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Hydraulic Analysis of a Groynes Arrangement on a Diversion Channel

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ABSTRACT: We simulated the hydraulic effect of an arrangement of seven groynes used as bank protection in a meander river whit a diversion channel. We used HEC-RAS 4.1 software calibrated with experimental data obtained in a reduced physical model, 1:40 scale. Three scenarios were simulated: a) in natural conditions; b) with a diversion channel and c) with a diversion channel and protection of groynes. Also, three different types of geometries of groynes were tested: i) as a barrier, with dimensions of average height, width, and length; ii) as a set of stepped obstructions and iii) as part of natural terrain barrier. Results show HEC-RAS (1-D), reproduced adequately the effects measured in the physical model, when groynes are considered as a barrier. The groynes arrangement produced an elevation in the free surface of water, which caused a greater branching of flow in the channel. This effect was not foreseen in the original design, but, in this case, was beneficial because protects a downstream city against floods. These findings suggest although HEC-RAS is a 1D model is able to simulate satisfactorily the hydraulics effects in the groynes arrangement, also the best way to simulate the groynes in Hec-Ras, was like a barrier.

Keywords: Groyne Arrangement, Channel Protective Works, Channel Geometry, Numerical Analysis, HEC-RAS

INTRODUCTION

The bank protection of rivers against erosion is essential in flood protection systems. Basic protections are: coatings, marginal dikes, and groynes. The objective is avoiding water flow contact with the river banks (Maza-Álvarez and García-Flores, 1996). The groyne operation has been studied through numerical models (McCoy et al., 2008; Jia et al., 2009; Papanicolaou et al., 2011), and experimental analysis (Weitbrecht et al., 2008; Roca et al., 2009; Yossef and De Vriend, 2011). In most of these studies, the assumption is that groynes emerge from the free surface water, they are perpendicular to the river bank and located on a straight channel. Conversely, in this work we simulated the hydraulic operation of an arrangement of seven groynes located to protect a river bank meander with a diversion channel. Groynes are submerged partially and oriented in angle with respecting to the right bank. We used HEC-RAS 4.1 (USACE, 2010) in the numerical simulation. The model was calibrated with experimental data from a physical model with 1:40 scale (Rivera-Trejo, 2011). Three scenarios were simulated: a) in natural conditions; b) with a diversion channel and c) with a diversion channel and protection of groynes. To find out the best way to represent the groynes geometry in the numerical model, three options were tested: 1) as a barrier, 2) as a set of stepped obstructions, and 3) as natural terrain (NT). The first option shown to be the best inasmuch as it reproduced closely the effect observed in the physical model.

MATERIALS AND METHODS

Case study

We chose a diversion channel (Figure 1), located on the De La Sierra River, in Tabasco, Mexico. Coordinates 1979779.7399 m N, 512603.3299 m E Figure 2). The channel splits part of the water flow circulates on the De La Sierra River toward to a natural lake, and decreases its free surface water to downstream direction, where the city of Villahermosa, is located and which is susceptible to suffer dangerous and expensive floods (Rivera-Trejo et al., 2010).

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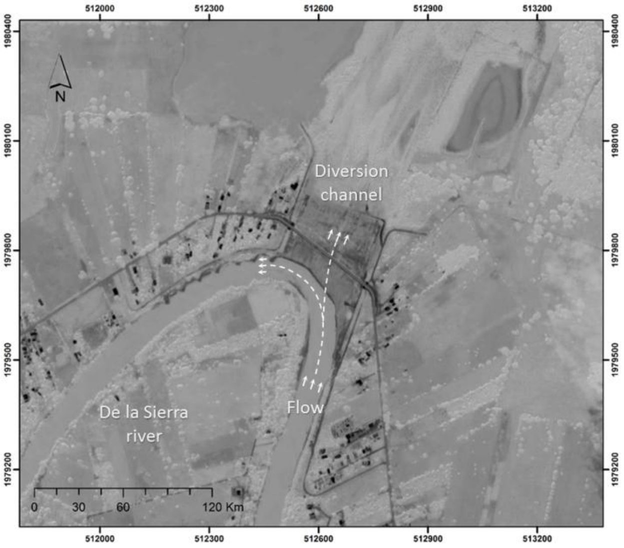

Figure 1. Study zone. Meander and diversion channel.

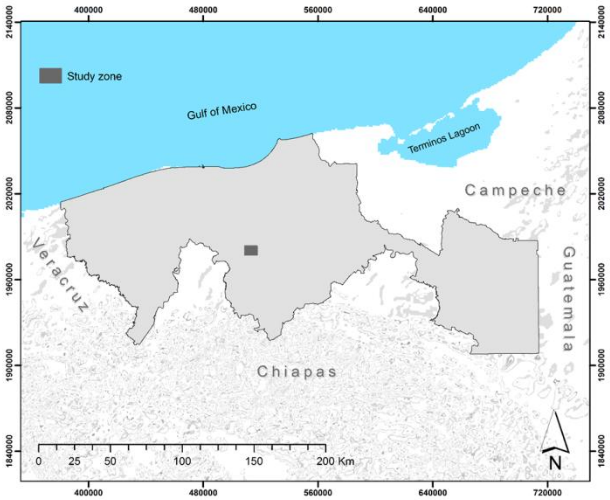

Figure 2. Tabasco State, Mexico.

Numerical model

We used HEC-RAS software coupled with HEC-GeoRAS tool (USACE, 2011), and a geographical information systems (GIS). Initially, from topography data we built a digital terrain model (DTM) (Figure 3). The meander, river banks, and flood flatlands were drawn. The cross-sections were defined for exporting and processing in HEC – RAS.

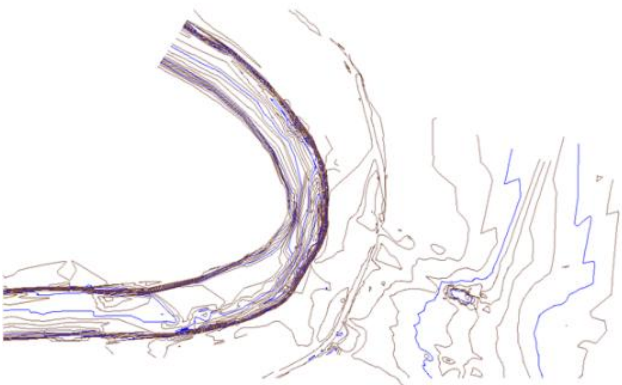

Figure 3. Topographic data.

Natural conditions

The model was calibrated in natural conditions after entering the geometrical setup. The calibration took values from the results of a physical model at 1:40 scale. We used a Manning "n" coefficient of 0.025 and simulated the experimental discharge flows. The downstream boundary conditions were the hydraulic slope and permanent flow. The hydraulic slope was calculated from the water surface levels (WSL) recorded during the experimental tests (Rivera-Trejo, 2011).

Diversion channel

When the numerical model reproduced the hydraulic conditions of the river in natural conditions, the diversion channel without groynes was entered and simulated. We employed upstream the Manning *"n"* coefficient of 0.023 and downstream of 0.0226; this was the result from the calibration of the numerical model in natural conditions. Because the meander and the diversion channel were built of same material, the diversion channel also employed a Manning coefficient of 0.023.

Boundary conditions from physical model are shown in Table 1. Downstream, on the meander was considered as an output condition, the water surface level (WSL) corresponding to each flow (Q) was obtained from the experimental discharge curve. The numerical simulation was compared with the experimental results and water profiles, measured in six sampling points: h1, h2, h3, h4, h5 and h6 (Figure 4).

Table 1. Boundary conditions.

$Q_{upstream}$ (m^3s^{-1})	**$Q_{downstream}$ (m^3s^{-1})**	**$Q_{diversion}$ (m^3s^{-1})**	**WSL (h4) (masl)**
1600	859	741	6.91
1501	875	626	6.70
1398	880	518	6.45
1307	890	417	6.30
1200	906	294	6.10
1100	897	204	5.90
1000	874	126	5.70
900	847	53	5.50

masl: meters above sea level

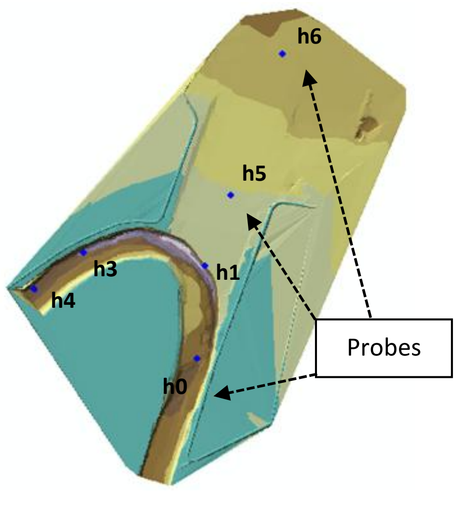

Figure 4. River curve with diversion channel and sampling points.

Diversion channel and one groyne

Because HEC-RAS lacks rules to enter the groynes geometry, we tested three option to the groynes: a) as a barrier, with dimensions of average height, width and length; b) as a set of stepped obstructions comprise the geometry of the groyne; c) as part of the natural terrain (NT), including the dimensions and elevations of the groyne directly on the digital terrain model (DTM). Figures 5a-c shows the considered options.

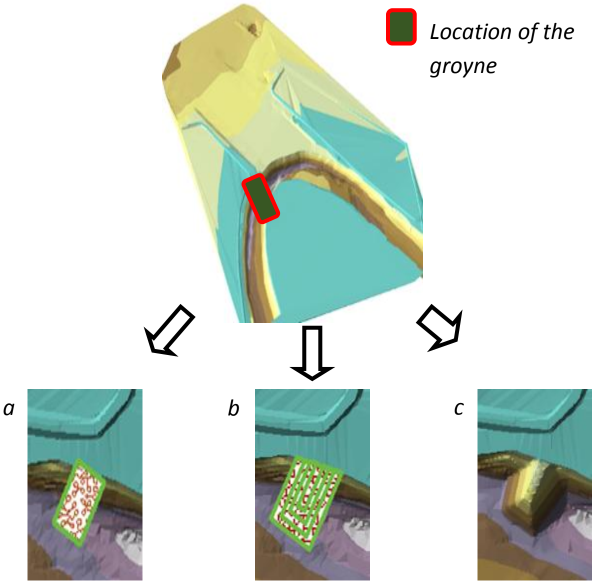

Figure 5. Geometrical options to enter the groynes: a) as a barrier; b) as a set of stepped obstructions; c) as part of the natural terrain.

After modelling the different experimental flows (Rivera-Trejo, 2011), we analyzed the differences between the WSL measured against the WSL simulated with the proposed geometry options (barrier, stepped, and natural terrain), and chose the best one. Then we entered the arrangement of seven groynes (Figure 6) to the numerical model.

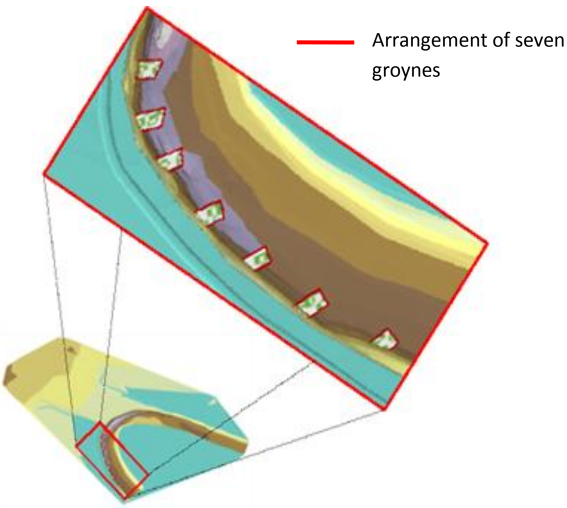

Figure 6. Seven groynes arrangement.

RESULTS

Natural conditions

Table 2 shows the proposed "n" Manning values, the flow discharge (Q) and the water surface level (WSL) obtained numerically and measured experimentally. The experimental behaviour was reproduced with Manning coefficients of 0.023 upstream and 0.0226 downstream.

Table 2. Roughness calibration

"n" Manning coefficient	Q (m^3s^{-1})	WSL (masl)
0.025	1305	6.63
0.024	1357	6.61
0.023	1417	6.61
0.023 and 0.0226	1438	6.59
Physical model	1450	6.60

masl: meters above sea level

Diversion channel

When natural conditions were simulated adequately, we proceeded to include the diversion channel. To define the Manning coefficient, we compared the difference between WSL experimental and numerical values. After calculating these differences, we got the cumulative Δh for each roughness. We chose n=0.032 to the diversion channel, because this coefficient generated a lower cumulative difference Δh=0.15 (Table 3).

Table 3. Differences in water surface levels (WSL) and different roughness coefficients.

Difference in *Δh* level (m)				
Q (m^3s^{-1})	**"n" roughness coefficient**			
	0.035	**0.032**	**0.030**	**0.023**
1600	0.42	0.47	0.61	0.71
1501	0.29	0.34	0.37	0.47
1398	0.15	0.19	0.22	0.32
1307	0.08	0.12	0.15	0.24
1200	-0.34	-0.26	-0.28	-0.19
1100	-0.37	-0.29	-0.31	-0.24
1000	-0.48	-0.42	-0.46	-0.41
Σ *Δh* =	**-0.25**	**0.15**	**0.30**	**0.90**

Diversion channel and one groyne

Experimental results (Rivera-Trejo, 2011) shown that after the placement of the arrangement of groynes, the branch flow increased. This behavior was unexpected; nevertheless, it was convenient, as we wanted to branch the greatest flow possible.

We compared the hydraulic profiles of the physical and numerical models to validate these results. The level recorded in probing h1 had of higher interest because it was located at the entrance to the derivation channel and upstream of first groyne (Figure 7).

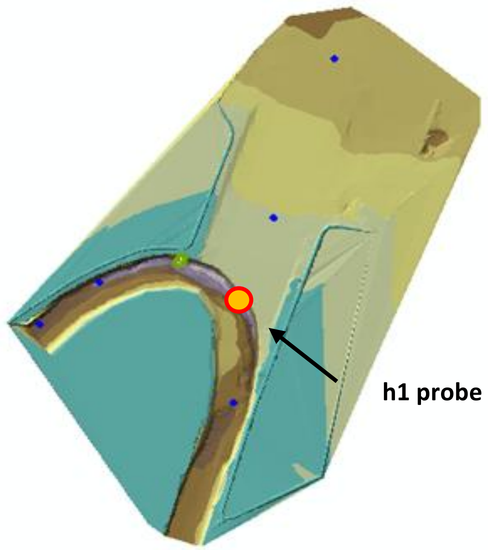

Figure 7. Validation point in diversion channel.

Groynes were simulated with three kinds of geometries: barrier, steeped and natural terrain. Table 4 shows the range for Δh recorded by the experimental measurements and each one of the geometrical groynes options. The flow discharge range in the river was from 1199 m³ s^{-1} to 1450 m³ s^{-1}.

Table 4. Differences in water surface levels simulated and types of geometrical models of groynes.

Difference of levels in h1			
Δh (m)	**Barrier**	**Stepped**	**NT**
Min	0.00	0.03	0.03
Max	0.11	0.11	0.11

It is observed in Table 4 that the range of variation of levels at the input of the diversion channel is similar. Meanwhile Table 5 shows: a) the experimental hydraulic profiles (WSL_{EXP}) generated with discharge flows from 1199 m³ s^{-1}, when diversion channel began to work, to 1450 m³ s^{-1}, the maximum discharge in the river; and b) the profiles resulting from the three geometries tested ($WSL_{barrier}$, $WSL_{stepped}$ and WSL_{NT}). Numerical results shown that the geometry considered as a barrier with dimensions of average width, height and length ($\Delta h_{Barrier}$), represents better the experimental conditions; also, this option requires less time to enter its geometry to the numerical model.

Seven groynes arrangement

The arrangement of seven groynes was added to the digital terrain model. All groynes were modeled as a barrier with average width, height and length. Figure 8 shows the operation of the diversion channel working with the arrangement of seven groynes. The horizontal axis represents the flow rate in the river, the left vertical axis is the flow rate in the diversion channel, and the right vertical axis is the water surface level measured in the h1 probing. This probe (h1) reflects the effect produced by the arrangement of groynes in the hydraulic levels of the diversion channel.

The discharge curves for the diversion channel generated with the experimental results (WSL_{div} - WSL_{Exp}) and the results of numerical modeling (WSL_{div} - WSL_{HEC}) do not reflect a significant variation in the branched flows.

Although for flow discharges greater than 1300 m³s^{-1}, simulated values shown an increment in flow discharge, it could be due that physical model lacks of storage zone, and the water tends to comeback. While in numerical model, this situation unhappens.

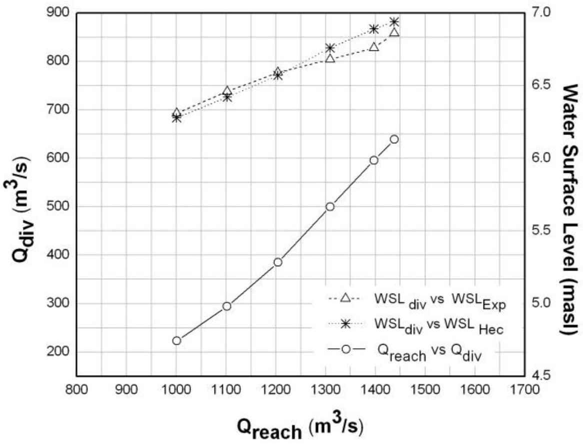

Figure 8. Operation of the diversion channel working with the arrangement of seven groynes.

CONCLUSIONS

The HEC-RAS software, which is a one-dimensional hydraulic model (1-D), was used to study the flow patterns in a river curve with groynes. This phenomenon has a behavior which is evidently three-dimensional (3-D); however, we explored the capacity of HEC-RAS had to resolve a 3-D case, found out good results. Experimental data were used to compare the results generated by the software. The calibration of HEC-RAS model with experimental data was made by testing the different values of the Manning roughness coefficient. Even when HEC-RAS is an important tool to private companies and government agencies, the adequate calibration process to validate results are not always performed. After calibrating the model, it was observed the most remarkable difference between the experimentally measured levels and those obtained in the numerical model appeared in the diversion channel zone. This zone is downstream of the channel, in the area constituted by filling material, the variation of level is due to the drag experienced in the material after the circulation of the different flows. In this case, HEC-RAS, as a 1-D model, does not consider these effects in its results.

Table 5. Effects of the water surface level measured in physical model (WSL_{Exp}), against water surface level simulated with different groynes geometries, as a barrier ($WSL_{Barrier}$), as stepped ($WSL_{Stepped}$) and as a natural terrain (WSL_{NT}).

Diversion flow rate	**WSL_{Exp}**	**$WSL_{Barrier}$**	**$\Delta h_{Barrier}$(m)**	**$WSL_{Stepped}$**	**$\Delta h_{Stepped}$ (m)**	**WSL_{NT}**	**Δh_{NT} (m)**
($m^3 s^{-1}$)	(masl)		(m)	(masl)	(m)	(masl)	(m)
1199	6.33	6.43	0.10	6.22	0.11	6.22	0.11
1307	6.40	6.40	0.00	6.37	0.03	6.37	0.03
1450	6.50	6.61	0.11	6.59	0.09	6.59	0.09
	Δh_{av}=		**0.07**		**0.076**		**0.076**

Also in HEC-RAS is nonexistent rule regarding the form of geometrically modeling the groynes, reason why three options were tested for modeling it: as a barrier with dimensions of average height, width and length; as a set of stepped obstructions; and as part of the natural terrain. We chose modeling the geometry of groynes as a barrier because we got the best results compared against experimental values, thrown by the other two options and, also, this option requires less time to enter its geometry to the numerical model. We think this result between the different alternatives was due to the good quality of topographical data entered to the model.

In this paper, only the elevation of the water surface level (WSL) was used as a comparison and calibration pattern. Nevertheless, if available other characteristics (such as shear stress, loss of power due to the curve, etc., which may also be generated in HEC-RAS) may be employed.

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Competing interests

The authors declare they have not competing interests.

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