of works of protection, geological and geotechnics investigations are committed. They allow an evaluation of the threat by the determination of the nature of instabilities and volumes concerned and the comprehension of the trips of the movements of ground as well as modes of propagation. The trajectory calculation study aims to evaluate the energy of the masses moving in a given point and to define their trajectory. It is based on topographical surveys and transversely precise profiles.

3.2. Protection against crumblings and falls of blocks

The choice of protections against the crumblings and the falls of blocks depend on many parameters : importance of the road traffic, economic stakes, natural environment, physical constraints and technical possibilities. The increase in the road traffic during last decades, related to the development of the island, requires increasingly high levels of protection.

The protection of the interurban ways calls means more elaborate than that of any mountain road, because of the increasingly pressing economic requirements. Thus, the most protected sections of road are located at the entries of the agglomeration (Saint-Denis, Saint-Paul). As soon as the road network is saturated and the vehicles are parked under cliffs, protection must be extremely effective, the probability of impact on vehicles being increased.

On the technical level, one can distinguish :

- Passive methods : it is a question of controlling the propagation of the masses moving by stopping their race with screens or by channelling them by deflectors.

Figure 6 - Deflecting nets on the road of the littoral

- Active methods: the protection aims at preventing the departure of the masses by anchorings or by installation of coatings on the walls of the cliff.

The screens :
These techniques are generally easy to implement. Screens are laid out across the slope, between the cliff and the road. If space available is sufficient, the screen is consisted a wall of gabions supplemented by a pit. For example, the road of the littoral is equipped over all its length with a system with pits and gabions which channels 99 % of the 10 000 tons blocks produced by cliff each year.

Wood screens or latticed and stayed barriers, are used when the road, exposed to stone falls, is joined with the foot of the relief.

On the glacis in foot of escarpment, protections consist of metal screens of nets provided with brakes whose role is to absorb energy (example : Cap La Houssaye).

Figure 7 - Stopping devices in the Cap La Houssaye

These devices can contain blocks of more than 5 tons. Their falling speeds reach 100 km per hour. The characteristics of the work are given according to the energy of the blocks.

The deflectors :
The trajectories of blocks and stones detached from the rock escarpments are complex. The rock elements roll, rebound, burst at the time of their impact. To protect itself from the unfavourable projections and rebounds, it is sometimes necessary to cover the escarpments by metal tablecloths of nets and / or nettings. The masses moving are guided in their fall to the foot of the relief where the traps (screens, pits) are built.

The coating of the walls :
This technique is employed on cliffs overhanging the roadways (example of cliff of the Cap La Houssaye, in the commune of Saint-Paul). The wall, cleaned beforehand, is covered by a tablecloth with metal nets, tended and plated against the rock. If the masses are bulky (several m^3), the net used is reinforced by cables or is doubled (double tablecloth). A very broad range of nets is proposed today by the industry : anti-submarine net or equivalents, nets with hexagonal mesh treated against corrosion, roasts adapted to the friable grounds. The combination of these various techniques of net can prove, in certain cases, unsatisfactory. Then, one carries out the covering of the wall by shotcrete. This process allows a proofing of the ground, which slows down its degradation.

In Reunion Island, the shotcrete is used for the treatment of the walls made up of layers of slags, sensitive to the weather aggressions (rains, dryness).
Its use is frequent when one wishes to consolidate the solid mass by anchorings, particularly in the urban zones.

Other techniques of protection :
Operations of caving of rock panels were carried out on particularly dangerous sites where the standard techniques presented above are delicate and dangerous to implement by the technicians operating out of cliff, in particular when the separated rock masses of the wall are in limit of stability (scale dislocated).

In order to reduce the vibrations, demolition is carried out by shootings in sequential mode with a weakest possible explosive unit stress. The anchoring of the rock masses makes it possible to stabilize the blocks of very great volumes (blocks or scales of several tens of m^3), which cannot be controlled by the current devices. The massive lava flows arming the tops of the escarpments are frequently anchored (example of the cliff of Manapany, on the commune of Saint-Joseph).

The entries of the road tunnels generally exposed to stone falls and crumblings are protected by reinforced concrete "caps" or by metal nets. The prolongation of the tunnel by a concreted structure ensures an effective protection against the falls of blocks (example of the tunnel of the ‘Cap Bernard’ on the road of the littoral).

The exceptional topographic conditions of the Reunion Island - ramparts of more than 1 000 meters – make that it is sometimes impossible to protect the road by the devices above mentioned. In this case, only solutions of avoidance (example : tunnel of Peter Both, rebuilding of a dam in the bed of the river ‘Arm of Cilaos’, ‘Ilet à Furcy’) allow to restore the route under acceptable conditions of safety.

Figure 8 : Avoidance of an active crumbling of 10 000 m3
(R.N. 5, road of Cilaos)

4. THE EXAMPLE OF THE ROAD OF THE LITTORAL, BETWEEN SAINT-DENIS AND LA POSSESSION

4.1. Way of the English to the current road of the littoral

The first realization of a connection between Saint-Denis and La Possession, goes up at 1735. Improved 40 years later, this way, passing by 'La Montagne' becomes the 'Chemin des Anglais' in 1810. The idea to pass by the coast shapes in 1854, under the impulse of the Governor Hubert DELISLE, but works undertaken are quickly abandoned.
It is only one century later, into 1955, that the department of La Reunion makes the decision to build, between Saint-Denis and the Possession, a modern road skirting the littoral.

The project consists in largely cutting down cliff to constitute a riprap base. The building site, undertaken in 1960, ends in the opening, in June 1963, of a bi-directional road, which replaces the mountain road (R.D. 41) – a 32 km sinuous and particularly difficult route. For lack of sufficient ripraps, the road follows the foot of cliff to nearest. The bad behaviour of the grounds makes it possible to carry out only two tunnels of which one is abandoned today. The road is thus very exposed with stone falls, even with collapses of average and large widths, which cause temporary accidents and closings of the route (from 19 to 75 days per annum).

By the jurisprudence DALLOT (judgment delivered by the 'Conseil d'Etat' on July 6, 1973), this administrative jurisdiction admits with this road the character of an exceptionally dangerous work likely to engage the responsibility for the State. In addition, the traffic passes from 3 400 vehicles by day in 1964 to 9 200 in 1971. In 1972, it is then decided to modernize this major economic interest route, while moving away it from the foot of cliff without too strongly exposing it to the cyclonic swells, while doubling its capacity.

This 2x2 ways road was brought into service in February 1976, after 29 months of work at the foot of a heterogeneous and discontinuous rock solid mass.
Located at a dimension average of + 8,60 m compared to the zero of the general levelling of Reunion Island (the marling of the island is of the order of one meter), it is protected from the sea by a "reinforced" earth wall and a carapace with concrete blocks to four feet. The cost of this new infrastructure rises to 860 millions French francs (value, 1976), that is to say 444 million € (value, 2003) for a linear of 11,5 km.

The water run-off, the strong rainfall, loading of the solid mass and the related phenomena of desiccation make cliff a fragile and evolutionary medium which continues with a clearly attenuated degree, to threaten the users on this new infrastructure. The new infrastructure remains subjected to specific crumblings of a few tons and great mass varying between 200 and 25 000 m3, which still make victims among the users (17 died out of 1976 with today, the last in 1997).

In parallel, the traffics grow to reach today 48 000 vehicles per day. The risks increase with the density of circulation and the occupancy rate of the ways. The legitimate aspirations with an increased safety are expressed in a stronger way. This is why, since 1983, was institutionalized the principle of swing of circulation, as soon as the intensity of the rain exceeds 15 mm in 24 hours, and this for one 72 hours duration. Indeed, it was observed that the fall of blocks is five times more frequent after an important rainy event than in dry period.

In addition, it proves that the first impact is 6 to 8 times more frequent on the roadway upstream than on the roadway downstream.

The whole, the roadway upstream is 4 times more reached than the roadway downstream and the masses concerned are more important.

The Paris administrative court of call, in its judgment delivered on May 16, 1989 – Minister for the Equipment against consorts BABET-IVOULA – validate the thresholds set up by the administration. In 1997, a commission of international experts chaired by Mr. MOISSONNIER confirms the coherence of the pluviometric thresholds and modes of exploitation selected.

Figure 9 - Crumbling of 500 m^3 on the road of the littoral, April 2003

4.2. To reconcile safety and fluidity

- Reinforcement of safety by passive equipment :

Since Years 1980 with today, the whole of linear is equipped with pits and walls in gabions a height from 2 to 4 meters. This device makes it possible to stop more than 99 % of the crumblings of small and average widths.

This device is supplemented by nets of protection on the most active and significant points, in particular at exit of the chief town, Saint-Denis (road point 1+000 to road point 3+500) which will not be any more the object of circulation swing from February 1998.

The Investments carried out in the 10 last years rise to 33 million €.

Figure10 - deflecting nets on the road of littoral (P.R.2)

- The implementation of the 2+1 system

In 1997, because of clogging of the route in period of swing, congestions of traffic induced at its ends, and road insecurity in bi-directional exploitation, the national director of the roads was led to choose an experimental mode of management of the road, with 3 ways (2+1) on the roadway side sea. This new mode of management is operational since 1999 for a specific investment of 12 million € (except the cost of the reinforced earth wall, also treated by macadam binding with this occasion: 27 million €).

This mode of management makes it possible to organize, in rainy period, 3 lanes on the roadway furthest away from cliff: 2 in the direction more charged, 1 in the other direction, according to the pendular motion of the traffic.

Figure 11 – A machine to transfer the blocks

In the absence of incidents, the flows of circulation thus run out are of 2 400 vehicles per hour in the 2 reduced ways and of 1 300 vehicles per hour in the single track.

The two directions of circulation are separated by a device of reserve intended to avoid the frontal shocks between vehicles; this device is made up of 5 000 concrete blocks some 2 meters length and 700 kg weight.

This chain of blocks, stored on the verge side sea, of a total weight of 3 500 tons, is moved by two machines of transfer which are activated independently or simultaneously. These prototypes move to 5 km/hour and allow an offset of the blocks of about 4 meters. One or two transfers are necessary for a passage into 1+2 then into 2+1. The swings of ends of the lanes are managed by metal devices of interruption of central reservation manually moved by agents.

The indication of information and police force by panels with variable messages is ordered since a center of management of traffic located in the buildings of the departmental direction of the Equipment.

4.3. The collection of rainfall records and the release of the swings

Four sites of the road of the littoral are equipped with automatic pluviometers separated by 2 to 4 km (P.R. 3+000, 5+500, 8+500, 12+900). These pluviometers are connected by optical fibres to a computer of METEO FRANCE services and doubled by pluviometers with direct reading.

Figure 12 - Road of the littoral in swing mode of management

The data are updated by step of 30 minutes. They are analyzed and an automat pre-alarm telephonically the operator as soon as pluviometry reaches 10 mm.

Beyond 15 mm, the operator receives a new message indicating to him that the threshold was exceeded; he implements then immediately measurements of circulation swing.

The machines of blocks move are activated as well as the regional center of management of traffic; this one coordinates the operations of swing, orders the panels of information and police and organizes information intended for the user. (faxes with the authorities and professionals of the road, media; interventions on the radio waves, and Internet).

A network of 30 monitoring cameras makes it possible to follow the advance the operations of swing and the evolution of the traffic.

Figure 13 - Photograph of the C.I.G.T.

The implementation of the swing lasts to the maximum 3 hours of time.

Each operation costs 15 000 € and requires the presence of 9 agents.

4.4. Assessment of exploitation and prospects

The new mode of management (3 ways on the roadway side sea, system 2+1) made it possible to decrease to a significant degree the accidentology related to falls of blocks.

It ensures a better reactivity and reliability at the time of the rainy events and offers a better safety to the users by preventing the frontal shocks. It made it possible to reduce half the congestions of traffic.

The increase in demand of displacements requires finding solutions complementary. It is necessary to continue the improvement of the safety of the route by the installation of new cliff devices. those will make it possible to reduce the durations of the swings.

With medium term, it is envisaged to modernize the route by a dam at sea on 7 km and a passage in tunnel on 4 km. A public transport in exclusive right of way standard train-tramway is projected.

5 - CONCLUSION

Two decades of natural risk management in Reunion Island, in particular on the exposed roads, show that it is possible to fight against the limited crumblings.

The stake of the next years consists in developing research and experimentation as regards forecast of the crumblings of great width, thanks to new technologies.