Utah State University

DigitalCommons@USU

International Symposium on Hydraulic Structures

Jun 29th, 4:00 PM - 6:00 PM

Evaluation of flexible barrier and sabo dam to control effects of debris flow in Santo Domingo Ravine

J. W. Cabrera Cabrera
Universidad Nacional de Ingenieria - Peru, juancabrera@uni.edu.pe

L. F. Castillo Navarro
Universidad Nacional de Ingenieria - Peru

Follow this and additional works at: https://digitalcommons.usu.edu/ishs

Part of the Hydraulic Engineering Commons

Recommended Citation

Utah State University
MERRILL-CAZIER LIBRARY

Evaluation of Flexible Barrier and Sabo Sam to Control Effects of Debris Flow in Santo Domingo Ravine

J.W. Cabrera Cabrera[1], and L.F. Castillo Navarro[1]
[1]Facultad de Ingeniería Civil
Universidad Nacional de Ingeniería
Lima, Lima25
PERU
E-mail: juancabrera@uni.edu.pe

ABSTRACT

The coast of Peru is characterized by the presence of ephemeral creeks, which drain water only during the wet season. The extremely dry soil and pebbles combined with precipitation produces debris flows in a seasonal geodynamic. This is the case of Santo Domingo ravine, which is located at eastern Lima and drains its water to Rimac River. In this article, the vulnerability of villages near to Santo Domingo ravine by debris flow and use of flexible barrier and sabo dams are analyzed. In the first stage, the liquid hydrograph of a 100 year return period was built, and a solid hydrograph, a relationship between volume concentration and time, was essayed. Then, both the liquid and the solid hydrograph are calibrated in a debris flow numerical model, and the vulnerability map is built. Finally, this model is coupled to the Rimac River to analyze the possible damming effect. Calibration of a numerical model was done in base to previous estimated volumes by the Japanese International Cooperation Agency (JICA). These first results permitted the definition of high-vulnerability zones, which will be a reference to evaluate efficiency of control measures. In a second stage, mitigation effects of flexible barriers application is simulated in base to Debris Flow Barrier from Geobrugg®. Also, the application of sabo dams was evaluated to by using "Kanako" debris flow simulator from Laboratory of Erosion Control, Division of Forest Science, Graduate School of Agriculture, Kyoto University, & SABO Technical Center. Results permit researchers to evaluate efficiency and select the most economical option.

Keywords: Debris flow, flexible barriers, floods, sabo dam, vulnerability.

1.   INTRODUCTION

Chosica is located on the floodplain of the Rimac River, around 850 m.a.s.l. in the Western Chain of the Central Peruvian Andes and surrounded by ephemeral creeks at the both sides. These creeks have normal geodynamic activity that includes debris flow occurrence during wet seasons. One of these ravines is Santo Domingo, which causes damage to population around its stream every year. City Hall tried to reduce their effects by building retaining walls around houses and "sabo" dams along the stream, but these were not a solution because they were undersized. It should be added that the main channel has been reduced to build houses, and it has been deviated in some sections; these changes increase velocity of debris and mudflow and erosion and sedimentation along the channel.

This situation suggests the necessity of research on centennial event magnitude and affected areas to organize a mitigation plan that could prevent future disasters; also, it is necessary to evaluate other alternatives that could be more efficient.

2.   STUDY ZONE

2.1.   Location

Santo Domingo ravine is located in Lurigancho district, Lima, at coordinates 76°22'35 " - 76°24'07" W and 11° 46'38" - 11°50'20" S. This watershed is part of the Hydrographic Basin of the Pacific and joins the river Rimac at the left bank. It has an extension of 4 Km^2 with a length of main channel of 3.85 Km, approximately. Altitudes vary between 850 m and 1750 m and have an average gradient of 23%.

The watershed consists of three well defined areas: a reception area formed by the slopes that are over 1300 m, this area serves as a funnel, which captures summer rains; a transit area between 1300 m and 950 m; and finally a material deposition area, known as "alluvial fan", which is fully developed.

2.2.   Geodynamic

The high watershed contain material presented in the bed gravel-sandy material with a low proportion of silt, which is loose. The slopes of both banks are composed of proluvial material from previous flows discoursed through the gorge; the materials of these ancient deposits have a silty clay matrix with gravel, blocks, and boulders ranging from 0.5 to 2 m in diameter.

In the middle part of the basin, both sides are affected by rill erosion that will undermine and cause landslides on top of the terraces. There lateral erosion undercuts at the base of slopes which causes destabilization. At the low watershed, a narrowing of the channel that is caused by the accumulation of blocks and proluvial material forming small cones is observed; proluvial material has about 5 m of power above the rocky outcrop; it appears the slopes are almost vertical.

Granulometry studies show that the material is low plasticity to non-plastic arenas, ranging from SC (loamy sand) to SM (silty sand) in the scheme of Unified Soil Classification System (USCS). Characteristics of this material make it suitable for the occurrence of possible mud flows against rain from moderate to high intensity.

3.   STUDY METHOD

3.1.   Data

For this analysis, topography data was based on National Maps from Instituto Geográfico Nacional (IGN) and ASTER information: main channel slope was estimated at 0.23, concentration time at 19.6 min, and lag time at 11.8 min. These values suggest it is almost impossible to organize an early warning system. Figure 1 shows the location of Santo Domingo ravine respective to the Chosica and Rimac Rivers. Simulations will show the affected area of the city.

JICA(1988) realized a vulnerability assessment in Rimac River basin and proposed an equation to estimate probable sediment deposit:

$$V = 14800.1,2.F.A \tag{1}$$

where F is coefficient of land cover (dimensionless) and A is the sub basin area (in Km^2). To Santo Domingo ravine, F=0.6, which correspond to less 60% of vegetation on sub basin area; their area is 4 Km^2 approximately. The volume estimated with JICA equation is 42624 m^3 and represents the volume of sediment that could fall.

To estimate peak discharge, SCS storm method was used. To estimate infiltration volume, analysis from CESEL (2004) was considered. According to them, Rimac basin headwater shows characteristic like hydrologic soil type "B" and values between 79 to 83 could be assigned like curve number. For this research, 82 was assigned.

To estimate maximum precipitation, data from Santa Eulalia gage station was used. Table 1 summarizes the precipitation analysis to return periods of 20, 50 and 100 years.

Table1. Maximum precipitation (mm)

Gage station	P_{20}	P_{50}	P_{100}
Santa Eulalia	29.40	34.00	38.30

With these values, the peak discharge to return period Tr=100 years was estimated in 9.4m^3/s, and the hydrograph was built. This hydrograph was used to build the solid hydrograph, which represents sediment volume concentration (C_v) at time. In general, a solid hydrograph should maintain the liquid hydrograph shape with the peak volume concentration located a few minutes before the peak of the liquid hydrograph.

For a debris flow event, the range of volume concentration was estimated between 0.22 and 0.45: starting at 0.22, increasing until 0.45, and decreasing again until 0.22. This hydrograph should be calibrated during simulation (values of volume concentration should be modified until one gets approximately estimated volumes by JICA (1988)). The calibrated solid hydrograph is shown in Figure 2.

Figure 1. Santo Domingo ravine. Left, delimited catchment. Right, debris on right side.

3.2.   Hyperconcentrated Flow Model

In normal conditions, rivers and stream flows contain sediments, but these don't affect the properties and behavior of water. However, if the sediment volume is high, water changes its characteristics and behavior like a new fluid. These kinds of flows are called hyperconcentrated flows (Julien, 1991). According to Julien (1991), hyperconcentrated flows could be classified in three categories: floods, mudflows, and debris flows.

Floods are formed by sands and volume concentration of sediments C_v<40%. Mud flows are formed by silts and clays and volume of sediment in the range of 45%<C_v<55%. Finally, debris flow represents a more complex fluid, with pebbles, woods, and with a wide range of diameters. Characteristics of events in Santo Domingo ravine define debris flows.

Debris flow modeling will be performed with the FLO2D software. This model requires topography data, the liquid-solid hydrograph, sediment properties, and rheological parameters. In hyperconcentrated flows, the Bingham plastic model has been widely used with high performance (O'Brien and Julien, 1988). According to these authors, it's generally accepted that viscosity and yield stress are related with volume concentration (C_v) by equations (2) and (3)

$$\eta = 0.0360e^{22.1C_v} \tag{2}$$

$$\tau_y = 0.181e^{25.7C_v} \tag{3}$$

where η is mixture viscosity (in poises) and τ_y is the yield stress (in dyna/cm^2). This volume concentration varies with discharge during a debris flow, and it should be input as a solid hydrograph (see Figure 2). According to O'Brien and Julien (1988), solid hydrograph peak before the liquid hydrograph peak. Specific gravity was assumed to be 2.65, in accordance with with JICA (1988) and CESEL (2004).
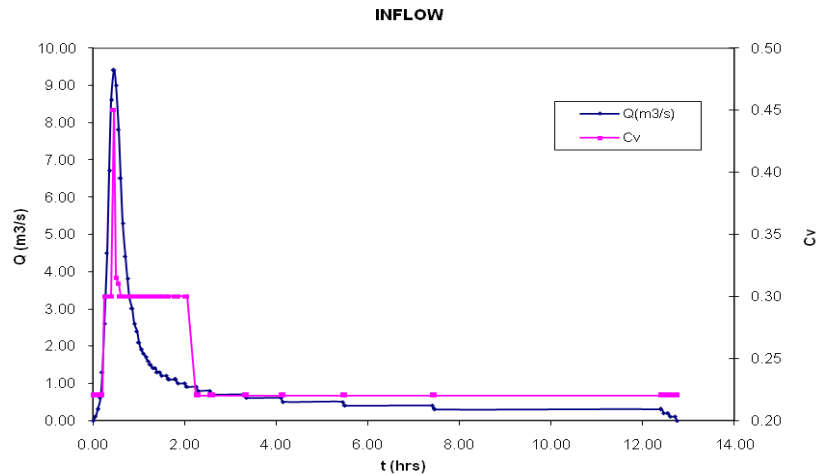

Figure 2. Solid and liquid hydrograph to be input to FLO2D software.

3.3. Hazard Maps

Hazard maps for debris flow events were developed by Garcia et al. (2003) and based in PREVENE (2001). This methodology establishes three hazard levels in similar a way to Swiss and Austrian standards to flood hazard maps (Fiebiger, 1997). More recently, INDECI (2011) have resumed all the related experience and assumed a similar methodology in Peru.

According this frame, Flood hazard risk is a function of both flood intensity and probability. Flood intensity is a function of both flow depth and velocity, as described in Table 2. Maximum depth represents a static analysis and the product of h-v represents a dynamic analysis.

Table 2. Definition of mud or debris flow intensity

Flood Intensity	Maximum depth h (m)		Product of maximum depth h times maximum velocity v (m^2/s)

High	h > 1 m	OR	$v.h > 1 m^2/s$
Medium	h < 1 m	AND	$v.h < 1 m^2/s$
Low	Undefined		Undefined

Flood probability is inversely related to flood magnitude and could be estimated like the inverse of return period. Categories of hazard risk are summarized in Figure 3. Each category is represented by a color to facilitate comprehension of non-technical authorities; each color is related with effects on buildings and structures. Table 3 shows the meaning of every color.

Table 3. Hazard risk levels according to PREVENE(2001).

Hazard Level	Map color	Legend
High	**Red**	People are in danger both inside and outside of structures. Buildings are in danger of being destroyed.
Medium	**Orange**	People are in danger outside of structures. Buildings may suffer damage or possible destruction depending on construction materials.
Low	**Yellow**	Danger to people is low. Buildings may suffer limited damage, but flooding or sedimentation may affect structures.

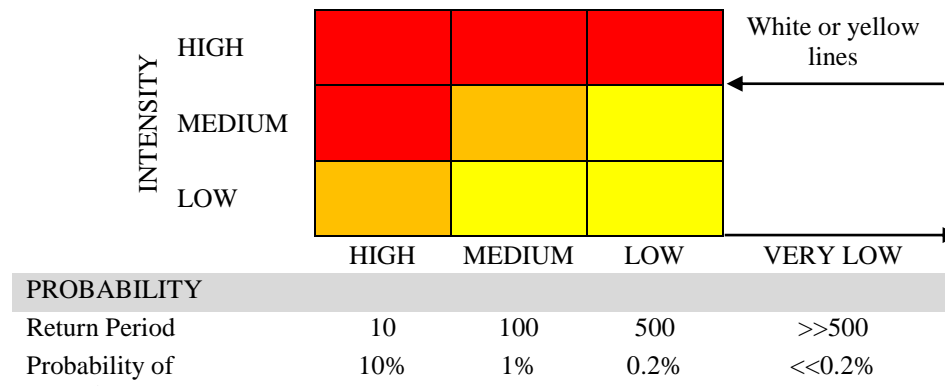Hazard maps were built by using the Mapper tool of FLO2D software.

Figure 3. Discrete hazard levels according to PREVENE (2001).

3.4.   Control Structures

3.4.1. Sabo Dam

"Sabo dam" is used to describe a group of different structures used to control debris flow; all of these functioning like dam. According to suggestions and experiences of Lien (2003), a check dam (also called "closed dam") was selected for Santo Domingo ravine because material on the zone and characteristics of the ravine. Check dams are closed-type and made of massive concrete and are conform for two dams, a main and a secondary (see Figure 4.a). According with JICA (2010), design discharge correspond to the rainfall of 100 years return period or the maximum rainfall in past records, whichever is larger.

The design discharge of Sabo dam is estimated by considering the ratio of sediment concentration α and using the equation

$$Q = Q'(1+\alpha) \tag{4}$$

where:

> Q = Design flood discharge including sediment (m³/ s)
> Q' = Peak flood discharge to 100 years return period (m³/s)
> α = Ratio of sediment concentration (ordinarily used is 10%)

The height of Sabo dam is defined by the depth of sediment. The opening of Sabo dam has a trapezoidal shape and follows the principles below:

1) The width of opening (B_1) should be at least 3m.
2) The height of the crest opening (H_c) is equal to

$$H_c = h_1 + h_2 \, Ij = Sj + \sigma j \tag{5}$$

where:

> h_1 = Depth of water. Estimated by using the general weir equation. It should be less than 3.0 m.
> h_2 = Freeboard (see Table 4).

Table 4. Proposed freeboard of opening

Proposed Discharge	Freeboard (m)
Below 200 m³/sec	0.6
200 – 500 m³/sec	0.8
500 m³/sec or above	1.0

Source: JICA (2010)

3) The side slope of opening (m^2) is usually 0.5. This typical slope is recommended by JICA (2010) because it provides enough stability.

A typical section is shown in Figure 4. Their operation and efficiency was evaluated with KANAKO debris flow simulator from Laboratory of Erosion Control, Division of Forest Science, Graduate School of Agriculture, Kyoto University, & SABO Technical Center. This software permits the evaluation of operation of check, slit, and grid dams.

3.4.1. Flexible Barrier

A different alternative is the flexible barriers, which are made of high-tensile steel wire netting and mesh. Large-scale field tests developed at the Swiss Federal Institute for Forest, Snow, and Landscape Research WSL (ETH) have shown that "these systems provide efficient, reliable protection against both shallow landslides and rockfalls" (GEOBRUGG, 2009). These kinds of barriers could have a maximum width of 15m without use of brackets (VX barriers), but it could have a width up to 25m with them, as shown in Figure 5 (UX barriers). Flexible barriers withstand high static and dynamic loads and may be installed with little amount of material and labor, which could reduce costs and installation time.

According to Volkwein et al. (2011), to design the barrier, the first step is to estimate a possible debris flow volume (VDF). According to Mitzuyama (1992), this VDF could be used to estimate the peak discharge (Q_p)

$$Q_P = 0.135 \, VDF^{0.78} \tag{6}$$

and the average flow velocity (v) will be estimated with

$$v = 2.1 Q_P^{0.34} I_s^{0.2} \tag{7}$$

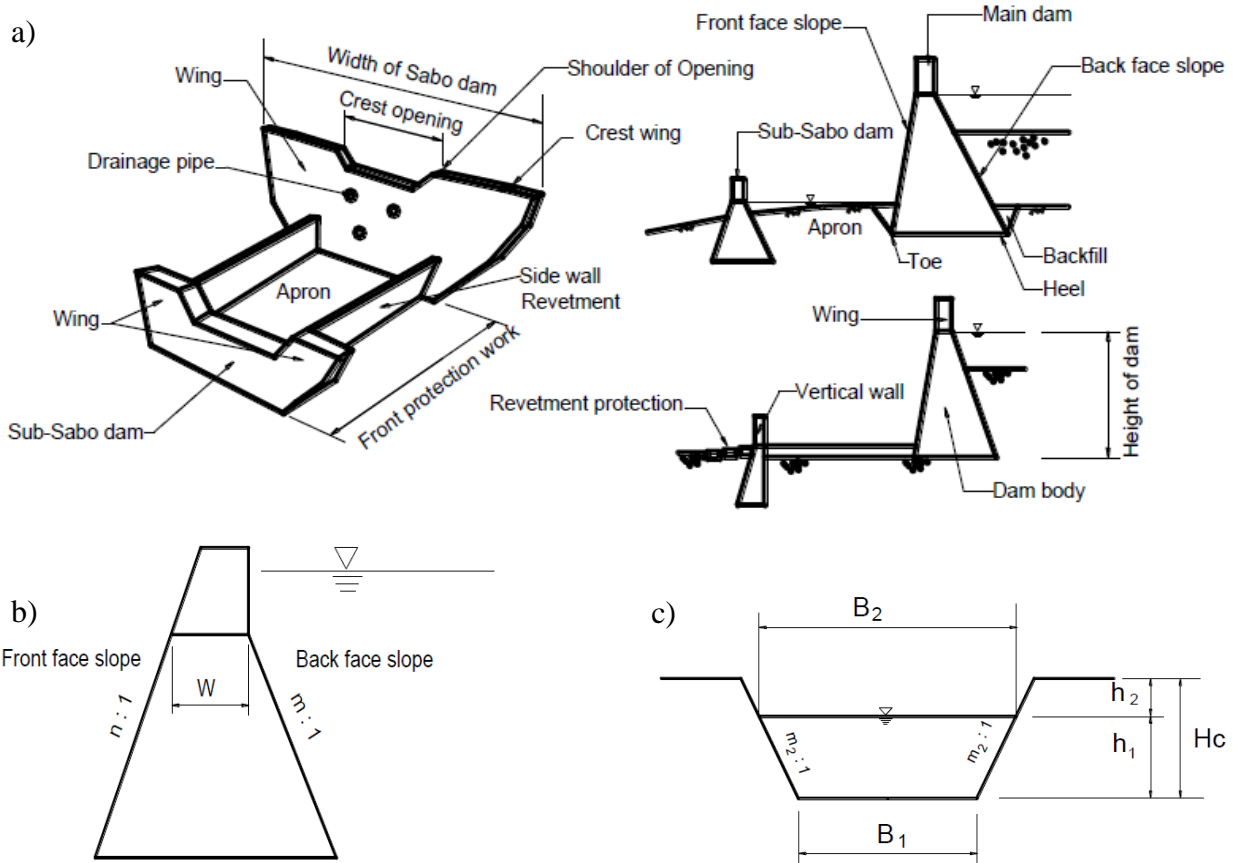where I_s is the gradient of the torrent.

Figure 4. Sabo dam. a) Components of Sabo Dam. b) Thickness of crest. c) Cross Section of opening.

Source: JICA (2010)

The barrier height is estimated assuming a rectangle section and dividing Q_p by $v.b$; however, the post-event height is usually 3/4 of its pre-event height, and the minimum barrier height is determined as follows:

$$h_b = \sqrt{V_R \frac{32}{9} \frac{1}{b_m} \frac{1}{sin\xi \left(\frac{sin\xi}{tan(\theta - \theta')} + cos\xi \right)}} \leq 6m \tag{8}$$

with V_R retention volume, ξ barrier inclination, and θ and θ' the gradient of the material before and after a debris flow event.

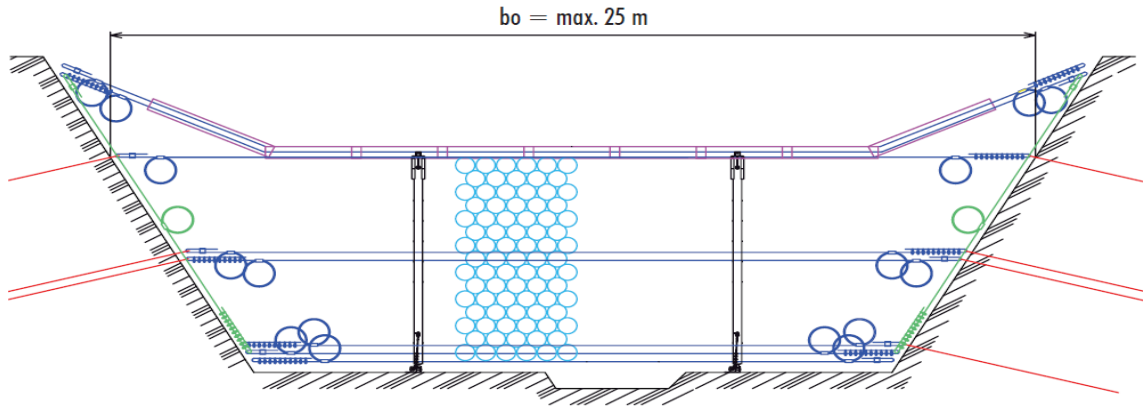A design was realized with the DEBFLOW dimension tool from GEOBRUGG.

Figure 5. Typical section of flexible barrier type UX.

Source: GEOBRUGG (2009)

4. RESULTS AND DISCUSSION

A bidimensional model was built with a 10m x 10m size grid, peak discharged $9.4m^3/s$, Manning coefficient of 0.04, and other characteristics described in the last item. Model outflow is summarized in Table 5.

Table 5. Model outflow

Overland Flow	Water (m^3)	Water + sediment (m^3)
Inflow hydrograph	14299.40	22257.70
Floodplain storage	11719.56	18031.50
Floodplain outflow hydrograph	2579.90	4226.20

Table 5 shows that 22257.7 m^3 of debris flow is produced and 4226.20 m^3 left the model; 2579.90 m^3 of this volume is water and 1646.3 m^3 is sediment that will be deposited on the ground. This event could affect population at the left side of Rimac River, in 146350 m^2 approximately. Distribution of sediment will depend on floodplains topography.

Figure 6-left shows the affected area: the maximum depth gets 3.45m and is located on Rimac River stream. Having accounted that the majority of houses have areas between $120m^2$ to $200m^2$, this area represents more than 1000 houses that could be affected by 0.1 to 1.6 meters depth of deposited sediment.

Also, this model suggests the possibility of a damming effect over the Rimac River and a possible secondary effect of floods on the city. To evaluate this secondary effect, a second model with a mean flow in Rimac River was simulated. To this goal, a mean discharge of $33m^3/s$ in Rimac River was assumed.

The model showed that Rimac River is not dammed by debris flow (Figure 6, right); instead, the Rimac River acts like a natural barrier, containing the debris flow. The consequence is an increment of the affected area in 25% approximately, getting $175600m^2$; however, not all this area could be considered hazardous because part doesn't have enough depth or velocity to represent risk.
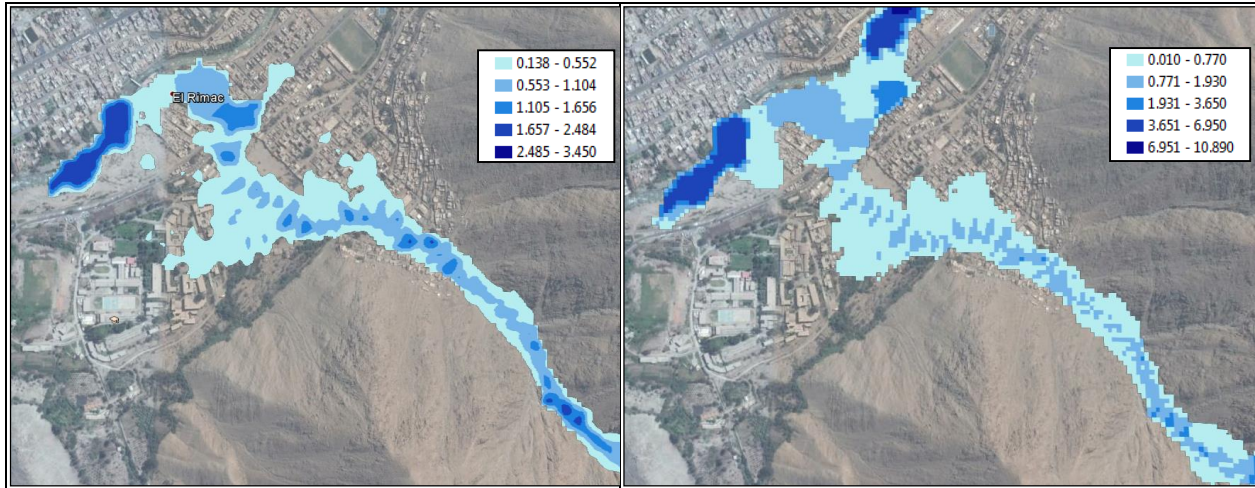
Figure 6. Deposition of Santo Domingo ravine on Rimac River. Left, deposition of debris flow caused by Santo Domingo ravine without consider discharges in Rimac River. Right, deposition of debris flow considering a mean discharge in Rimac River. *Tr*=100 years.

According to this last model, the debris flow hazard map was built (Figure 7). The affected area is estimated to be 103105m^2, and affected houses could be 516 (assuming a mean surface of 200m^2 by house). Also, 220 of these houses are in high risk and could collapse.
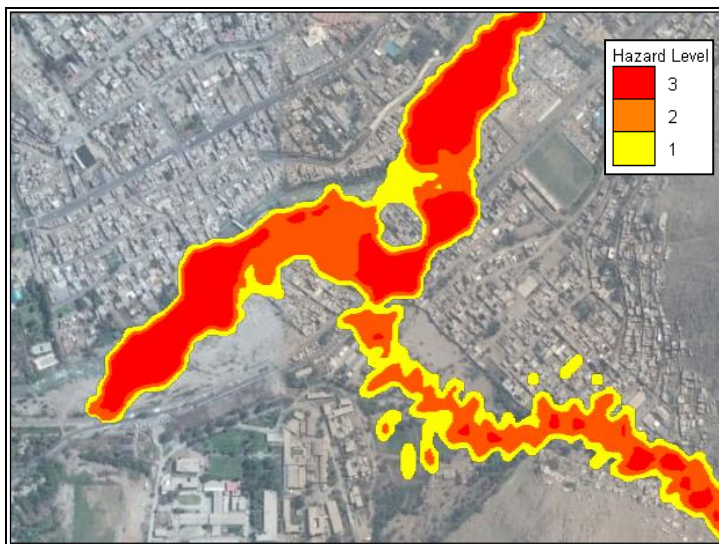
Hazard risk	Areas (m2)	Affected houses - 200m2 (approx)
High (red)	43935	220
Medium (orange)	40860	204
Low (yellow)	18310	92
Total	103105	516

Figure 7. Hazard map to debris flow in Chosica. *Tr*=100 years.

To control debris flow, different heights of sabo dam (*H*) were essayed. For this goal, ineffective flow areas were defined to different heights, according to dimensions of sabo dam. The best selection correspond to *H*= 7.4m. Figure 8 shows effects of this structure on Santo Domingo ravine; sediment volume is absolutely retained.
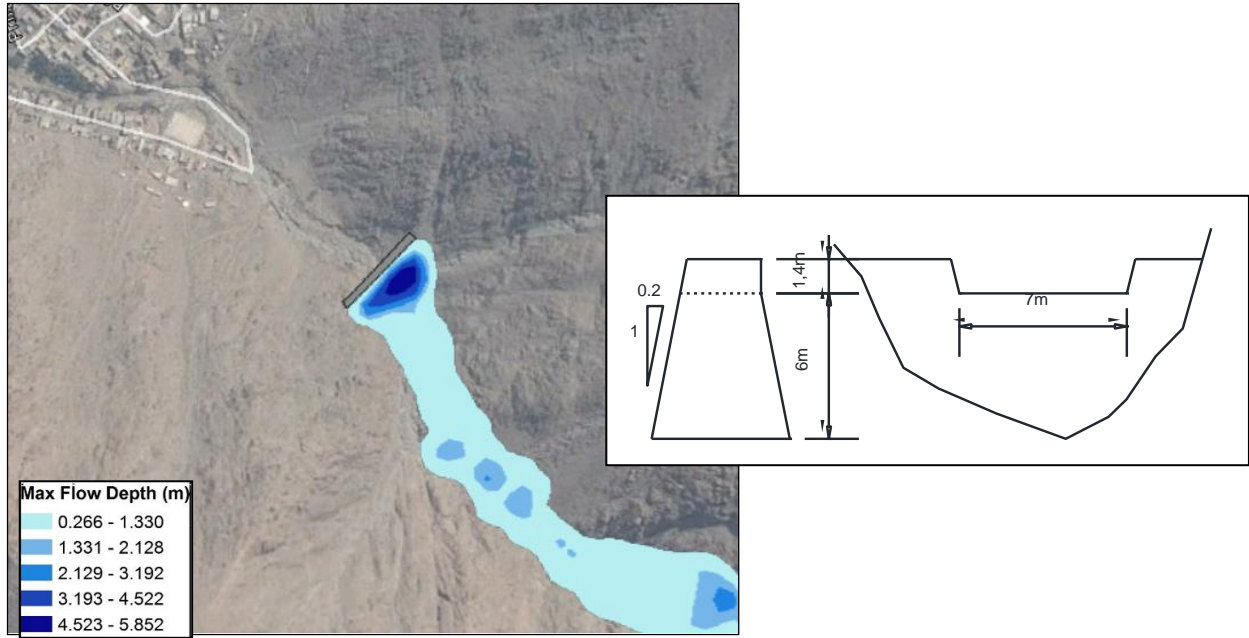
Figure 8. Deposition of Santo Domingo ravine with a sabo dam. Height = 7.4m. Tr=100 years.

Operation of sabo dam was evaluated with KANAKO. Results suggest that the best height of sabo dam is 14m, the double of FLO2D (see Figure 9). This result is oversized because KANAKO does not consider effect of banks on retained sediment volume and considers the stream like a rectangle shape.
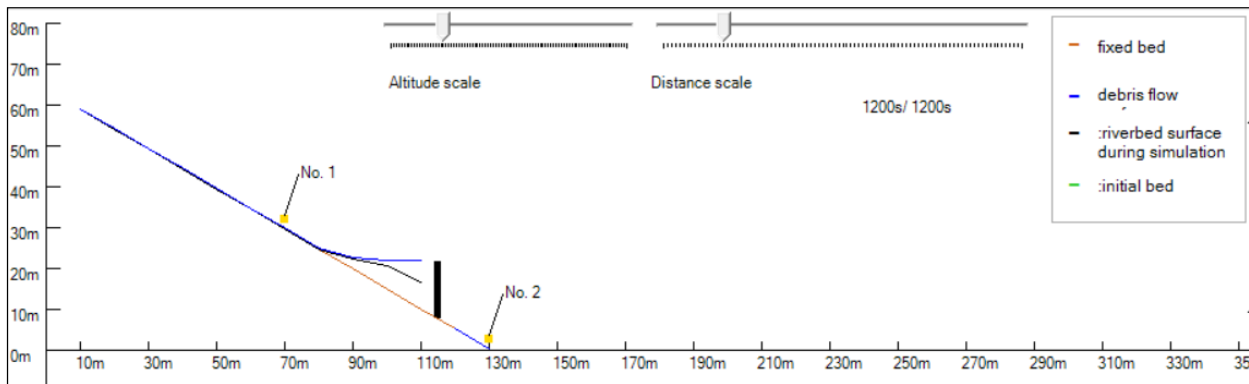

Figure 9. Evaluation of sabo dam with KANAKO. Height = 14m.

To analyze convenience of a flexible barrier, the total volume of sediment estimated with FLO2D was considered (approximately 7800m^3). DEBFLOW shown that it will be necessary 12 flexible barrier type UX180-H6 located along of the stream; every barrier will contain between 861 and 635m^3 of sediment. Steep slopes reduces the retention capability of every barrier and increases the number and the cost of this alternative.

5. CONCLUSIONS

Simulation show that more than 500 families could be affected by debris flow in a centennial event. To avoid this disaster, it is necessary to define evacuation routes and organize the population. The hazard map shows safe areas that could be considered for this goal.

Sabo dam shows the best performance like control measure to these conditions, including high slopes and debris flow. This performance and the possibility of using local material in construction represent an important cost reduction. Flexible barriers show low performance to high slopes and high costs to this conditions and type of barrier. Other products should be tested to verify a better solution.

In respect to software, FLO2D shows the best performance to simulate debris and mudflow, and permits estimation of the optimum height to the sabo dam and its efficiency. On the other hand, KANAKO shows that oversize structures because consider rectangle shape on streams however, could be used in narrow channels.

This methodology could be applied along of the Peruvian coast and mountain where this kind of geodynamic is common in the rainy seasons.

6. REFERENCES

CESEL Ingenieros S. A. (2004) Estudio hidrológico de la quebrada Collana. Lima, Peru.

Fiebiger, G. (1997) Hazard mapping in Austria. Journal of Torrent, Avalanche, Landslide and Rockfall Engineering. 61(134), 121—133.

García, R et al (2003). Hazard mapping for debris-flow events debris flows and warning road traffic at in the alluvial fans of northern Venezuela bridges susceptible to debris-flow. In: Rickenmann, D., Chen, C. (Eds.), 3rd Int. Conf. on Debris-Flow Hazards Mitigation. Millpress, Rotterdam, The Netherlands, pp. 589–599

GEOBRUGG (2011). Barreras flexibles de anillos para retención de flujos de detritos: la solución económica. . Boletin Técnico.

INDECI (2011). Manual de estimación del riesgo ante inundaciones Fluviales. Cuaderno Técnico N°2. INDECI. Marzo 2011.

Japan International Cooperation Agency (1988) The Master Plan Study on the disaster prevention Project in the Rimac basin. Lima-Perú.

Japan International Cooperation Agency (2010) Technical standards and guidelines for planning and design of sabo structures. Tokyo-Japan.

Julien, Pier Y. et al. (1991) Rheology of Hyperconcentrations. Journal of Hydraulic Engineering, Vol. 117, No. 3, March 1991, pp. 346-353. American Society of Civil Engineers (ASCE). Washington – U.S.A. 1991.

Mitzuyama et al (1992) - Prediction of debris flow peak discharge. Proc. Interpraevent, 4: 99-108, Berne.

O'Brien, J. & Julien, P. (1988) Laboratory analysis of mudflow properties. Journal of Hydraulic Engineering 114(8), 877–887. ASCE.

PREVENE (2001) Contribution to "Natural" Disaster Prevention in Venezuela. Technical report Project VEN/00/005. Cooperation: Venezuela—Switzerland—PNUD.