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LANDSLIDES DAMS INDUCED BY DEBRIS FLOWS IN QUEBRADA DEL TORO (PROVINCE OF SALTA, ARGENTINA)

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ABSTRACT

The *Quebrada del Toro* is the valley of Río Toro, located southwest of Salta City, in northwestern Argentina. During the summer months, in the catchment of its tributaries, debris flows occur with relative frequency. Such processes of mass transport bring important volumes of materials inside of the main collector (Río Toro) and its alluvial plain, and they produce the narrowing, or sometimes the occlusion (landslide dam) of the main riverbed.

These processes frequently occur, for example, in the Río Candado, a tributary on the left of the Río Toro. The consequence is an important sediment supply, coming from such a tributary, which has produced a marked modification of the longitudinal profile of the Río Toro, due to the systematic aggradation of the reach situated close to the confluence between the two streams.

A direct consequence is affecting of the bridge of "Ruta Nacional 51", situated in the immediate vicinities of the confluence, where often in the period of summer rains (when the water discharge increases) the overflowing of Río Toro occurs, with floods that produce the interruption of this important road. In fact, the aggradation of the river bed due to the accumulation of detrital material (that usually cannot be eroded by low water discharge), when the discharge in the Río Toro is increasing, during the summer period, produces easily the overflow of the stream, flooding the lower Ruta Nacional 51.

The available data show that the defense built during the '80s to protect the road (two meters in height over the river bed), now are completely buried due to the floods produced by the debris flows from the *Quebrada del Candado*. A solution to the problems of the Río Toro in this reach, related to the processes of debris flows, could consist both in the construction of works intercepting the solid transport, and above all, defense works from the erosion of the slopes, to prevent the source of mobilization of the detrital material within the catchment of the Río Candado.

Key words: *Argentina, debris flows, risk*

INTRODUCTION

The *Quebrada del Toro* is the main valley of Río Toro, a stream located southwest of Salta City, in northwestern Argentina (Fig. 1). The Quebrada is a tectonic, narrow and deep valley, and it is one of the most characteristic areas of the morphostructural region named *Cordillera Oriental* (Argentine Andes). In this area of the chain the processes due to gravity have a decisive role in the shaping and evolution of the relief and, even more, of the hydrographical system that is the object of the present study.

In fact the *Quebrada del Toro* is covered, for all its length, by the homonymous stream (Río Toro), an important river carrying its water to the artificial basin of Cabra Corral, having received the supply of several minor tributaries. Among these lateral *quebradas*, an important contribution is represented by

Fig. 1 -Location of study area

Río Candado, not only for its water discharge, but also for its solid transport due to debris flow processes originated inside its catchment that frequently reach the confluence with Río Toro and produce landslide dams in the alluvial plain of the main stream (Cencetti & Rivelli, 2008).

The aim of the paper is to highlight the importance of debris flows produced along the Río Candado, as an important factor of control in the fluvial dynamics of Río Toro, due to formation of landslide dams at their confluence.

GENERAL SETTING

STUDY AREA

The confluence between Río Candado and Río Toro is easily reachable during the year from Salta City, through the *Ruta Nacional 51* (Fig. 1) and is located at an height of about 1950 m above sea level.

The catchment of the Río Candado is located in an arid region from a climatic point of view, with average yearly rainfalls included between 200 and 250 mm, and concentrated in few events, with torrential rains which occur almost exclusively during the summer months. Moreover, important snowfalls don't occur: they are very unusual and not much significant.

The lithological characteristics of the basin are very homogeneous, because the only outcropping bedrock is constituted by low grade metamorphic rocks of Precambric age, diffusely fractured and weathered with, at the top, recent sediments of fluvial or gravitational origin.

With regard to climate, which plays a decisive role in the development of the present morphogenetic processes, it is moderately dry, with important thermal range between day and night that produce degradational physical processes in the rocks (thermal stress weathering).

CHARACTERISTICS OF THE RELIEF

In order to consider the debris flow processes occurring inside the catchment of Río Candado, we need to linger over the characteristics of the relief.

We are in a mountainous environment with presence of inner, narrow valleys, bounded by generally not much steep slopes.

In the specific case, the catchment of Río Candado measures 11 km^2 in area, so that it represents the most important subcatchment of Río Toro, considering the extension. Moreover, this tributary is the only one, among those supplying the main stream, which have a water discharge during all the year, so that it assures a continuous flow in the Río Toro (this is an important aspect regarding to the generally dry conditions of the whole area).

The extension of the basin and its water availability represent very important elements from a geomorphologic point of view, in particular regarding to the occurring of gravitational mass movements.

In the catchment of Candado, the minor altitude of the divide located in the eastern portion of the same, allows the humid masses of air proceeding from East to discharge a larger volume of water as rainfalls, with respect to the others subcatchments located around. All this explains the presence of water during all the year in the riverbed of Candado.

GEOMORPHOLOGICAL CHARACTERISTICS

The evolution of relief allows clearly to identify the processes responsible for the shapes that characterize itself.

Above all tectonic activity was and it is the main responsibility of the conformation at "juxtaposed blocks" which can be observed in the region and constitutes the main structure of the relief; moreover, the exogenous processes have effect on these, incessantly changing their shapes.

With regard to the geomorphological processes, we need to distinguish the present processes, typical of dry environment, from the past ones, occurred during a colder and more humid climatic period, revealed by the abundance of detrital material covering the bedrock.

During this more humid climatic period, indeed, the larger volume of rainfalls supported fluvial activity and sheet floods more intense and continuous, allowing the sedimentation of wide blankets of debris constituted by not consolidated material, collected inside the different hollows of the catchment.

Such material is, at the present time, the main source of sediments which are mobilized in the triggering and routing phases of debris flows.

With respect to degradational meteoric processes, we have already discuss that the thermal stress weathering is the dominant process; it produces a considerable volume of loose material that can be affected by mass movement developing in debris flows. Many times, indeed, the mass movements (prevalently slides) obstruct the channel of Río Candado, producing small temporary dams that accumulate water until the break occur, mobilizing the debris and triggering the debris flows. They reach the confluence with Río Toro, often producing the occlusion of the main stream.

The specific fluvial process in the small catchment of Río Candado has not great significance, due to the reduced volume of rainfalls that doesn't allow, considered the consequent low water discharge, either erosional activity, or solid transport of fluvial origin, important in order to shape the relief.

The most important effect of the fluvial (even if slight) erosional processes, appears in the destabilization of terraced fluvial sediments that are undermined at the base; it favours the action of the flows when these ones move towards the lower sections of the basin, because they can, at their turn, incorporate a larger volume of material produced by the erosional activity of the stream.

The debris flows, at present time, are the most important morphogenetic process, both for the shaping of relief, and for the secondary effects produced out of the limits where they were generated.

Considering the abundance of detrital material accumulated at the borders and the bottom of all lateral valleys of Candado, the trigger of debris flows is very easier, above all when torrential rainfalls occur, responsible of a quick saturation and destabilization of the loose material.

On the field, you can see superficial evidences (lobate forms) of recent phenomena; on the cuts of ancient outcropping sediments in Candado, you can deduce that the flows occur from a long time, considering also the volume of accumulated material and remobilized by new events (Figs. 2-3).

The presence of lobate forms at the present raised with respect to the riverbed, due to the intense and fast tectonic activity, points out a constant movement of the

Fig. 2 - Ancient sediments of debris flows outcropping along the riverbed of Río Candado

Fig. 3 - A detail of the sediments produced by debris flows in the catchment of Río Candado

flows from a long time ago, even if, unfortunately, specific studies are not in order to date these sediments and so allow a greater accuracy in the study of the evolution of the processes and of the resulting sediments.

This consideration is corroborated by the observation of the cuts in the terraced sediments located at the hollows in the minor valleys of Candado, where it is possible observe levels with blocks of rocks about 1 m in diameter, irregularly arranged, combined with material having smaller dimensions, alternated with thin layers set in order, of fluvial facies, with a stratified subhorizontal structure. Due to the energy of debris flows along the Quebrada del Candado, they can entrain a lot of material from the riverbed or from the terraced sediments, already eroded by fluvial current.

So, flows develop reaching the alluvial plain of Río Toro (Figg. 4-5), often producing the occlusion of the riverbed by means of landslide dam (this phenomenon is not infrequent along this river, also during ancient periods - Trauth & Strecker, 1999; Viera & Cencetti, 2008) and building fans that accumulate until 240,000 cubic meters of material; this one is placed on the riverbed of the main stream, producing temporary lakes.

Figs. 4-5 - The debris flows occurring along Río Candado reach the riverbed of Río Toro, often producing its temporary occlusion

By considering the classification proposed by Harvey (Harvey, 2002), both the accumulated material on the original cone and inactive at present time (coinciding with a more humid period than the present, characterizing this area during the past time), and the present sediments, correspond to the so named *aggradational fans* (composite deposition) by the Author.

CONSEQUENCES OF THE FLOWS OF CANDADO

The debris flows produced in the watershed of Candado, except for the loss of areas used by agriculture (even if any real information exists about the agricultural surface eliminated by the debris flows), don't produce enormous problems or inconveniences; not so the ones reaching the riverbed of Río Toro.

In the area of confluence between the two streams, Río Toro has a riverbed measuring about 200 metres in width. The debris flows coming from Río Candado are constituted by cobbles having mean diameter between 15 and 30 cm, with a matrix that has a variable grain size distribution (from minute gravel until clay). The debris flows build an alluvial fan with marked slopes next to the apex of cone (20%), gradually lower proceedings towards the front which enlarges in the riverbed of Río Toro for about 200 metres in lenght. The main body of the cone modifies noticeably the gradient of the same Río Toro, due to the accumulated material in the riverbed. So the gradient is reduced upstream (5‰), due to the aggradational process occurring when the obstacle striving for obstructing the water flow; after, the gradient progressively increases next to the main body of the cone (10‰), until to reach, downstream, the stable value of about 15-16‰ (Fig. 6).

Referring to the gradients assumed by Río Toro, we can understand that the cone built by debris flows coming from Río Candado is strongly asymmetric: indeed, with respect to its central longitudinal axis, there is a larger volume of material downstream, along Río Toro, that is where the debris flows are channelled (see sketch in Fig. 6).

The total blockage of the riverbed of Río Toro, often produced when intense debris flows occur and reach the right rocky bank of the riverbed, usually has short life (not more of about ten days). After this period, the overflowing of Río Toro occurs.

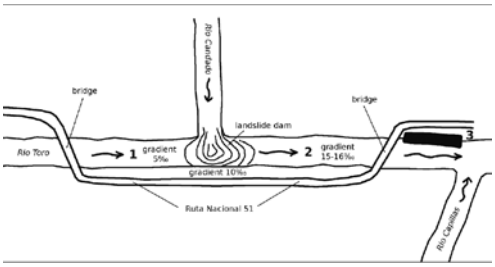

Fig. 6 - Sketch of the reach of Río Toro affected by the debris flows coming from Río Candado. 1) aggradation of the reach upstream the confluence, due to the landslide dam; 2) aggradation of the reach downstream the confluence, due to the redistribution of material mobilized by the debris flows coming from Río Candado

But another important consequence of the temporary occlusions produced in the riverbed of Río Toro occurs. We already have discussed about the accumulating of material upstream the landslide dam: this phenomenon, particularly during the rainy period, increases the already difficult problem of the flooding affecting the nearby bridge (Fig. 7).

This fact, indeed, forces to carry out periodically the cleaning of the riverbed, in order to regain the flow cross-section under the bridge. It causes a high cost of maintenance of the road, that has vital and strategic importance, both for the region, and the access road to the harbours of Pacific.

The consequences of the occlusions occurring in Río Toro affect also the reaches located downstream.

Indeed, when the dam break occurs, the volume of water suddenly flowing produces the mobilization of a lot of material that is distributed along a reach 4 kms in length, until the confluence with another dangerous creek, Río Capillas, increasing the already critical problem of the flooding of this reach (Fig. 6).

Due to material accumulating in this reach of Río Toro, the sedimentation is more rapid and this fact negatively affects the road and others present infrastructures. The sedimentation produces the aggradation of the riverbed, affecting the cross-section under the bridge. The gap between the riverbed and the lower part of the bridge (about 4 meters) has reduced to 2 meters after the supply of Candado, so that the removal of material has needed, with high cost because the same needs to be moved elsewhere, due to the impossibility to accumulate it nearby.

Due to the aggradation of the riverbed of Río Toro, the stretch of Ruta Nacional 51, which is located

Fig. 7 - The bridge located upstream the confluence of Río Candado with Río Toro, frequently affected by floods during the rainy periods

Fig. 8 - The longitudinal defense work built on the left bank of Río Toro, downstream the confluence with Río Candado. It needs frequently to be raised, due to the aggradation of the riverbed

on left bank, is at the present time at the same elevation of the riverbed.

In order to avoid interruptions of the road during summer months, due to the flooding of Río Toro, a longitudinal defence work was built in 1980, about 400 meters in lenght (Fig. 8), raised with respect to riverbed of about 2 meters.

This one, due to the accumulation of sediment, showed reaches completely covered by material, so that in 1995 a new level about 1 meter in height was built. At the present time, in some parts, it needs a new increase in height in order to provide effective protection of the road.

Due to the systematic accumulation of material coming from Candado, the road is still in a very critical situation which needs intervention, even if complementary to the execution of the longitudinal defense work.

Considering the characteristics of the catchment

of Candado and the influence of the landslide dams in the behaviour of Río Toro (that turns into the described problems affecting Ruta 51), interventions need to avoid the trigger of debris flows so that the development of landslide dams can be averted.

The most suitable solution, due to the cost of execution, convenience, gettable results and low environmental impact, seems to be the building of transverse works devoted to detain as well as possible the sediments and to reduce the slope and the stream power, in order to preventing the transport and the consequent accumulation of material due to the occurring debris flows.

All this could be accompanied by the building of works for the control of erosional processes along the slopes (mattresses, fences), suitable for prevent the mobilization of material along the slopes during the the raining periods.

CONCLUSIONS

Debris flows occurring in the Quebrada del Candado cause serious damages over all along the final reach, where they produce landslide dams on the confluence with Río Toro, and various problems in different portions of Ruta 51 which needs high costs of permanent maintenance.

The risk mitigation and the reduction of the damages cannot be solved by means of building of passive defenses, but they need to provide the building of works devoted to reduce the possibility of triggering the flows.

The intervention could be extended at the basin scale and it could affect the upper portion of the catchment, by means of building of transverse works and works for the control of erosional processes along the slopes. By reducing the gradient and retaining the material, this could mitigate the effects of flooding which systematically occurs in the lower part, close to the confluence with Río Toro.

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