Resilient River Defenses in the Vicinity of the Titicaca Deltas: Slope Stability Analysis of Dikes

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Abstract

Flooding in the Lake Titicaca basin poses a critical risk to communities and infrastructure, and endangers human lives. Dikes are commonly used to protect against flooding, but their stability is essential to their effectiveness. This study examines the stability of embankment slopes on the Ilave River dams through hydraulic and geotechnical modelling, using the limit equilibrium method with specialized software. This analysis was applied to sections between 2 and 5 m in height, with variable slopes, and considering scenarios of constant seepage and seismic loading (0.12 g). The hydraulic analysis of the design flow rate Q100 of 1360 m³/s determined a maximum water level of 3819.56 m a.s.l. and was used to establish the crest elevation of the embankments. The slope of 1.5:1 upstream and 1.75:1 downstream on a dam of ≤ 2 m yielded safety factors of between 1.45 and 1.54 under critical conditions. Embankments ranging from over 3 m to 5 m in height, reinforced with a drainage system and a cut-off trench rather than 2.0-metre piping, showed an increase in the safety factor from 2.5 to 11.6. They therefore possess high stability and resilience, making them safe in the face of extreme events. Adaptive design, redundancy and seepage control are essential to reduce the risk of extreme flooding and protect riverside communities that were vulnerable along certain stretches of the river. It is hoped that the recommendations from this research will contribute to improving the safety of riverside communities based on hydraulic and geotechnical modelling, thereby ensuring the long-term viability of these river defenses.

Keywords: *flooding, slope stability, flood defense infrastructure, piping, levee resilience*

1. Introduction

Flooding is a major hazard in the Peruvian Andes, posing a threat to lives and infrastructure. Among the recurring natural phenomena in the region are floods, which have caused damage to various infrastructure [1]. River defenses are integral components of flood management systems and play a crucial role in protecting human settlements, agricultural land, and critical infrastructure from the adverse effects of flooding. Flooding in riverbeds or streams is a problem that occurs in the lower and middle reaches, generally due to a lack of elevation, as well as breaches in dykes or excessive seepage [2,3], in general, flooding in low-lying areas can lead to more severe waterlogging, crop loss and other environmental problems [4,5] and the flooding caused by the interaction with nearby lakes lasts even longer [6]. River embankments are frequently used to prevent flooding, but their effectiveness depends on their stability. More permeable soils allow water to pass through them at higher rates; seepage through embankments or beneath foundations can cause serious damage, starting with the pipes and leading to the subsequent failure of the embankment [7,8], high water levels in the dykes can cause seepage, breaches in the dyke body, and dyke failure, leading to flooding [9–11]. The ability of an embankment to withstand adverse weather conditions, water-level fluctuations, and other environmental stresses without failing is known as embankment resilience. It is essential to ensure that embankments are resilient, as their failure can have catastrophic consequences, including flooding, property damage, and loss of life [12,13]. With the growing impact of climate change, it is essential to incorporate climate resilience into embankment engineering [14]. The integrity and functionality of dykes and embankments are seriously threatened by climate change, extreme weather conditions and changes in rainfall patterns [15]. Resilience, on the other hand, is also important as it enhances the ability to cope with uncertain yet extreme events that may occur over the long lifespan of geotechnical infrastructure [16,17].

The Peruvian Altiplano is not spared from the disasters caused by flooding; in this regard, the major rivers of the Lake Titicaca basin—such as the Ramis, Ilave, Coata, Huancané, Suches and Illpa—have caused flooding, generally with a greater impact on the lower reaches, that is, near the lake's mouth [18], these stretches are meandering rivers and are prone to flooding and bank erosion [19]. In the case of the River Ilave, whose waters have caused damage to homes, farmland, livestock, educational facilities, road infrastructure, healthcare facilities, and other infrastructure, as well as causing erosion of the riverbanks, with a latent risk of flooding.

During the rainy seasons of 1986, 2000–2001, 2006, and 2020, severe flooding occurred in the lower reaches of the River Ilave, primarily downstream of the existing bridges in the town of Ilave. One of these bridges was even severely eroded, leading to its destruction. Downstream, flooding affects numerous agricultural areas and homes. This highlights the need to rebuild the river defence embankments. The importance of these protective structures is justified by the damage that could result if the embankment

slopes were to fail due to a lack of shear strength or other failure mechanisms.

The main objective has been to determine the stable cross-section of the channelising embankment in response to the various stresses to which it will be subjected. To this end, various cross-sections and slope configurations have been studied in order to determine the safety factor (SF).

2. Features of the study area

2.1 Location and background

The Ilave River basin is located in the Puno region, in the provinces of El Collao, Chucuito, and Puno, in the far south-east of Peru (Figure 1). The study section lies between 16°05'30.2" S, 69°37'56.3" W and 15°59'58.4" S, 69°26'37.9", on the right and left banks of the Ilave River, corresponding to the lower course of the Ilave River up to its mouth at Lake Titicaca, which is characterised by a low longitudinal gradient and a meandering channel, for which an overflow of the river waters would be catastrophic.

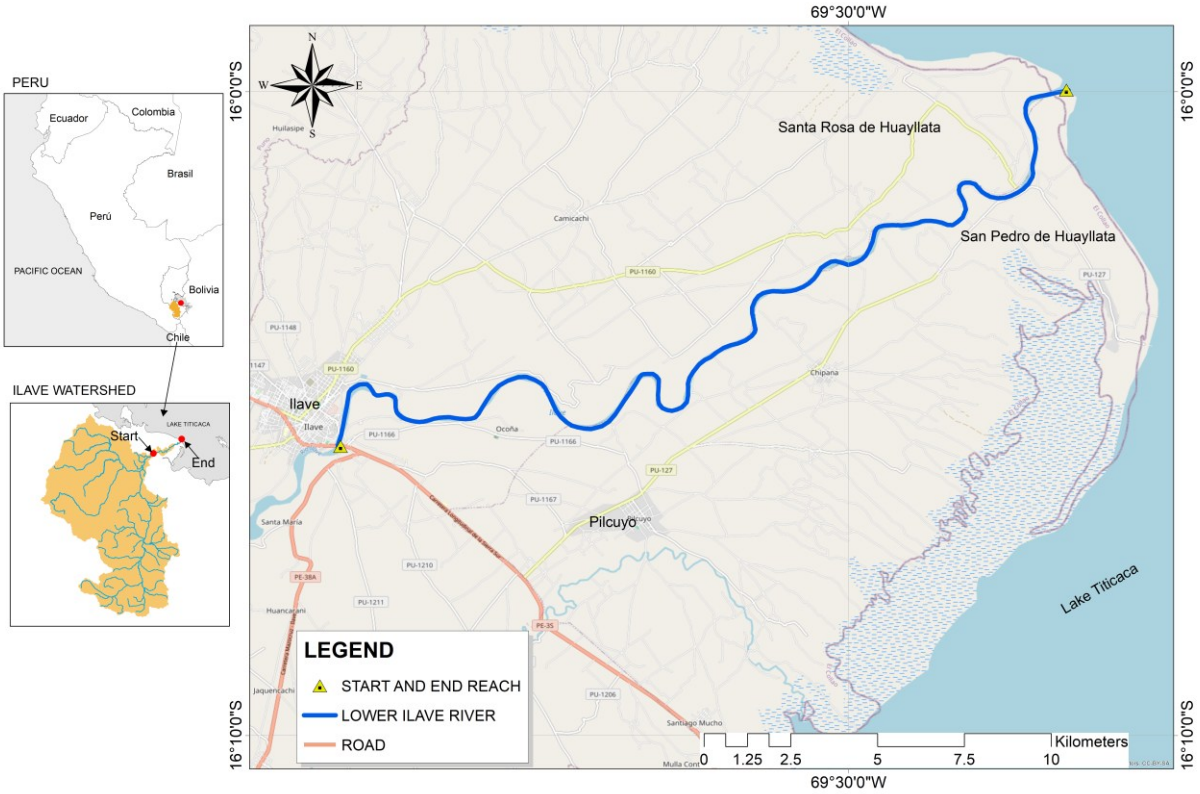

Fig. 1. Location of the section of the Ilave River under study

The damage has affected 1,950 families, representing a population of 7,247 people; in terms of housing, 21,247 homes were affected, of which 647 were on the verge of collapsing [20]. In terms of crops, the damage affected a total of 3,368.06 hectares, whilst in the livestock sector, losses amounted to 3,384 sheep. As for infrastructure in the education sector, 15 pre-school, primary, and secondary schools were affected; in terms of roads, damage extended over 61 km in the district of Pilcuyo.

With regard to the damage caused in the district of Pilcuyo by the flooding of the Ilave River (right bank), the total cost has been estimated at S/ 23,243,423.04, covering damage to the population, housing, agriculture, and infrastructure.

Lake Titicaca provides the reference level for the river's flow. It is considered unstable due to its sensitivity to fluctuations in water levels, which are characterised by periods of heavy rainfall and drought. This has led to the accumulation of alluvial deposits, as evidenced by a small island at the river's mouth into the lake and sediment bars in various sections of the Ilave River.

2.2 Design of the dykes

In order to implement river defences, the issues affecting the various sections of the river under study were first identified; namely the absence of dykes, dykes of insufficient height, dykes constructed with inappropriate materials and suffering from excessive seepage, bank erosion on curved sections, sedimentation on other sections, and flooding of agricultural land, homes and public infrastructure (Figure 2a). Accordingly, the main ways of mitigating the problem are proposed (Figure 2b) for typical rivers near Lake Titicaca.

The proposed dykes were designed to channel the river on both banks of the Ilave from the community of Ocoña to the mouth of the Ilave (San Pedro de Huayllata), based on the geomorphological assessment findings. This sector is characterised by low terraces and uneven ground ('unconsolidated' soils), which cause flooding and lateral erosion, respectively, due to the Ilave River's high water levels and agricultural land use. Consequently, the breakwater protection sections are located within the main river channel, but the embankments are situated away from the main channel (Figure 2b). They have a trapezoidal shape with a crest width, upstream and downstream slopes, and a cut-off trench.

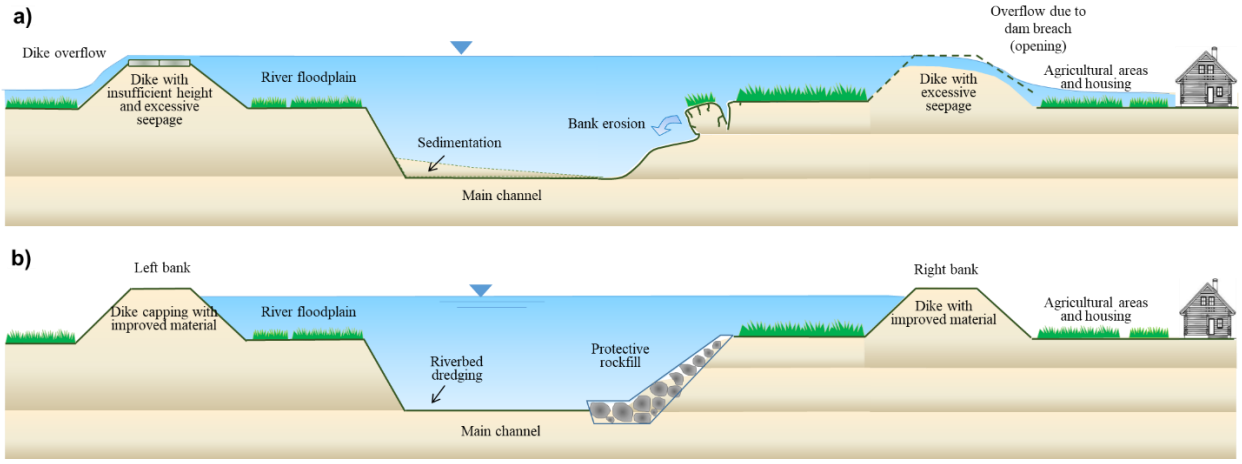

Fig. 2. Diagram a) Flooding issues and river dykes in the lower highlands b) A possible solution to the problem

2.3 Hydrology and hydraulics

The study area was identified as the Ilave River basin, extending from the watershed to its mouth at Lake Titicaca; as the source of the maximum discharges, covering an area of 7,705 km², up to the Ilave bridge station; and the section where the river defences are located (24 km), situated between the Ilave River bridge (junction with the Puno-Ilave-Juli-Desaguadero road) and the point where the Ilave River flows into the lake.

The geomorphological characterisation of the Ilave river basin and, in particular, the analysis of its response to rainfall (response: slow, moderate and rapid, such as floods and high water levels), and based in particular on two parameters (the compactness coefficient, $K_{c\ Ilave} = 1.55$, and the drainage density, $D_{d\ Ilave} = 0.30$), the Ilave river basin would have a 'slow to moderate' response to rainfall [21].

The analysis of maximum river flows, based on daily maximum flow records for the period 1960–2016, was used to determine design peak flows for different return periods (Table 1), which served as the basis for the hydraulic simulation.

Tab. 1. Maximum instantaneous design flow rates

Return period (years)	Maximum instantaneous flow (m^3/s)
2	384
5	645
10	817
20	983
50	1200
100	1360
200	1520
500	1730
1000	1890

Cross-sections of the study section were obtained by conducting bathymetric surveys of the river channel at 50-metre intervals using GPS and a total station during the low-water season. The topographical data for the section of the Ilave River under study, from its mouth at Lake Titicaca and upstream, covered a length of 25.5 km, comprising 102 topographical sections (T 1: 0+000 km to T 102: 25+500 km); in this case, the 0+000 kilometer mark corresponds to the river's entry into the lake.

The Manning roughness coefficient for the section of the River Ilave under study was determined using field data and the methodology proposed by Cowan [22,23], roughness values of n = 0.030 and n = 0.040 were obtained for the main channel and the secondary channel, respectively.

The gradually varying flow equation used by HEC-RAS is solved using the standard step method for natural watercourses. The water depths or hydraulic levels reached during the modelled flood events were used to calibrate and validate the model.

2.4 Geotechnical parameters and failure mechanism

2.4.1 Material properties for slope stability and seepage analysis

The material parameters for the foundation and the embankment body, namely unit weight (γ), saturated unit weight (γsat), cohesion (c) and angle of internal friction (ϕ) were obtained from standard laboratory tests used for slope stability analysis and are shown in Table 2.

Tab. 2. Material parameters of the foundation and body of the levee

Material Type	γ_d (kN/m^3)	γ_{sat} (kN/m^3)	c (kPa)	ϕ (°)	c' (kPa)	ϕ' (°)	K (m/s)
1. Foundations	16	19	15	22	0	30	1E-03
2. Dike	17	20	45	15	2	28	1E-06
3. Filter	16	18	0	33	0	33	1E-04

Furthermore, rock mechanics plays a role in determining the quality of the rock for riprap works on the river's downstream bank, specifically for limestone (Ocoña Quarry) and other rocks found in the vicinity.

2.4.2 Geometric cross-section of the dyke

Based on the natural cross-section of the terrain, the typical cross-section of the embankment is superimposed onto the natural terrain on both banks of the river; the crest elevations of the embankment have been determined by considering a maximum instantaneous flow with a 50-year return period. Two main criteria were taken into account when selecting the optimal cross-section of the embankment:

(1) Cost and

(2) Compliance with the minimum safety factor (SF) for the critical condition to which the embankment will be exposed (see Table 4).

Given that the channelisation has variable heights ranging from 2 to 5 m (Figure 3), the analysis aims to determine the minimum cross-section for different embankment heights until the calculated SF corresponds to the permissible SF.

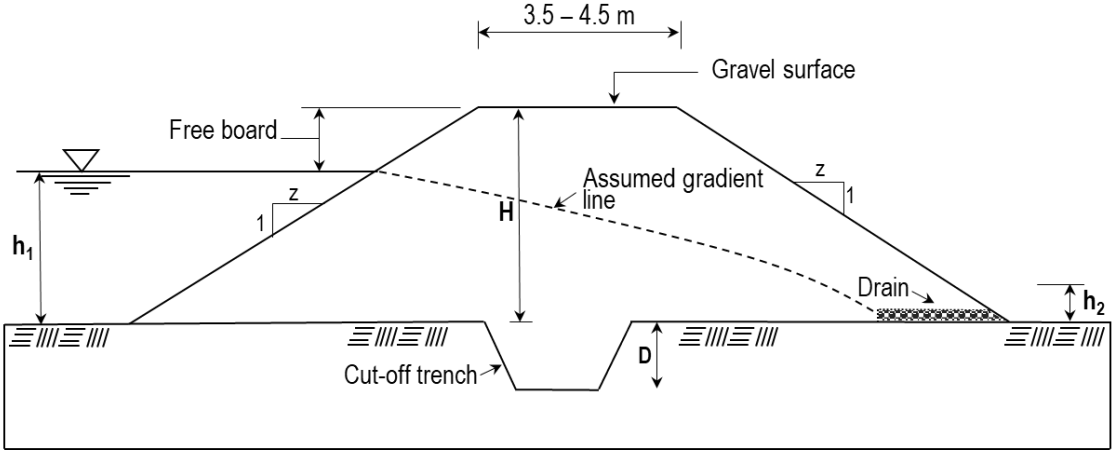

Fig. 3. Diagram of a typical cross-section under analysis

2.4.3. Slope stability analysis

A slope stability analysis was conducted on the Ilave River channelisation embankments to determine the optimal geometric cross-section for this structure.

Overall slope stability is usually assessed using an indicator known as the safety factor, or macro-stability, and has been described in detail by various authors [24,25]. The safety factor, calculated using the modified limit equilibrium method for a circular failure surface and analysed using segments, is expressed by equation (1).

$$\boldsymbol{FS} = \frac{\tau_f}{\tau_d} \quad (1)$$

$\tau_f = c' + (\sigma_n - u)tg\phi'$ = shear strength of the soil

$\tau_d = W sen\ \alpha$ = actuating shear force

Donde: c' = effective cohesion

$\sigma_n - u$ = net normal stress

W = weight of the ground due to gravity

The safety factors against sliding were calculated using the material properties to be used in the construction of the embankments. The methodology employed was Bishop's method, which relates soil strength to the shear stress required to maintain limit equilibrium [26,27]. The relative slope stability calculations were carried out using the SLOPE/W geotechnical software package, which is widely recognised for its reliability. This has enabled a detailed analysis of a wide variety of geometric cross-sections and failure configurations until a minimum safety factor was obtained.

2.4.4 Minimum safety factors for the cases analysed

The failure mechanisms in earth dams are mainly due to overtopping, internal erosion, external erosion, rotational failure, operational failure, and impact [28]. For the case study, a failure mechanism has been assumed for both wet and dry conditions, with seismic effects occurring both upstream and downstream. The analysis was carried out for the post-construction condition (dry conditions) and for constant seepage (the most unfavourable condition).

For the various sections of the dam, a slope stability analysis was conducted, accounting for the following scenarios.

- Upstream slope: (i) Analysis at the end of construction without an earthquake (ii) Analysis at the end of construction with an earthquake (iii) Analysis with constant seepage without an earthquake.
- Downstream slope: (iv) Analysis at the end of construction without an earthquake (v) Analysis at the end of construction with an earthquake. (vi) Analysis with constant seepage without an earthquake

For our analysis of slope stability under seismic loading, a horizontal seismic coefficient of 0.12g has been used.

The minimum safety factors required are shown in Table 4, in accordance with the US Corps of Engineers [29].

Tab. 3. Minimum safety factors for levee slope stability

Type of slope	Applicable stability conditions and required safety factors			
	End of construction	Long-term (constant infiltration)	Rapid drawdown [a]	Earthquake [b]
New levees	1.3	1.4	1.0 to 1.2	(see below)
Existing levees	--	1.4[c]	1.0 to 1.2	(see below)
Other embankments and levees	1.3[e,f]	1.4[c]	1.0 to 1.2[f]	(see below)

[a] Rapid drawdown analysis. S. F. = 1.0 applies to reservoir levels prior to drawdown under conditions where it is unlikely that these water levels will persist for prolonged periods prior to drawdown. S. F. = 1.2 applies to the reserve level, which is likely to persist for prolonged periods prior to drawdown.

[b] Please refer to ER 1110-2-1806 for guidance; this is a manual for seismic stability analysis.

[c] For existing slopes where landslides or significant deformations have previously occurred and subsequent analyses have been carried out to determine the design shear strengths, lower safety factors may be used. In such cases, probabilistic analyses may be useful in supporting the use of lower safety factors for the design.

2.4.5 Analysis of seepage and the risk of piping

An analysis of seepage through the dam body and its foundation was carried out for the condition of the dam's maximum cross-section and foundation material subject to the pipe-lining process.

The analysis was based on determining the flow network beneath the foundation under maximum hydraulic load. The flow network was solved using the GEOSLOPE SEEP/W software, which is based on solving Laplace's equation using the finite element method.

The flow network through the foundation for the maximum section of the embankment was determined for the following conditions:

Case 1. Embankment with a homogeneous cross-section without a drain at the foot of the downstream slope.

Case 2. Embankment with a homogeneous cross-section, including a drain at the foot of the downstream slope.

Case 3. Dike with a homogeneous cross-section, including a drain at the foot of the downstream slope and a 2 m deep cutting trench.

Piping is defined as the movement of foundation material caused by the rate of seepage. Tubing generally occurs when the seepage pressure at any point in the foundation is greater than the saturated unit weight of the soil above that point. To determine the seepage pressure, the safety factor against tubing was calculated using equation (2) [24].

$$\boldsymbol{FS_p = \frac{\gamma_{sat}}{\gamma_w}\frac{D}{h_f}} \quad (2)$$

Where:

γ_{sat} = the saturated unit weight of the foundation material

γ_w = specific weight of water

D = Distance between the foundation level and a point below it.

h_f = loss of friction between the point of analysis and the foundation surface

Where there is a drain at the foot of the slope (as is the case in this study), the formula to be used for the safety factor for the piping is:

$$\boldsymbol{FS_p = \frac{\frac{D\gamma_{sat}}{\gamma_w} + \frac{\gamma_{drain}}{\gamma_w}}{h_f}} \quad (3)$$

Where:

γ_{drain} = Saturated specific weight of the drain

The recommended safety factor values range from 4 to 10. The higher value is generally used when the characteristics of the foundation are uncertain.

2.5 Infrastructure resilience

Two key indicators for assessing the resilience of embankment structures are slope stability and seepage [30].

This study has primarily examined the various flow rates in the River Ilave, specifically the events of 3 March 1986, 20 February 2001, 18 January 2006, and 14 February 2020, during which extraordinary peak flows occurred, leading to flooding and damage in the area. These events provided a unique opportunity to assess the resilience of the dykes. Furthermore, a field survey was conducted on selected sections of the constructed dykes.

Resilience involves an iterative process of planning for future stressors or disturbances, resistance to damage, recovery and adaptation in order to better respond to future adverse scenarios or disturbances; therefore, during the preparation of the design study, the basic design requirements must be met, focusing on a) geomorphology and hydraulics, b) geotechnics and structure, and c) resilience and risk. In this case, emphasis has been placed on the embankment slope stability.

3. Results

3.1 Hydraulic modelling

The hydraulic simulation for the 24 km reach between 1+250 and 25+250 km, comprising 97 simulation sections: Si-Hi 1 to Si-Hi 97, from downstream to upstream; the simulated discharge values were: Qmax-inst-20 = 983 m³/s, Qmax-inst-50 = 1200 m³/s, and Qmax-inst-100 = 1360 m³/s.

Table 4 shows the water levels reached; based on these, the corresponding crest levels of the embankments on both the left and right banks were determined.

Tab. 4. Hydraulic levels and adopted crown elevations

Section of the river	Station (km)	Water surface q_{100} (m.a.s.l.)	Levee elevation (m.a.s.l.)	Slope of levee
	20+750	3819.56	3819.76	
Reach 1				0.00026
	18+250	3818.92	3819.11	
Reach 2				0.00036
	17+250	3818.55	3818.75	
Reach 3				0.00041
	13+250	3816.92	3817.12	
Reach 4				0.00023
	08+750	3815.88	3816.08	
Reach 5				0.00038
	05+500	3814.53	3814.85	
Reach 6				0.00210
	05+000	3813.60	3813.80	
Reach 7				0.00048
	02+000	3812.16	3812.36	
Reach 8				0.00137
	01+250	3811.13	3811.33	

3.2 Slope stability

Table 5 summarises the values obtained from the stability analysis for a 4-metre-high embankment with upstream slopes of 1.5:1 and downstream slopes of 1.75:1. For this analysis, the critical condition has been taken to be that of constant seepage without seismic activity. Note that, for the final construction condition with seismic loading, the SF values exceed the minimum requirement.

Tab. 5. Safety factor based on analysis

Analysis	Condition	S.F. of the analysis	Minimum S.F.
Upstream 1.5 : 1	1. End of construction without an earthquake	3.26	1.4
	2. End of construction with an earthquake	2.46	1.0
	3. Constant seepage without an earthquake	1.26	1.5
Downstream 1.75 : 1	1. End of construction without an earthquake	3.66	1.4
	2. End of construction with an earthquake	2.38	1.0
	3. Constant seepage without an earthquake	1.34	1.5

As the section analysed above did not meet the critical condition, a calculation was carried out for this section at a height of 2 m, which, in this case, met the requirements.

Table 6 presents the results of the analysis for embankments of different heights and cross-sections under the critical condition.

Tab. 6. Results of slope stability analysis for critical conditions

Dike type	Height of the dyke	Section Upstream; Downstream	S.F. analysis Upstream; Downstream	S.F. Minimum
I	<2m	1:1.5 ; 1:1.75	1.45 ; 1.54	1.5
II	2-3m	1:1.75 ; 1:1.75	1.42 ; 1.47	1.5
III	3-4m	1:1.75 ; 1:2.00	1.47 ; 1.41	1.5
IV	4-5m	1:2.00 ; 1:2.25	1.56 ; 1.52	1.5

Figure 4a shows the results of the stability analysis for a 5-metre-high downstream embankment, whilst Figure 4b shows a screenshot of the seepage analysis for the same case.

It is accepted that the safety factor (SF) values may in some cases be slightly lower than the minimum SF, mainly because the stability analysis assumes that the stresses and the geometry of the slope are two-dimensional; however, actual landslides occur not in two, but in three dimensions, with three-dimensional safety factors being greater than those calculated on the basis of a two-dimensional analysis, due to the stabilising interaction of the material adjacent to the potential landslide section.

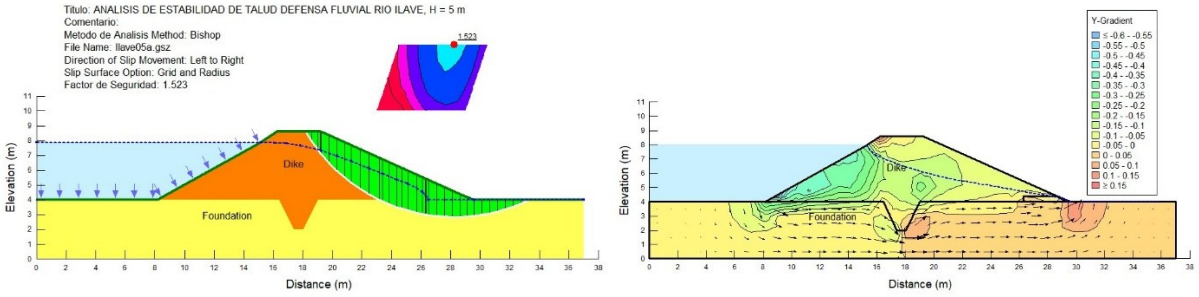

Fig. 4. Output from the geotechnical software programme (a) SLOPE/W for slope stability (b) SEEP/W for seepage

3.3 Filtration analysis results

Table 7 shows the piping safety factor results for each analysed case.

Tab. 7. Results of analysis for critical condition

Case	D(m)	(H1 – H2)(m)	SF
1	0.60	0.45	2.50
2	1.50	0.45	10.5
3	1.60	0.45	11.6

Cases 2 and 3 show that the safety factors for the pipe installation meet the recommended safety factor requirement. Case 3 presents an analysis in which heavy, sandy material is present as foundation material to a depth of less than 1.50 m.

Fig. 5. a) Section with sediment bars b) Ilave River floodplain c) Cacuce sand extraction site d) Urban area along the Ilave River

During the field survey of the constructed sections of the river defense, it was observed that the sections where flooding has occurred due to high water levels depend on various factors; many have a wide floodplain which presumably acts as a flow buffer (Figure 5b), other sections, which have rock-filled revetments as protection, mainly on curved sections, have suffered general scouring of the riverbed (Figure 5a). The extensive sections in the lower zone where aggregates for concrete are quarried are causing significant geomorphological changes to the riverbed and banks; they also create vehicle access roads that may eventually lead to flooding (Figure 5c). Meanwhile, the urban section in the town of Ilave is protected by rockfill; although it causes concern during every rainy season, it has not suffered major damage in recent years (Figure 5d).

4. Discussion

The section of the Ilave River analysed is typical of the Altiplano near its mouth at Lake Titicaca; it features river defenses that are largely constructed, with some sections also made of local material, riprap, and extensive floodplains. In general, no issues relating to slope stability or seepage are apparent. There are signs of paths leading to the river for animals to drink, as well as several sections of vehicle access roads used for the extraction of aggregates for concrete, which alter the stability and height of the embankments. Considerations regarding the temporary extraction of aggregates from the riverbanks have also altered the landscape and the geomorphology of the river channel [31,32].

It is clear that the design and construction of the dykes were properly supervised and managed in order to control seepage and maintain the stability of the dykes. Public perception of the dykes is positive in terms of ensuring safety against flooding, given their proximity to residential areas, economic infrastructure, and agricultural land [33]. However, as the riverbanks continue to deteriorate and erode along the study section and elsewhere, due to rising river levels or other human-induced factors, the protection offered by these riparian barriers is also diminishing.

An accurate geotechnical classification of embankment cores and sediments is essential, as, in general, the use of clay soils for embankment construction appears to provide greater strength, followed by sand, whilst silt embankments tend to suffer the most damage [34]. However, care must be taken to avoid constructing dykes from purely silty soils, as they are more vulnerable to surface damage.

Perhaps the most important principle regarding the resilience of river embankments is the need to reassess after each stressor or disturbance. Resilience can only be achieved through an iterative process of planning, assessment, and adaptation. Whether it is a major flood or an earthquake, design guidelines must be reassessed after every extreme event, based on the available data and on-site damage assessments [35], as more extreme events are expected. Regulations and design processes that help to improve resilience must be incorporated into the updated standards, whilst factors that lead to increased damage must also be addressed in these revisions [36]. Consequently, initial efforts have been made to assess the effectiveness of the designs implemented and their in-situ performance, using safety factors, material types, and the current condition of the dykes as indicators of resilience for comparison following a future critical event [37].

Sudden rises in river water levels and hydraulic engineering provide the means to plan for future events, as adherence to these

guidelines during the design of dykes increases resilience to the next event; consequently, more resilient dykes help to increase the resilience of the river system as a whole [34].

Beyond structural issues, it is expected that the principles of resilience will need to be incorporated into dam and embankment safety programmes, which will require significant changes to the safety culture [38], both in the design and construction phases [39].

It is also advisable that conservation measures take into account nature-based solutions [40], an approach that in Peru has been referred to as natural infrastructure.

5. Conclusion

Our findings regarding the hydraulic and stability analysis of embankment slopes along the River Ilave provide crucial information for the design of resilient flood defences near lake deltas. It is worth noting that the study reveals that 2-metre-high dykes, with upstream slopes of 1.5:1 and downstream slopes of 1.75:1, meet critical stability requirements under constant seepage conditions, thereby addressing the deficiency identified in flood defence strategies.

With regard to alignment and topography, it is advisable to move away from the riverbank in order to reduce the height of the embankments. A toe drain should be installed when the embankment is 3 metres or higher. Software tools that incorporate calculations for both the safety factor against sliding and the construction of flow networks are essential. To prevent high seepage rates beneath the foundation, a 2-metre-deep trench should be excavated and backfilled with embankment material when the sand foundation (SP) is less than 1.50 metres deep.

In addition, during the operation, samples should be taken of the materials carried by the river, and continuous monitoring should be carried out along the embankments, which will aid a better understanding of the embankment's composition and help mitigate the risk of piping. For sections not yet constructed with the specified material, construction supervision and coordination protocols must be applied to mitigate the risks of seepage and instability during embankment operation. Controlled and compacted fill must be used to construct the embankments. Furthermore, the water levels reached by the River Ilave must be taken into account when determining the crest levels of the channelisation walls or embankments.

Future research should expand the scope of this study to include long-term monitoring of dyke performance across various environmental conditions. Such research could explore integrating adaptive management strategies that account for dynamic changes in hydrological patterns and sediment transport processes. Furthermore, subsequent studies could examine the socio-economic impacts of dyke construction and maintenance to provide a holistic understanding of the benefits and challenges associated with resilient river defenses.

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