Debris Flow Modelling Incorporating Structural Mitigation Measures with FLO-2D

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***Abstract*— Debris flow is common in season of significant rainfalls, an area with this recurrent problem is Huaycoloro river basin in Lurigancho district, Lima-Perú, this paper objective is modeling Huaycoloro river basin debris flow impact analysis of the structures in these natural disasters with FLO-2D software. Methodology to analyze it began with geomorphology and topography input data. Model was calibrated according to data flood signs of last debris flows events in study area. Using FLO-2D, this is modeled for 500 years return period and according to results optimal location of structures were analyzed at different location scenarios. Pre-dimensioning of structures was done in base of impact force produced by flow for aforementioned return period with aim of location them at specific points where depth developed by flow is important, and this way, incorporate structures to digital elevation model and as results allowed us to reduce 1.4 meters depth and 0.7 m/s of velocity in all system compared to initial scenario without structures. In conclusion structures allows us to improve disaster mitigation conditions caused by debris flows.**

***Index Terms*—debris flow, Structures, FLO-2D, flood control, modeling flood**

I. Introduction

Climate change in recent years has taken on significant importance, so the natural effects caused by it are extreme, manifesting itself through increased sea temperature, which causes evaporation and consequently heavy rainfall that can cause flooding, landslides and debris flows. This change in sea temperature, specifically in the Pacific Ocean off the Peruvian coast, is manifested by the *El Niño* phenomenon. This event occurs frequently during the rainy season in Peru, and the most frequent are the debris flows whose rheological classification belongs to the Non-Newtonian flows and which are commonly called huaicos in Peru, which throughout their development cause damage and have a negative social, economic and environmental impact in certain areas that are directly influenced.

Therefore, to have control of impacts that debris flows could cause, detailed studies are proposed, making use of numerical models that allow us to represent reality parameters with greater accuracy and according to the responses to be able to create of hazard, risk and vulnerability maps, such is the case of the study carried out in Tantará in Huancavelica in which the simulation of debris flow with the numerical model FLO-2D [1] and in Santa Eulalia, the two of them located in Peru where it was possible to identify input variables for model such as: topography, hydrological data, rheological data of the riverbed (yield stress and viscosity), resistance to laminar flow, roughness coefficients, percentage of sediment concentration, and consequently through simulation obtain responses of mean velocities, mean flow depth, impact force produced, and representation of the total flooded area due to debris flow event.

According to the aforementioned, this article proposes the simulation of two different scenarios to obtain the mean flow depth and velocity, in the Huaycoloro river basin located in the Lurigancho district in Lima-Peru where mathematical model FLO-2D will be used and according to these answers propose the positioning of mitigation structures in critical points, pre-dimension them according to impact force for return period of 500 years corresponding to such structures. In addition, their stability will be analyzed with the sliding and turning factors, once having it, the models of structures will be incorporated for their simulation and in this way analyze if such structures have a mitigation or reduction impact compared to the results pertaining to the simulation with no structures to culminate with analysis in a general way if it is possible to control the roll waves caused by the phenomenon drastically. All this research will be carried out in order to reveal whether the proposed structures in a general way positively mitigate or reduce the effects that a debris flow may have along its trajectory, comparing different positioning scenarios of the structures and determine which of them is the optimal according to the results obtained.

II. Methodology

A. Study Area

The study area is of approximately 9.04 km² which corresponds to the dejective cone that the Huaycoloro basin has in the district of Lurigancho, located in the East

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of Lima-Peru, where the Huaycoloro creek is located. The elevation with respect to the sea is in range of 283.6 to 569.7 meters (Fig. 1) According to history of that area of Lima, this region had a history of debris flow which had a high impact due to the destruction of houses, tracks and critical damage to the bridge that connected this district with the metropolitan Lima [2].

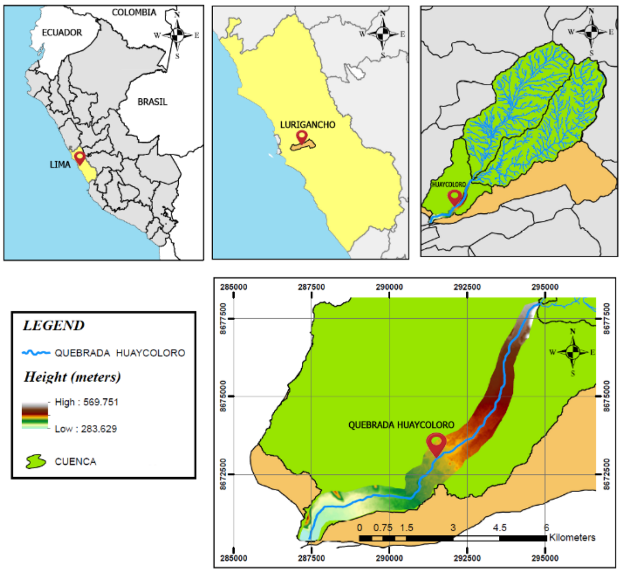

Figure 1. Studied area.

B. *Mathematical Model FLO-2D*

The mathematical model of the FLO-2D software is proposed by O'Brien and Julien, which is a two-dimensional model that idealizes the behavior of a debris flow as closely as possible with a quadratic rheological model which is represented in the following equation:

$$\tau = \tau_y + \mu \frac{\delta u}{\delta y} + C_1 \left(\frac{\delta u}{\delta y}\right)^2 \quad (1)$$

where yield stress generated is represented by τ_y, the dynamic viscosity is μ and C_1 the coefficient that represents the turbulent or dispersive flow parameter.

Another of the equations that the mathematical model considers is the continuity equation and the momentum conservation equation whose equations respectively are:

$$i = \frac{\partial h}{\partial t} + \frac{\partial_t V_x}{\partial_x} + \frac{\partial_h V_y}{\partial_y} \quad (2)$$

The continuity equation is given by representing the rain intensity with letter *i*, depth with h, components of the velocities averaged in each coordinate axis V_x and V_y and finally the time with *t*.

$$Sf_x = S_{ox} - \frac{\partial h}{\partial x} - \frac{v_x}{g}\frac{\partial v_x}{\partial x} - \frac{v_y}{g}\frac{\partial v_x}{\partial y} - \frac{1}{g}\frac{\partial v_x}{\partial t} \quad (3)$$

$$Sf_y = S_{oy} - \frac{\partial h}{\partial y} - \frac{v_y}{g}\frac{\partial v_y}{\partial y} - \frac{v_x}{g}\frac{\partial v_y}{\partial x} - \frac{1}{g}\frac{\partial v_y}{\partial t} \quad (4)$$

The momentum conservation equations for each coordinate axis are determined by having S_{ox} y S_{oy} as the components of the bottom slope, g as the acceleration of gravity, h as the depth of flow, and Sf as the slope of friction along the riverbed.

For the input data of the FLO-2D model, the viscosity (η) and yield stress (τ_y) equations will be used, which will potentially be increased with the sediment concentration that will be carried out with reference to the literature of the manual of the FLO-2D [4]

$$\eta = \alpha_1 e^{\beta_1 C_v} \quad (5)$$

$$\tau_y = \alpha_2 e^{\beta_2 C_v} \quad (6)$$

C. *Simulation Scenarios*

We will consider two alternatives, the first in which the terrain to be modeled does not have any alteration in its original parameters and the second will be those in which the terrain model has the structures incorporated into its configuration.

In the first alternative, simulations will be carried out for two return periods, the first will be 100 years in order to calibrate and validate the input parameters comparing the results with the real information of the study area and the second will be 500 years once the parameters are validated, they will be used for the designs of the longitudinal dikes [3] and it will help us to obtain critical results and thus estimate and pre-dimension the structures.

The second alternative will use the structures incorporated in the DEM and this way simulate with the calibrated and validated data, and the modeling will be carried out with 9 combinations of location of the two different structures at the critical points obtained in the alternative without alterations.

D. *Input Data*

The parameters obtained for the input information to the FLO-2D numerical model are the following in Table I:

TABLE I. INPUT DATA

Parameter	Unit	Value
Manning's coefficient	s/m^(1/3)	0.06
Laminar flow resistance	Pa.s	1000
Percentage of fine soils by deposition	%	3.9
Sediment concentration	m3/m3	0.45
Yielding effort	Pa	153.628
Viscosity	Pa.s	1.055

Another input that gets into the model is the hydrograph (liquid flow) obtained in the HEC-HMS platform (Hydrologic Engineering Center - Hydrologic Modeling System). In addition, the hydrographs of debris flows generated in the modeling in the first alternative will be used. (Fig. 2)

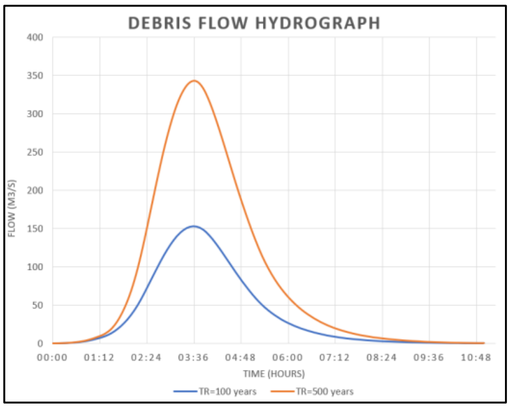

Figure 2. Input hydrographs.

III. Results

A. Structureless Modeling

The first results will be those that have not been considered in the structures, this means obtaining the depths of the flow, speeds and impact force. To perform the calibration, only the results of mean flow depth for a return period of 100 years have been compared and its validation was obtained with the flood signs in the study area of the last debris flow events. To do this, four control points were taken into account: the first, located at coordinates 287479.39 m East and 8670585.54 m South, the second located at coordinates 288049.00 m East and 8671466.00 m South, the third located at coordinates 291077.00 m East and 8672416.00 m South and finally the room located at the coordinates 291388.00 m East and 8672839.00 m South.

With the response obtained in the previous paragraph, the model was made for a return period of 500 years, the response of which has been the flow depth, velocities, impact forces and finally its subsequent pre-dimensioning for the mitigation structures.

In Fig. 3 the modeling result for a return period of 100 years is shown, where it is compared with the real data, whose results with the information taken in the control points were the following, in the first control point 3.1 meters, 2.60 meters in the second, 2.50 meters in the third and 2.90 meters in the fourth.

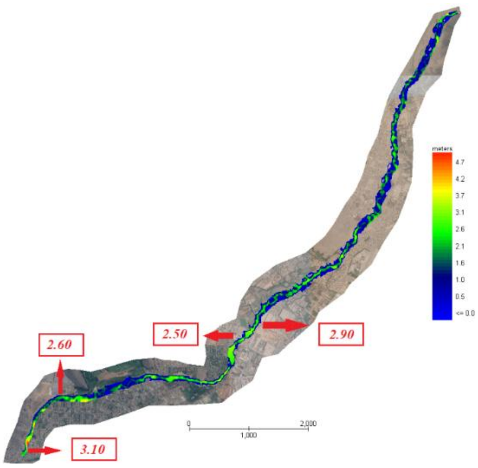

Figure 3. Flow depth Tr =100 years.

Model Calibration

For the model calibration, data collection of the flood signs was carried out at each control point left by the last events of debris flows and the depth results of 3, 2.7, 2.6 and 2.75 meters were obtained in the four points already mentioned (Fig. 4).

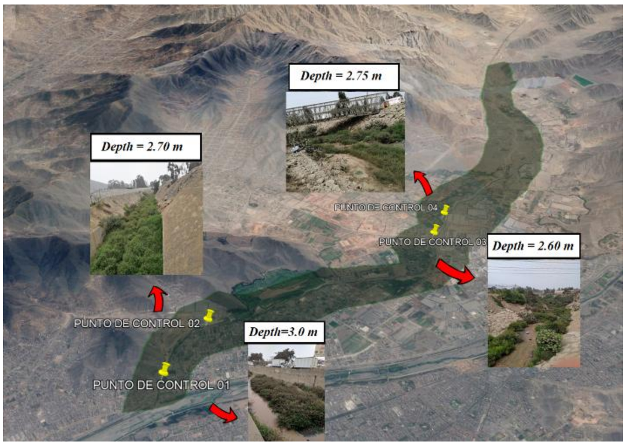

Figure 4. Depth of the flood sign of the control points.

From the information obtained in the field and the modeling carried out in this work for a return period of 100 years, was obtained that the correlation factor between the data collected in the field and our modeling are quite good, so it can be deduced that the income of the input data is valid.

Fig. 5 shows the results that were obtained for a return period of 500 years whose maximum depth responses represented in atypical values are 6.4 meters. However, an average depth along the channel is in the interval between 3.6 to 4.3 meters deep along the creek.

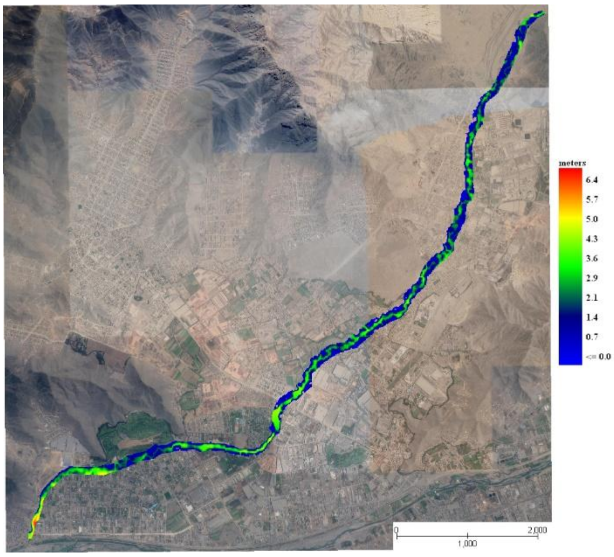

Figure 5. Flow Depth Tr = 500 years.

In Fig. 6 the average velocity that fluctuates along the creek of 3.8 m/s in the critical zones.

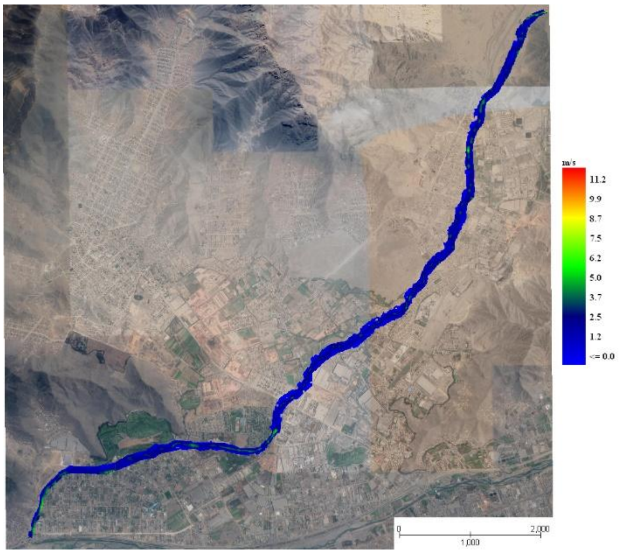

Figure 6. Flow velocities Tr = 500 years.

In addition, the impact force was obtained for the return period of 500 years whose values are in the order of 182.59 KN/m and 194.77 KN/m, these impact force responses have been taken from two location points of the structures where the analysis has been considered (Fig. 7).

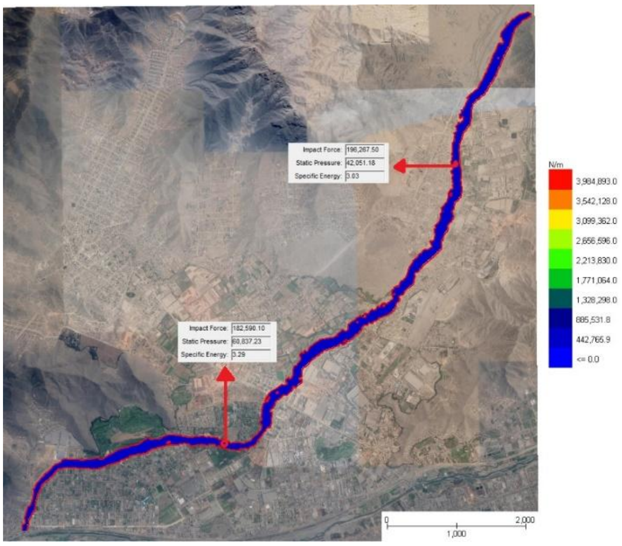

Figure 7. Flow impact forces Tr = 500 years.

B. *Pre-dimensioning of Structures*

For the pre-dimensioning of the structures we have that at the location points (Fig. 8) that have a maximum average depth of 4.3 meters in position 01 and 4.50 meters in position 03, so the height will be estimated as the immediate upper integer of 5 meters, of equal magnitude of the width, which includes 0.70 meters of foundation, the length of the structure will be according to the opening of the channel at the specified point including anchors on the margins of this, considering a width of 28 and 26 meters for positions 1 and 3 respectively adding 1 meter to each side for the anchoring that must have, finally the first structure of 30 meters (Fig. 9) and the second of 28. (Fig. 10)

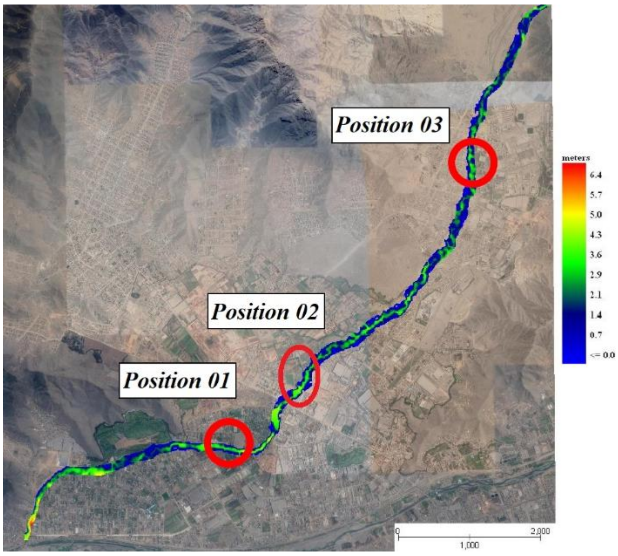

Figure 8. Structure positioning zones.

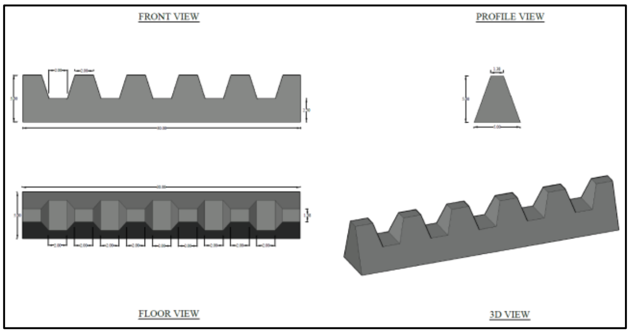

Figure 9. Structure 01.

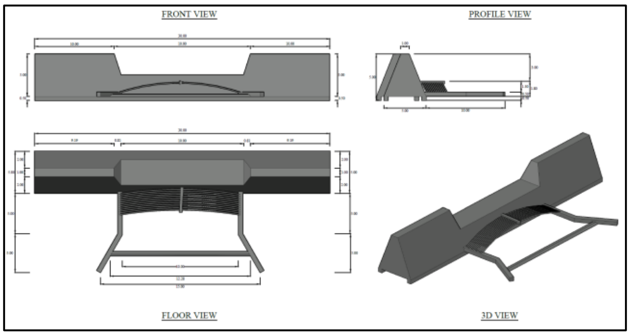

Figure 10. Structure 02.

To verify the stability of each of the structures, the analysis of the sliding and turning factors was performed (Table II) for both structures, obtaining the following result:

TABLE II. STABILITY FACTOR

SAFETY FACTORS			
	Required	**Calculated**	**Condition**
Slip factor	1.00	1.69	Accepted
Turn factor	1.00	1.10	Accepted

In Table II it can be seen that the calculated safety factors are acceptable for the dimensioning of the structures used and whose force value developed by the debris flow has been calculated for a return period of 500 years.

C. *Modeling with Structures*

The modeling with structures for a return period of 500 years with different location scenarios, as it is seen between Fig. 11 and Fig. 13:

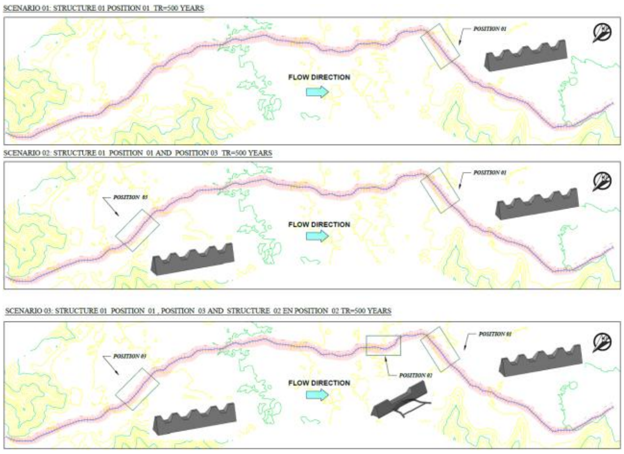

Figure 11. Scenario 01,02,03.

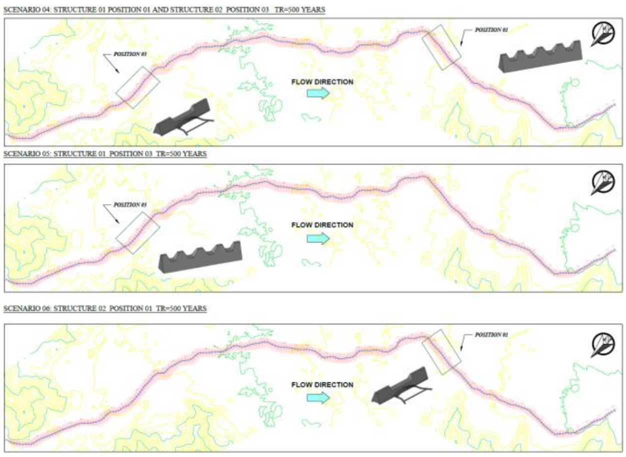

Figure 12. Scenario 04,05,06.

Figure 13. Scenario 07,08,09.

According to these scenarios, the structures will be incorporated into the DEM to perform the modeling of these structures in interaction with the debris flow, for which the following results were obtained, shown in Table III to Table VI:

TABLE III. STRETCH RESULTS 01

SCENARIOS	POSITION 01	
	MAXIMUM AVERAGE DEPTH (meters)	MAXIMUM AVERAGE VELOCITY (m/s)
500 years	**3.80**	**4.20**
1	3.40	4.00
2	3.20	3.00
3	3.40	3.30
4	2.90	3.10
5	3.20	4.10
6	3.30	3.80
7	3.10	3.60
8	3.00	3.20
9	3.60	3.30

TABLE IV. STRETCH RESULTS 02

SCENARIOS	POSITION 02	
	MAXIMUM AVERAGE DEPTH (meters)	MAXIMUM AVERAGE VELOCITY (m/s)
500 years	**4.40**	**3.80**
1	4.13	3.10
2	3.60	3.10
3	3.20	2.40
4	3.80	2.90
5	3.50	3.30
6	3.60	3.40
7	3.50	3.20
8	3.60	3.10
9	3.50	3.40

TABLE V. STRETCH RESULTS 03

SCENARIOS	POSITION 03	
	MAXIMUM AVERAGE DEPTH (meters)	MAXIMUM AVERAGE VELOCITY (m/s)
500 years	**3.60**	**4.00**
1	3.60	3.50
2	3.20	3.00
3	3.35	3.20
4	3.40	3.10
5	3.00	3.00
6	3.40	3.50
7	3.30	3.80
8	3.50	3.00
9	3.10	3.10

TABLE VI. SYSTEM-WIDE RESULTS

SCENARIOS	GLOBAL	
	MAXIMUM AVERAGE DEPTH (meters)	MAXIMUM AVERAGE VELOCITY (m/s)
500 years	**4.20**	**3.80**
1	3.40	3.10
2	3.30	2.90
3	3.20	3.20
4	2.80	3.10
5	3.30	3.20
6	3.10	3.20
7	3.15	3.00
8	2.70	2.80
9	3.40	3.10

According to the results in the specific locations shown above, and at the level of the whole system, it can be deduced that scenario 4 (which is the combination of structure 1 in position 1 and structure 2 in position 3) has optimal results compared to the frameless modeling for the 500-year payback period.

The final positioning of the structures can be seen in Fig. 14.

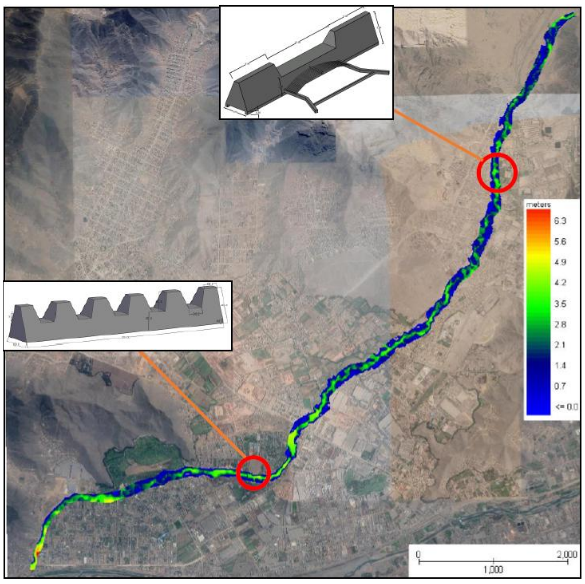

Figure 14. Modeling with structures TR=500 years.

IV. ANALYSIS OF RESULTS

The According to the results shown above, the most optimal combination of structures is given by modeling scenario 4, which had better behavior facing the debris flow, in which it is determined that there is a difference in the depth of debris flows throughout the system of 1.4 meters with respect to the modeling of 500 years with no structures and a decrease in speed in the order of 0.7 m/s on average of the entire stream. These results have been obtained as follows: in section 01, 2.9 meters of average depth and 3.10 m/s of average speed were obtained, in section 02, 3.8 meters of average depth and 2.90 of average speed were obtained and finally in the Section 03 was obtained 3.40 meters of average tie and 3.10 m/s of average speed. However, at the level of the entire system of the entire stream, the predominant results (Table VI) of 2.80 meters of average depth and 3.10 m/s average speed.

Apart from the flow depth that was shown (Table VI), the response of the roll waves caused by the changes of section in the effects of the structures was also analyzed, therefore we will use the Vedernikov number for, which is represented in the following equation:

$$V = (\beta - 1) * F \tag{7}$$

Where β is the exponent of the expenditure curve and F is the Froude number at a specific point. According to the theory of neutral stability, the Froude number does not vary in a wide range in the development of the channel, being the most sensitive to variations (β *-1*), so this theory makes the similarity of $V = 1$ to determine the value of β with a neutral Froude reference number (Table VII) for which the following relationships are obtained according to the developed section [5].

TABLE VII. B VALUES

β values corresponding to Fns values			
β	**Types of friction**	**Cross section**	**Fns**
3.00	Laminate	hydraulically wide	0.500
2.67	Laminate - Turbulent (25% Manning turbulent)	hydraulically wide	0.600
2.63	Laminate - Turbulent (25% Chezy turbulent)	hydraulically wide	0.615

For the calculation of the Froude number *(F)*, the flow velocity and depth at position 3 and 1 have been used, to then obtain the β value, the result can be observed in table VIII and IX.

TABLE VIII. SYSTEM-WIDE RESULTS WITHOUT STRUCTURES

WITHOUT STRUCTURES				
	Froude number	**Beta**	**Vedernikov's number**	
POSITION 01	0.592	2.67	0.987	V<1
POSITION 03	0.575	2.67	0.96	V<1
Analysis				
Roll waves developing downstream				

TABLE IX. SYSTEM-WIDE RESULTS WITH STRUCTURES

WITH STRUCTURES				
	Froude number	**Beta**	**Vedernikov's number**	
POSITION 01	0.581	2.67	0.969	V<1
POSITION 03	0.537	3.00	1.074	V>1
Analysis				
Roll waves reduction downstream				

According to the results obtained for the calculation of the roll waves in the models with no structures (Table VIII) for position 03, a Vedernikov's number less than 1 was obtained, which means that the roll waves are in recession. However, it can be noted that in position 01 this value increases and even though it continues to mean that the roll waves are in recession while the flow develops downstream, this value would increase and the Vedernikov number will be greater than unity, which means that the roll waves increase in size and this may be the cause that roll waves have been observed in the lower part of the creek as shown in Fig. 15. On the other hand, the analysis of data obtained with the most optimal modeling with structures (Table IX) shows us that for position 3 the Vedernikov number is slightly greater than 1, which means that the size of the roll wave can be maintained or slowly increased, however at the moment of interacting with the structure at position 01, the Vedernikov number is reduced, which means that the roll waves were controlled and reduced by the structure, which refers to the recommendation made by Ponce [6] for the reduction of these waves, which is to distribute the flow of the channel in various sections and thus mitigate the development of roll waves downstream, so the section of structure 1 (Fig. 16) would help to control this downstream effect and not cause an increase in the size of these waves since they could cause the flow to overflow and the destruction of the elements close to it.

Figure 15. Roll waves "El Niño Costero" event, 2017 Lima-Perú.

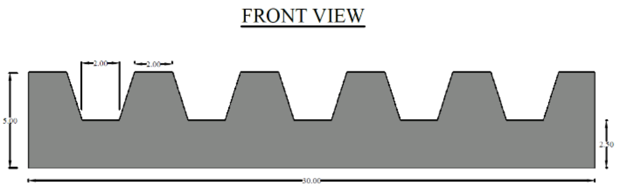

Figure 16. Structure cross section 01.

V. CONCLUSIONS

Calibration for the flood model was made for a return period of 100 years which allowed validating the input data.

Scenario 04 was the most suitable for the application of structures, reducing the depth and average speed of debris flow by 1.4 meters and 0.7 m/s respectively at the level of the entire riverbed compared to the model without structures.

The structures were pre-dimensioned based on the impact force obtained from the modeling without structures for a 500-year return period, which is considered more critical for this research.

The Vedernikov's number calculated for scenarios 01 and 03 without structures was 0.987 and 0.960 respectively, as these values are lower than one, they indicate that the rolling waves are decreasing downstream.

The Vedernikov's number calculated for scenario 01 with structures was 0.969 as this value was less than one, indicating that the presence of the structure helps reduce downstream rolling waves.

The Vedernikov's number calculated for scenario 03 with structures was 1.074, as this value is slightly larger than one, indicating that the rolling waves are slowly increasing in size.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors participated in the investigation and modelling R. Loaiza, A. Aranibar. Investigation advisor M. Jara. All authors had approved the final version.

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