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Evolution of the Tazones Lighthouse slope (Cantabrian coast, N Spain). Multidisciplinary monitoring between 2018 and 2020

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We thank Anonymous Referee #2 for his/her revision. We really appreciate the comments and suggestions. In the revised version of the manuscript, we have included the suggested amendments and we have clarified and explained in detail those parts that raise doubts to avoid misunderstandings. Please, check out our point-by-point answers below.

Yours faithfully,
María José Domínguez-Cuesta (on behalf of the co-authors)

Point-by-point response

GENERAL COMMENTS

I was greatly looking forward to reviewing this paper being a subject of interest and some experience to me. However, the paper is very limited in scope and has a number of failings which fall short of the standard to be published in the journal:

Response. Until now, there is a significant lack of data on the evolution of Cantabrian Coast cliffs and, particularly, in the contribution of slope instabilities to their retreat. Taking into account the Referee's comments, we have rewritten some paragraphs in order to point out that the scope of our work is to present the first results of an ongoing research about the coastal retreat focused on a cliff case study. We consider that the results have a wide scope, since the studied section is similar to the rest of the Cantabrian Jurassic coast and, therefore, the results can be extrapolated to a broader sector.
Otherwise, in the new version of the manuscript we have corrected all the errors indicated by the Referee.

1. **Limited scientific data is presented, basically several years of surface movement data, some rainfall analysis, and three joint measurements. Consequently there is insufficient site investigation to support the narrative which is somewaht speculative and confused in places. Even some of this limited data is poorly presented e.g. the joint data plotted on a steroenet is not provided.**

   Response. The results that we present are the first of an ongoing research, and we hope to can improve them in the coming years. Our paper presents two years of uninterrupted monthly monitoring of an active landslide that affects the cliff of the Tazones Lighthouse. Moreover a study of aerial photos of the previous 3 decades has been done. Thus, for the first time on the Cantabrian Jurassic coast, we have done detailed monitoring: ground techniques topographic monitoring correlated with rainfall data taken in situ and with high resolution topography data taken by UAV. We consider that our paper contribute to know how the cliffs of the Cantabrian rocky coast behave, since until now there was a significant lack on this issue. According to the Referee's comment, we have more rigorously explained the results and avoided all kind of speculation in the discussion. In the new version of the manuscript, we have also adequately detailed the bedrock structural information, which had not been sufficiently shown. Following the Referee's suggestion, we have collected more joint data and we have added a new figure with the stereographic projection of the family joints and a histogram of the joint spacing (Jv, that gives the number of discontinuities per cubic meter).

2. **The site is compared to Holderness UK which is unfortunate because this does not provide a comparative analogue to support the observations at Tazones. The two sites are formed in very different geologies, the former Quaternary soft sediments subject to high rates of cliff toe erosion and episodic rotational failures. The latter being formed in Jurassic rocks that appear controlled by bedding and structural discontinuities.**
   Response. We agree with the Referee suggestion and, related to the comparison with Holderness, we have clarified that the lithologies and structural control are very different. In the new version of the manuscript the results have also been discussed in comparison to other rocky coasts of the world.

3. **The authors present a short snap shot in time in the development of the landslide for which there is evidence of pre-failure as far back as 1984. The evolutionary setting in space and time is fundamental to understanding the causes, mechanisms and behaviour of the landslide; the authors have not done this. They could have produced a detailed geomorphological map of the coastal slopes and foreshore to set the landslide in context with the surroundings. They make no mention of the foreshore and the potential changes and contribution of erosion in the landslide development. What influence has the nearby groyne played in the exposure of the cliffs to high energy waves I wonder.**
   Response. Following the Referee's suggestion, we have added an explanation of the evolution of the cliff prior to 2018 in the Setting section of the new version of the manuscript. We also describe the characteristics of the cliff coast and its erosion. Moreover, a geomorphological map has been included in the new version of the manuscript to set the Tazones Lighthouse landslide in context with the surroundings. In addition, we have included a paragraph indicating that the coastal drift in this area comes from the West, so the groyne located east of the study cliff does not play a fundamental role.

4. **Some considerable assumptions are made without site validation i.e. no ground investigation or testing of soils has been carried out or presented. This would be an expectation for a landslide investigation.**
   Response. Following the Referee's suggestion, the characterization of the massif was carried out in the geotechnical stations where, in addition to taking structural data, an identification of the lithologies was carried out, accompanied by the maximum specialists of the Jurassic in Asturias. The degree of alteration of the massif has been revealed, which on the surface is much greater than in depth and, depending on the lithology, increases rapidly with exposure to meteorological agents. Main properties of sandstone and marl lithotypes (density, porosity, uniaxial compressive strength) have been determined, both under dry and saturated conditions. Likewise, the RMR geomechanical classification of the sandstone and shale rock mass is included.

5. **The authors are confused about the landslide mechanism and reference to Holderness. It may have helped if they had referenced international landslides classifications such as Varnes 1988; Dikau and Brunsden 1996. Also, reference to other literature on Jurassic coast landslides e.g. Lyme Regis, UK. The dominant control is the sub-horizontal bedding which forms basal shear surfaces. The vertical cracks and joints form detachment surfaces. The discussion and narrative is rather speculative and not supported by evidence with the exception of the movement and rainfall records.**
   Response. We agree with the Referee's suggestion. We consider that we had not explained well the comparative to Holderness retreat. We have introduced some clarification sentences to avoid misunderstandings related to it, complementing them with references of other parts of the world, such as the ones the Referee indicates, among others. In the new version of the manuscript, we have been rigorous in applying the terminology proposed by Varnes, as the Referee suggests. Thus, we explain in depth that the control of this movement is a planar slide on the marl bedding surface layers; the blocks that slide are individualized due to two families of very marked discontinuities in the massif that have been studied and now well described. The discussion has been rewritten in a rigorous and non-speculative way, according to the results obtained in the work, based on geological, geomorphological, geotechnical and topographic evidence.

6. **The conclusion that the landslide will evolve "without involving large volumes of material in a single episode" is simply wrong from the photo evidence, which clearly indicates potential for deep-seated landslides, which are episodic in time.**
   Response. We agree with the Referee's assessment and to avoid being speculative, we have changed the phrase focusing only on the behavior observed on the cliff during the two monitoring years. The study of the current evolution of the cliff face and of the rocky massif characteristics does not lead to think about a great movement, since the nature of the rocky massif and its structural configuration favor the individualization of decimetric or metric blocks (linked to the Jv represented in the new figure). In addition, it has been observed that as the landslide advances in the upper part, in the cliff there are rockfalls, and flows that gradually release the material.

7. **The strength of the paper is the relationship between rainfall and ground movement. What is presented is consistent with other well investigated deep landslide sites e.g. Moore 2020 Undercliff, Isle of Wight. But the issue is this is a short snapshot in time and in no way can be used to corroborate the evolution of the site over longer time scales, in this case up to 3 decades.**
   Response. As we mentioned above, these are the first results of an ongoing investigation. Although, as the Referee says, we only have a short snapshot, we consider them relevant given the lack of data so far. However, as indicated by the Referee, we have modified various paragraphs throughout the manuscript, discussing our results and keeping them within the short time frame.

8. **Finally, the standard of English would need to be improved for publication. The structure should also be improved, better introduction and reference to appropriate literature op.cit., expand the approach to set the site in context (geomorphology!); presentation of results section, discussion and conclusions. As it stands, the paper falls short of achieving this.**
   Response. The new version of the manuscript has been revised in detail and edited by a native English speaker. On the other hand, we have deeply changed the structure following the Referee's indications: we have improved the Introduction section by adding references, we have included a geomorphological context and a map, we have separated Results from Discussion, we have moved some data to the Setting section and we have changed some Conclusions.

SPECIFIC COMMENTS

9. **Minor changes at lines 17, 111, 112, 186, 524**
   Response. Mentioned minor changes have been modified.

10. **Line 17. what is the significance of elevation??**
    Response. The sentence has been changed to clarify that the 38 monitored control points are located over an old abrasion platform (rasa) at between 95 and-110 m asl.

11. **Lines 25-27. provide refs**
    Response. Following the Referee's suggestion, some references have been added.

12. **Lines 37-38. give examples?**
    Response. Following the Referee's suggestion, some examples and references have been added in the new version of the manuscript.

13. **Lines 49-50. Holderness is a soft rock coast formed in Quaternary sediments, soft clays; is this comparable to the Cantabrian coast?**
    Response. We have added the precision that this is a measured retreat on a clay coast on Quaternary sediments. On the other hand, the results have been discussed in comparison to other areas of the world.

14. **Lines 126-130. why not use dGPS rover?**

Response. As it can be seen in the orthophotography of the area, several control markers are located on the edge of an eucalyptus forest and others markers in an area with fruit trees, which compromises the reception of GPS signals. The working procedure used, based on observations made with a total station, is very reliable and provides better precision in altimetry than GPS.

15. **Lines 139-143. ground control? Accuracy of point cloud?**
Response. A ground control has been performed through the comparison of points extracted from the model with 9 GPS control points evenly distributed throughout the study area. It allowed to obtain an accuracy lower than 2 cm. In the surfaces within the study area, the accuracy of the 3D Cloud is of +/- 3 cm horizontally and of +/- 7 cm vertically. A more extended explanation about these issues has been added in the new version of the manuscript.

16. **Lines 145-146. quality of the google historical data is not that great or revealing, it does not show pre-failure of the cliffs**
Response. We fully agree with the Referee's comment. Although the quality of Google's historical data is not as good or revealing, we have considered this dataset as a reference to establish the state of the cliff prior to 2018. We have rewritten the text to clarify this issue.

17. **Lines 158-161. what validation of these indexes has been carried out?**
Response. A phrase highlighting the value of the AWC index for the study of landslide- triggering has been added to the new version of the manuscript. The use of AWC index was analyzed in the context of two different rainfall episodes occurred in Asturias. A statistical correlation between landslide records and soil moisture conditions has been carried out, showing that the majority of these avent occurs with soil moisture conditions over 80%. The results of this research are widely described in the work of Valenzuela et al. (2018), whose reference is included in the text.

18. **Lines 161-162. some considerable assumptions being made without site validation i.e. no ground investigation or testing of soils carried out!**
Response. Taken into account the Referee's comment, a new phrase has been included to better characterize the model and to clarify the input data used to develop it. Daily Water Balance Models for the Spanish territory are developed following a methodology implemented by the Spanish Meteorological Agency and detailed in the work of Botey and Moreno (2012). Input data considered are: i) daily precipitation and insolation values from weather stations; ii) atmospheric pressure, temperature, relative humidity and wind speed data from HIRLAM numerical weather prediction model; iii) soil type and texture, regarding the NRCS-USDA Soil Taxonomy; (iv) depth of the vegetation roots, following the land uses database Corine Land Cover; and (v) slope values. Output data are continuous models in raster format (25 km^2 cell size) obtained by using kriging interpolation. The methodology includes the validation of the model with in situ measurements. We agree with the Referee, since a water balance model developed at a national level implies a considerable amount of assumptions. However, considering the lack of other kind of information, and the observed correlation between the AWC and the occurrence of landslide in Asturias (Valenzuela et al., 2018), the used data are considered suitable of the addressed approach.

19. **Lines 163-164. with assumptions**
Response. The sentence has been modified to better fit what was done in the paper, indicating that the information management by GIS has allowed to better analyzing it as a whole.

20. **Line 174. a geomorphological survey and map of the coastal slope would have been useful; have you engaged a geomorphologist in the assessment?**
Response. Following the Referee's suggestion, we have added a geomorphological map in the new version of the manuscript to set the Tazones Lighthouse landslide in context with the surroundings.

21. **Lines 185-186. include if you are referring to them, the reference is not helpful**
Response. In Lopez-Toyos et al., a summary of the visible cracks in orthophotos and aerial photographs between 1984 and 2017 is shown. However, since it is currently in press we agree with the Referee that the reference is not helpful and, therefore we will remove it if it is not yet published when we finalize the new version of the manuscript.

22. **Lines 200-201. The mechanism of failure of the analogue site is not the same; you are describing a block slide, whereas Holderness is classical rotational failures in glacial till i.e. not structurally controlled.**

You clearly need a better introduction to landslide classification e.g. Varnes or Dikau & Brunsden, to set your observations in context
Response. As previously said, we agree with the Referee's suggestion and we have introduced some sentences to avoid misunderstandings related to the comparison with Holderness. We have modified our allusions in this regard in the new version of the manuscript, both in the Introduction and Discussion sections, complementing them with references such as the ones the Referee indicates, among others.

23. **Lines 208-209. You haven't presented any data of the inclination of bedding or joints; present your observations in a stereonet**
Response. Following the Referee's suggestion, we have collected more joint data and we have added a new figure with the stereographic projection of the family joints and a histogram of the joint spacing (Jv, that gives the number of discontinuities per cubic meter).

24. **Lines 211-212. present the data!**
Response. Following the Referee's suggestion, we have collected more joint data and we have added a new figure with the stereographic projection of the family joints and a histogram of the joint spacing.

25. **Lines 214-216. what evidence do you have for this?**
Response. Following the Referee's comment, we have added some sentences in order to clarify this issue. As indicated by García-Ramos et al. (2013), exposure to meteoric waters of the Lastres Formation sandstone beds causes weathering, such as highlight the yellow-ocher colors. Thus, the evidence comes from our observations in the field and their comparison with a detailed research work made by other scientists who are experts in Jurassic Cantabrian lithologies. In addition, the reference Ruiz de Argandoña et al. (2005), in which they describe the fresh sandstone of the Lastres Fm. has been added. Moreover, some properties of altered sandstone and marl (density, porosity and uniaxial compressive strength) have been determined.

26. **Lines 217-220. interpretation/speculation not supported by data or evidence**
Response. As previously mentioned, some properties of marl (density, porosity and uniaxial compressive strength) have been determined. Under saturated conditions, the total disintegration of the marls occurs, acquiring a soil-like behavior of high plasticity and estimating a reduction of their internal friction angle below 10º. In addition, we have introduced some sentences to describe the translational slip occurred in November 2019, after a rainy period, affecting the FG3 marker (Fig. 4D). We think that this small-scale example, which had a layer of marl as its slide base level, is illustrative of what is happening on the entire slope.

27. **Lines 223-224. this is very general**
Response. Following the Referee's comment, we have added other more specific references to discuss our results, although we consider necessary/interesting to retain the Selby (1993) reference, (even if it is very general, as we also agree), because is illustrative about our statements.

28. **Lines 228-230. why not map the evidence of old scars along the frontage to prove the point. You may well be right but the narrative is too general and speculative**
Response. As previously mentioned, following the Referee's suggestion, we have added a geomorphological map in the new version of the manuscript. Old scars of the surroundings are shown in that map.

29. **Lines 235-236. confusing; you are actually describing episodic failures on timescales of 10-70 years which results in drammatic recession and loss events, gradual implies annual retreat**
Response. We have changed the phrase to avoid misunderstanding. We focus on the observed cliff behavior during the two monitoring years.

30. **Lines 239-241. this contradicts the evidence you have presented which clearly shows an episodic block slide has developed**
Response. Focusing on our observations made during the 2 years of monitoring of the Tazones Lighthouse landslide, we do not expect a generalized fall of the entire mass of the slope that is affected by cracks. We have changed the phrase to avoid misunderstandings and clarify the behavior observed on the cliff, releasing the material little by little and not suddenly.

31. **Lines 249-251. this is a short interval during the development of the landslide.**

You need to comment on this
Response. According to the Referee's comment, we have broadened the discussion in this regard mentioning that it is an ongoing research and that in this article we only present the first 2 years of monitoring. Therefore, our conclusions must be limited to the short period considered.

32. **Lines 261-262. this is a poor analogue**
Response. We agree with the Referee suggestion and, related to the comparison with Holderness, we have clarified that, although the lithologies and structural control are very different, our mention was related to similar retreat rates. In the new version of the manuscript, the results have also been discussed in comparison to other coast areas of the world.

33. **Line 267. present the data.**

Also, no attempt is made on the coastal geomorphology, state of the beach, and influence of the groyne to the ENE
Response. Following the Referee's suggestion, we have added two new figures with the stereographic projection of the family joints and a geomorphological map. In addition, we have included a descriptive paragraph about geomorphology and coastal drift in this area indicating that the groyne, located east of the study cliff, does not play a fundamental role.

34. **Lines 249-251. this is a short interval during the development of the landslide.**

You need to comment on this
Response. Based on the Referee's comment, we have added a sentence in the discussion to highlight the limitations of having such a short monitoring interval during landslide development.

35. **Lines 286-290. Is it surprising there is a close link between groundwater, rainfall and deep landslide displacement? There are plenty of examples in international literature; the Jurassic coast in southern England**

A far more relevant analogue than Holderness

Response. In accordance with the Referee's comment, we have qualified the discussion, emphasizing not only that the movement is related to the wet periods. Going further, we comment in detail about wet periods that have caused more movement. Related to the comparison with Holderness, as previously mentioned, we have clarified the former version of the manuscript. Also, the results have also been discussed in comparison to other coast areas of the world.

36. **Lines 322-324. see my previous comment on this. The paper is weak because you have not presented the site and situation, geomorphological context of the shoreline or coastal cliffs. There is no point modelling waves until you have done this**
Response. Following the Referee's suggestion, we have added a geomorphological description illustrated with a new figure in which a geomorphological cartography can be seen.

37. **Lines 231-332. you have not presented an evolutionary model, only a short snapshot in time**
Response. The evolutionary model of the area was not an aim of the study. Therefore, we agree and we have totally changed the sentence according to the Referee's comment.

38. **Lines 331-334. too late to present data in the conclusions**
Response. These data were presented at the beginning of the Results section. Please, see line 181. Moreover, we have added a new figure with the stereographic projection of the family joints in the new version of the manuscript.

39. **Lines 339-341. this is consistent with similar deep seated failures of the Jurassic coast of England**
Response. Following the Referee's comment, we have expanded the Discussion section, adding new references regarding the retreat on the Jurassic coast of England.

40. **Lines 352-353. this conclusion is not supported by the observations and limited evidence presented**
Response. Taking into account the Referee's suggestion, we have rewritten the sentence, pointing out that the results of this work represent an important contribution to the knowledge of how the cliff coast of the Cantabrian coast behaves, taking into account the scarcity of previous works.

41. **Lines 380-382. relevance?**
Response. This reference is mentioned in the manuscript to illustrate that the interest in the coastal retreat has usually focused mainly on the sandy coasts, due to their attractiveness for human and tourist occupation, while less attention has been paid to rocky coasts. In our opinion, this reference is relevant to emphasize the importance of the study of the target area.

42. **Lines 383-384. translate into English?**
Response. The reference with the original title is provided, since it is a work published in Spanish. So, being strict, we think that it is not adequate to translate it into English.

43. **Lines 386-388. relevance?**
Response. Following the Referee's comment, the reference has been eliminated.

44. **Lines 389-390. translate into English?**
Response. The reference with the original title is provided, since it is a work published in Spanish. So, being strict, we think that it is not adequate to translate it into English.

45. **Line 504. ortho**
Response. This is the way in which the orthophotos published by the government of Spain should be cited, as stated at http://www.scne.es/productos.html (i.e. *OrtoPNOA 2017 CC-BY 4.0 scne.es*).