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Riskcoast: A South-European approach for coastal landslide hazard: presentation and results

M Gasc-Barbier¹, Y Thiery², C Garnier², L Raveneau¹, S Bernardie² and A Chanal¹

¹Cerema Aix-en-Provence, France

²BRGM Orléans, France

³BRGM Bordeaux, France

Muriel.gasc@cerema.fr

Abstract. RISKCOAST is a European project, co-funded by the South-West European (SudOE) Interreg V programme (<https://riskcoast.eu>), which aims to develop tools to prevent and manage coastal geological risks related to global warming: land movements mainly, but also other phenomena such as the evolution of water tables. The aim of this project is to study geological risks in coastal areas related to climate change, with a focus on improving the coordination and effectiveness of means of prevention, disaster management and rehabilitation of disaster areas. After a presentation of the whole project, we will focus on a specific site in the French Basque coast where a landslide impacts a very touristic area. An hydrogeomechanical model of the landslide is realized with FLAC3D and a parametric study is proposed to determine the most important parameters, and to define possible safety factor game value.

1. Introduction

The coastline in general, and particularly in South-West Europe, is highly vulnerable to the effects of climate change [1]. These are substantially modified natural spaces due to significant urban pressure, where marine and terrestrial processes interact. Most local economies are linked to tourism, while, at the same time, the increase in the frequency of extreme weather events leads to an increase in geological risks, which can have a significant impact (direct and indirect costs, social and economic impact).

Riskcoast is a project funded by the European fund Interreg SudOE (South-West Europe) which promotes innovation to deal with various hazards: landslides, erosion and soil loss after torrential events, erosion of the foreshore and retreat of deltas. Coastal processes are very complex and can have cascading effects that are difficult to predict. Riskcoast aims to take into account the full chain of risks that threaten the coast, from the knowledge of hazards to the proposal of natural post-crisis rehabilitation measures. Risk management in the broad sense involves, depending on the territory, a very large number of institutions. Riskcoast will propose to develop strategies for better coordinated and effective risk management, by establishing and encouraging a transnational cooperation network, by facilitating the development of innovative tools, methodologies and solutions to build a common front against coastal risks. This type of cooperation must lead to more effective risk management.

The products generated will support the three phases of emergency management with: (i) prevention (ii) response and (iii) rehabilitation and will be validated during two participatory exercises. The new tools, at the interface between the scientific community and civil society, will adapt to the requirements

of the parties involved in risk management and will be based on satellite and airborne techniques, advanced numerical modelling, and laboratory experiments, supplemented, of course, by field missions.

2. Presentation of Riskcoast Project

Riskcoast started in November 2019 and will end in October 2022. It is conducted with Spanish scientists (CTTC, Telecommunications Centre of Catalonia, IGME, Geological and Mining Institute of Spain, UGR, University of Granada, Asitec, a Spanish SME), Portuguese scientists from IGOT (Geography Institute of Lisbon) and French scientists (BRGM and Cerema). Various partners from the territories concerned by the project are also involved as end-users, mainly representatives of different institutions in the territories concerned. The aim of this project is to study geological risks in coastal areas related to climate change, with a focus on improving the coordination and effectiveness of means of prevention, disaster management and rehabilitation of disaster areas. The whole project is presented here with the initial goals and the actual achievements. It is presented by work packages (WP). All deliverables can be found on Riskcoast website: <https://riskcoast.eu/en/results/>.

2.1. WP1: Strengths and Weaknesses in Geological Risk Management

WP1 is dedicated to the identification of different geological hazards in coastal SUDOE regions, with an emphasis on identifying existing gaps and differences between the different actors involved. The first action is to share information between Sudoec countries by drawing up a map of the major events that occurred in the last ten years, with a detailed description of them, including the damages generated. For instance, in Spain, a total of 74 extreme events were recorded in the inventory resulted in 111 deaths and 44 injuries. In terms of economic losses, a total of €827.9 million was achieved, distributed mainly on the coast of Andalusia, Ceuta and Melilla with some €500 million in losses, followed by the Levantine Mediterranean coast with €312.2 million. The synthetic resulting map can be found on riskcoast website: [results/ products/producto-1-2-mapa-eventos-sudoe](https://riskcoast.eu/en/results/products/producto-1-2-mapa-eventos-sudoe).

For each region and for each type of risk, the current legislation on including natural hazards in urban and territorial planning, emergency action protocols, including actors involved and coordination, thanks to questionnaires specifically designed for Riskcoast. About 50 end users of the Sudoec region were interviewed.

A single report synthesizing the three countries results is delivered. It presents the management of coastal geological hazards in the Sudoec space, the participants of the analysis and cases reported, identified fortresses, identified weaknesses and action to be taken. The deliverable, in Spanish, can be found in the website [deliverables/1-3-1-informe fortalezas y debilidades en la gestion de riesgos costeros](https://riskcoast.eu/en/results/deliverables/1-3-1-informe-fortalezas-y-debilidades-en-la-gestion-de-riesgos-costeros).

2.2. WP2: Risk Mapping for Urban and Territorial Planning

The objective of this WP is to develop a set of useful maps for the steps of risk prevention and management. Taking geological hazards into account in urban and territorial planning is of major importance in order to avoid urban planning and the development of infrastructure in areas at risk. Homogenizing the contents, scales, legends, etc. of hazards, vulnerability, risk and exposed elements maps is a task that Riskcoast deals with in order to create useful mapping tools, in language that is understandable to managers and in which all elements of the territory are collected. Unfortunately, Riskcoast was unable to propose maps in the whole Sudoec area, but only on specific areas, where local authorities were involved in deep. In the area of Majorca and Granada in Spain, Lisboa in Portugal, and in the Basque coast in France, inventories (maps of landslides and assessment of damage), maps of landslides susceptibility, maps of exposed elements are produced. Again, all technical reports can be found on Riskcoast website.

2.3. WP3: Development of management tools based on integrated study of river and coastal dynamics

This WP is focused on the identification and the analysis of the hydrological and hydraulic processes involved in coastal risk from a holistic perspective. This approach includes the analysis of the basin

system and its response to the different climate scenarios, the interaction of water flows and sediment with existing infrastructure along the river system, the implications of these processes for coastal dynamics and the effects of different extreme scenarios on coastal processes. The work is focused on the Guadalfeo Basin, located in the south of the province of Granada and characterized by being a mountainous watershed, combines spatial and temporal variability of hydrometeorological agents and a dynamic rainfall. To get more information on that WP, please see [2, 3, 4].

2.4. WP4: Tools to support early warning systems for different types of risk and coastal models

This WP aims to adapt existing tools or develop new ones, if necessary, based on remote sensing data (satellite/drone/land) that can contribute to early warning systems in the face of different risks and types of coasts. The aim is to provide an integrated solution capable of absorbing data from different sensors and generating maps that can be used to support prevention and warning against geological hazards.

Mondoni [5] presents a general review on the utilization of SAR to monitor landslide and ground movements. Reyes-Carmona [6, 7] present the case of the El Arrecife Landslide, located on a slope of the Rules Reservoir (Southern Spain), as an example of geological and motion data integration for elaborating a preliminary hazard assessment, based on Insar data. Gallo, [8] propose the integration of UAV-Based Photogrammetry and 3D Modelling for Rockfall Hazard Assessment, based on the Cárcavos Case.

2.5. WP5: Crisis Management Exercise

This WP is dedicated to the realization of two tabletop exercises, one in France and one in Spain, dedicated to the crisis management. Tools developed by the other WP, and more specifically, WP4 will be tested during the tabletop exercises. The Spanish one, in Majorca (Balears, Spain) will occur in April 2022 and the French one, in the Basque coast, in May 2022. The objective is to mobilize: (i) the scientific partners of the project with local expertise in order to place them in a position of scientific support for risk management, and (ii) risk management and emergency management practitioners who are able to use (directly or through scientists) the tools made available by the project and also to learn from the use of the tools. The practitioners will help to analyse the potential contribution of the tools, help, if needed to adapt them. Reciprocally, practitioners will have access to new tools that could be useful to risk and crisis management.

2.6. WP6: Natural rehabilitation and preventive measures for adaptation to climate change

It is planned to draw up a catalogue of natural rehabilitation measures, classifying them as measures for adaptation to climate change, mitigation, prevention or rehabilitation of damaged or affected areas. Each of these solutions or measures will be considered as a standard solution, designed for any location and any risk.

3. French Area – Questions and Models

In the framework of WP4 and WP5, the modelization of a identified landslide was decided. The purpose of this modelling is dual: on the one hand, to compare deformation obtained with remote sensing technique developed in WP4 and deformation estimated by numerical modelling, on the other hand to obtain, if possible, limit values of thresholds that would trigger emergency. Thus, it was decided to work on the real morphology of a site and to realize a sensibility analysis of the soils and rocks properties, in order to consider their variability and uncertainty.

3.1. Presentation of the Site Chosen for Numerical Simulations

Landslides affect a large part of the Basque coast: at least 79 landslides along the 6 km coast are identified. Infrastructure (road, pipes...) are concerned and, moreover, it has been estimated that up to 40 shops and 529 houses or building will be impacted by 2043.

We choose a representative landslide in Bidart (Figure 1). Bidart as well as the whole Basque coast is a very touristic area. This landslide affects parking places, gas pipes, and the road that is the only

access by car to the beach emergency station. This area is studied by the BRGM since 2018, in connection with the municipality. Figure 1A presents the location of Bidart, the area surrounded in red is the site under study. Figure 1B is an overview of the area affected by the landslide where road and parking places can be localized and affected by recent cracks (Figure 1C, 1D, 1E).

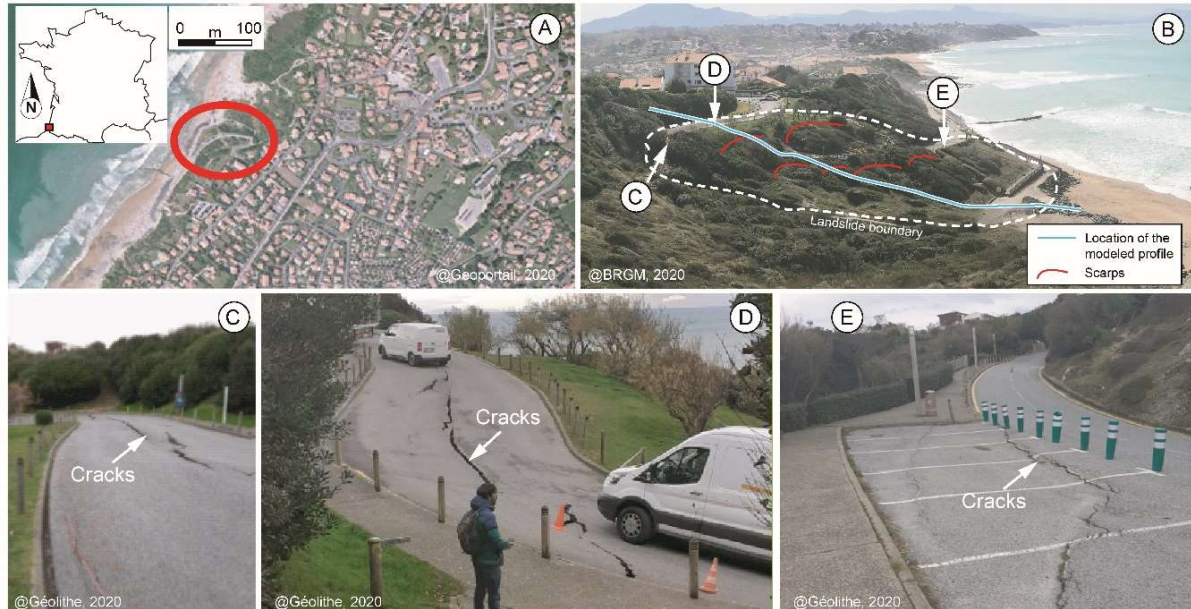


Figure 1. Location and view of the landslide. A Location. B. Boundary of the landslide and location on the slope. C, D, E. Cracks (year: 2020)

As part of the geotechnical diagnostic mission carried out for the municipality of Bidart, surveys were carried out by an external design office. 2D geological sections have been proposed and one of them, the 2D geological section containing the most sub-layers was chosen, in order to test the most important complexity. The soil and rock layers are described as follows:

- less than 1 m wide alluvial layer at the top of the slope (called further ‘alluvions’) and at the bottom of the slope, in order to protect the beach from the sea, riprap were placed,
- sandy embankments and road-level facilities (called ‘backfilled’),
- 1 to 3 m of clay, sandy and gravel slope deposits containing flysch debris (called ‘clay marl with gravel’),
- a large amount of flysch alternating limestone banks and grey clay marls (called ‘flysch’),
- a soft clay marl level in flysch between 8 and 10.5 m deep (called ‘clay marl’).

Considering the on-filed observations and such 2D geological model, slip failure explaining the landslide is possible on two levels: at the interface with the flysch roof and in the clay layer marl. The geotechnical diagnostic mission only gave partially physical and mechanical properties of the terrain encountered. The other part was proposed, considering our knowledge of the area existing literature [9]. As no information about failure criteria exists, a Mohr-Coulomb failure criterion is chosen. Table 1 presents the values used in the study.

Table 1. Mechanical and hydraulic properties of the soil with γ (kN/m³), specific weight, E (GPa), Young Modulus, ν (-), Poisson's ration, C (kPa), cohesion and ϕ (°), friction angle.

rock	γ (kN/m ³)	E (GPa)	ν (-)	C' (kPa)	ϕ' (°)
Flysch	17.9	26	0.31	10	21.5
Clay marl with gravels	20	26	0.28	25	20
Clay marl	15	27	0.25	15	17
Backfill	19	0.005	0.25	19	15
Riprap	22	1	0.25	22	03
Alluvions	16	0.05	0.3	16	33
Hydraulic properties	γ (kN/m ³)	k (m/s)	K _f (GPa)	e (-)	
Water	10		2.2		
Clay rocks		10 ⁻⁹		0.4	
Flysch		10 ⁻⁹		0.2	

3.2. Software

FLAC3D (Fast Lagrangian Analysis of Continua in three dimensions) is a well-known 3D numerical modelling software developed by Itasca (www.itascacg.com) for geotechnical analyses of soil, rock, groundwater, buildings and infrastructure, and ground support. FLAC3D utilizes an explicit finite volume formulation and proposes a factor of safety prediction based on the Shear-Strength Reduction (SSR) method. The SSR method consists in gradually reducing the shear strength of the material to bring the potentially unstable slope to a state of limiting equilibrium. If the Mohr-Coulomb failure criterion is used (C: cohesion, ϕ : friction angle), the safety factor F is defined according to the equations:

$$C^{test} = \frac{1}{F^{test}} C \quad et \quad \phi^{test} = \arctan\left(\frac{1}{F^{test}} \tan \phi\right)$$

Series of simulations are carried out from test values of the safety factor F^{test} , gradually reducing the cohesion C and the angle of friction ϕ , until slope failure occurs. A bracketing approach is used to reduce F^{test} . Details can be found on FLAC3D Theory and Background manuals [10].

3.3. Model

As part of the geotechnical mission, 2D stability calculations were computed. Thus, not to complicate comparisons or introduce variations that would be due to variations in local topography rather than to mechanical parameters, a model in pseudo-3D was realized. Thus, the third dimension is reduced and correspond to a slice. The 3D model corresponds to an extrusion of the 2D model with a thickness of one meter. The 2D model is calibrated to the geological section given by the geotechnical field survey and then enlarged to free itself from the edge effects. For example, it has been chosen to extend its size back (horizontally) by about three times and forward (in the sea) by one so that the surface drops linearly to level zero. Figure 2 shows a zoom of the model centered on the study area, where all the lithologies described above are represented. The mesh of the model is adapted to reduce the computation time: refined mesh on the study area and coarser beyond.

3.4. Choice of Parameter for the Sensitivity Analysis

The purpose of sensitivity analysis is to test the response of the model when the numerical values of part of the parameters are changed. It is decided to test the variations in cohesion and friction angle in clay marls, clay marl with gravel and flysches, because these materials are heterogenous and their characterization presents a great variability. To study the influences of the parameters, it is decided to focus on the safety factor thus, as Young's moduli, and Poisson's ratios have no influence on F, they were kept constant.

Max and mean values tested are chosen beyond reasonable values for C and ϕ in the materials considered, in order to cover a wide range of data. To make a systematic analysis and look at the influence of the parameters independently of each other, it is decided that each simulation corresponds to the variation of a single parameter. As it is more detrimental, all calculations are realized considering saturated conditions, except for flyshes where, for two calculations, a water table at the level of the bottom of the clay marl layer was also considered.

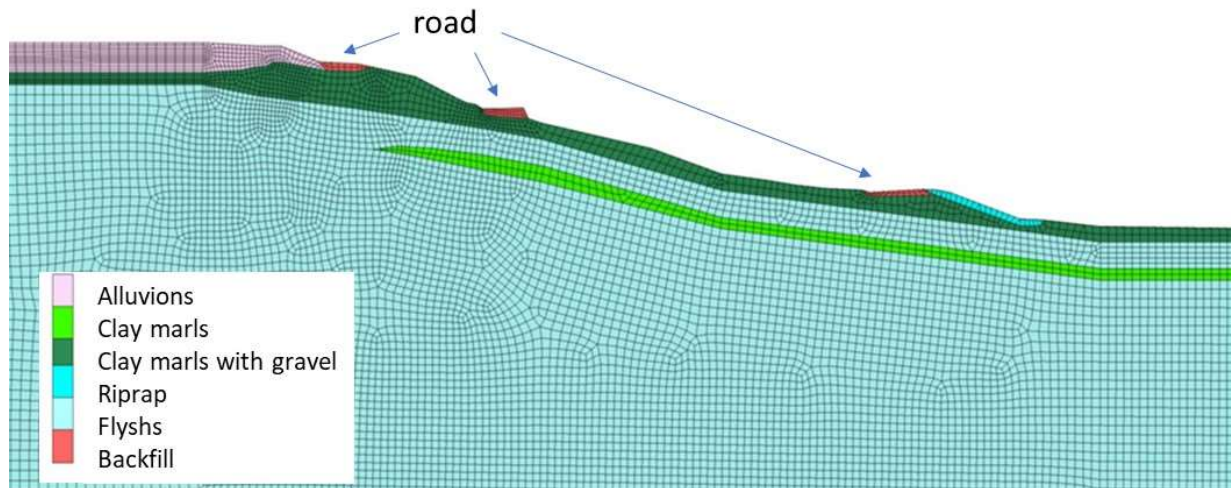


Figure 2. Cross section of the numerical model for the interest area

4. Results

4.1. Shape of the Unstable Zone

Figure 3 shows the distribution of shear stresses after the calculation of the safety factor (zoom is a bit more important than on Figure 2). It is obtained with the mechanical parameters given in Table 1. The red area on the figure is the critical area identified by the calculation, located in the flyshes, downstream under the riprap at the beach level and not on the slope where the disorders are observed on the site. This observation remains true regardless the set of parameters used in the sensitivity analyses: failure always occurs in the flyshes. The reference safety factor calculated with table 1 values is 1.09 (Figure 3), which is very slightly above 1. A value above 1 indicates that the slope is supposed to be stable but, here, as it is only very slightly above 1, the slope can be considered at the limit equilibrium.

4.2. Results of the Sensitivity Analysis

Table 2 shows the safety factor (F) values obtained by Flac3D modelling. When the Mohr – Coulomb parameters of one material evolve all the others are kept constant, corresponding to those given in table 1.

Except for 3 cases ($C'=0$, $\phi'=0$ or 10 in the clay marl with gravel and $C'=0$, $\phi'=15$ in flyshes) all computed factors of safety are above 1. This means that the slope is supposed to be stable. As mention above, failure always occurs in the flyshes but depending on the Mohr-Coulomb parameters, the shape of the critical area evolves a little.

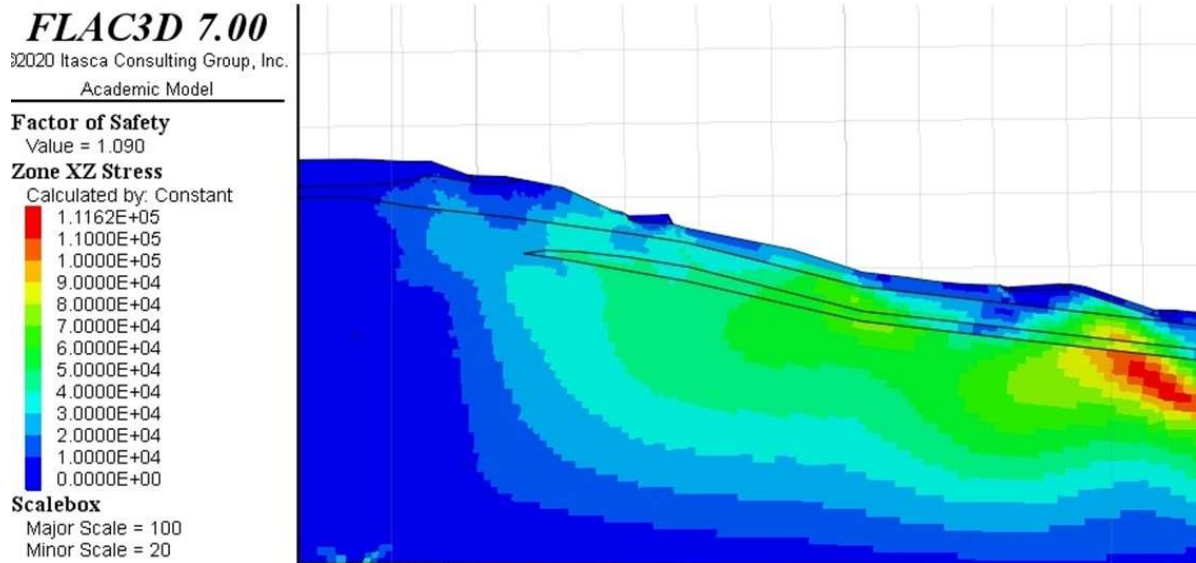


Figure 3. Factors of safety and shear stress measured in the area of interest

Table 2. Safety Factor obtain by varying Cohesion C (kPa) and friction angle ϕ ($^{\circ}$) respectively for clay marls, clay marls with gravels and flysches. The mechanical parameters of the other materials are given in table 1

Clay marls.					Clay marls with gravel					Flysches			
C'	φ'				C'	φ'				C'	φ'		
	10	15	20	25		10	20	30	40		15	21.5	27
10	1.09	1.09	1,082	1.09	0	-	-	1,074	1,066	0	0.998	1.09	1,074
15	1.1	1.07	1.09	1.09	10	1.07	1.07	1,074	1.06	0*	1,042	1.53	
20	1.1	1.07	1.09	1.08	20	1,098	1,074	1,066	1.09	5	1.03	1.09	1.08
25	1.09	1.09	1.09	1.1	30	1.09	1.09	1.08	1.1	10	1.06	1.09	1.09
30	1.11	1.09	1.09	1.09	40	1.09	1.09	1.09	1,098	15	1.09	1.09	1.09
35	1.1	1.09	1.08	1.09									
40	1.1	1.09	1,082	1.09									

* here the water level is supposed to be at the bottom of the Clay marl

4.3. Other Calculations

To be sure that the – large – weight of riprap does not influence the position of the instability, numerical modelling are also performed with riprap properties taken equal to clay marl with gravel. Neither the calculated factor of safety nor the critical area evolve significantly ($F=1.082$).

Surface displacements are also calculated with FLAC3D and were supposed to be compared with ground movements measured in WP4 with InSar data. Unfortunately, ground movements in the area were not conclusive enough to be compared and improvements are still under developments.

5. Conclusion

Riskcoast is a European project focus on risk assessment and management, of ground instabilities in the coastal area of the south-western Europe. In the framework of WP4, to improve our knowledge on material behaviour to an early warning system, a real landslide representative of those affecting the French Basque coast was modelled.

To consider the natural heterogeneity of the materials encountered and the uncertainties on the mechanical parameters, a sensitivity analysis, based on the values of the security factors calculated with Flac3D was conducted. Whatever the set of parameters tested, security factor obtained was very slightly

above or very slightly below 1. Thus, the slope can be considered at the limit equilibrium. Considering the simple Mohr-Coulomb law used, the results can be considered as correct.

Nevertheless, the model should be improved by refining the mesh to ensure that local layers are well considered. Another improvement would be to test other constitutive law, such as creep law, and finally it could be interesting to deepen the influence of variations of the water level on the stability of the slope.

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