Response letter to MS No: nhess-2022-43- Decision

Entitled "Hazard Assessment of Earthquake –Induced Landslides Based on a Mechanical Slope Unit Extraction Method**"**
15th April.2022

Dear Editor,

We sincerely appreciate the editor's/reviewers time and effort in evaluating our manuscript. We agree with and accept all the comments and suggestions from the Editor and Reviewers. We have carefully and thoroughly revised the manuscript according to the editors/reviewer's questions and comments. In the revised manuscript, changes are shown by using the track changes mode. The point-to-point responses to the comments are detailed as follows:

Editor

Comment: You as the contact author are requested to individually respond to all referee comments (RCs) by posting final author comments (ACs) on behalf of all co-authors no later than 04 Aug 2022 (final response phase).

Response: Thank you for your comment and suggestion.
We agree with your opinion. According to the Reviewers' comments and suggestions, the questions have been answered based on the thoroughly revised manuscript.

Anonymous Reviewer (RC)#2

The manuscript has a reasonably good motivation. However, there are some fairly large points that I believe need further consideration. Below, I outline two main points to address before giving some detailed line-by-line comments:

Comment 1: Unfortunately, the manuscript was not written well and this effects my revision as a whole because I had a hard time following the flow and messages the authors are trying to convey. There are some terms (e.g., conventional, hydrological, and mechanical methods) that are not really well explained but continuously being used throughout the manuscript. I am sure the authors are clear about what they are referring to but unfortunately the same is not valid for the readership. Also, the structure of the manuscript is a bit "out of ordinary". There is no flow like introduction, study area, data, method, results, discussion, and conclusions. This also makes the text difficult to follow.

Response: Thank you very much for your question. This question has three parts and has been answered as such below

i) Message and flow of the manuscript

Landslide hazards can be predicted before it occurs or can be analyzed after it has already happened. This analysis or prediction can be determined on a minor or regional scale. To determine how susceptible an area is to landslides on a regional scale, the site must first be divided into smaller units termed "mapping units." These mapping units could be based on grids (Grid cell) or slopes (slope unit). The research used the slope unit method for the susceptibility analysis because landslides occur on slopes (Xie et al., 2003). the slope unit approach involves extracting slope units which could be done using many methods. The simplest among the methods many researchers use is the conventional and the hydrological process methods. These two methods also have drawbacks (Wang et al., 2019). To rectify these drawbacks, a new slope unit extraction method is proposed (mechanical method) termed point by segmentation slope unit extraction method.

After obtaining the slope units, there is a need to predict or analyze the possibility of slope displacement. The most appropriate displacement method is Newmark's sliding block displacement. The Newmark's sliding block is a rigid block method appropriate for infinite slope units with definite depth (below 3m). however, Rathje & Antonakos (2011) pointed out that ground motion parameters for displacement analysis or prediction on a regional scale can be altered to consider both shallow and deep failure due to their interaction with the sliding soil material. A framework for predicting earthquake-induced displacement is therefore proposed based on Zhang et al. (2019) to overcome the problems of defining slope displacements as infinite sliding blocks with shallow depth, to consider it as a finite failure, especially in less cohesive soil materials whiles considering the effect of pore pressure and slope geometry in determining the safety factor Fs.

The prosed slope unit and displacement methods are tested in Ghana (West Africa) to determine how susceptible Ghana is to landslides. Although they have no strong landslide database, they have a record for minor landslides and earthquakes. A predictive landslide inventory based on Jibson & Keefer (1993); Tsai et al. (2019) is used. The method states that the prediction accuracy for slope displacement under seismic loading should depend on the relationship between the threshold and predicted displacements (noting an allowable threshold displacement between 5-10 cm depending on the residual slope). Using the displacement map in Fig.9 (b), areas within the slope units having predicted displacement above 10 cm was selected as the probably failed areas in this study and used to validate the research in Ghana.

ii) Conventional, Hydrological, and Mechanical methods (Explanation)

Slope unit and all other terms have been explained in the introduction section of the reviewed manuscript on page 3, lines 4-16 as,

A slope unit is the left or right band of a sub watershed usually extracted from the digital elevation model (DEM) using geographic information system (*GIS*) software (Wang et al., 2019). The method for extracting the slope unit involves delineating a watershed from a DEM, then reversing the DEM to delineate another watershed. The two watersheds are merged to end the extraction of the slope unit (Cao et al., 2011). This slope unit extraction method is termed the hydrological slope unit extraction method (*Fig. 1a*) (Cao et al., 2011). Slope units extracted with the hydrological method are usually based on the surface hydrological process. This makes it impossible to identify variations in slope gradients beyond the hydrological flow direction, resulting in a sudden change in slope gradient. As such, slope units extracted using the hydrological methods suffer heterogeneity effects primarily associated with slope units extracted using high-resolution *DEM* (Guzzetti et al., 1995; Wang et al., 2019, 2020). The hydrological slope unit extraction method produces irregular boundaries and conjoined slope conditions. This occurs because it barely distinguishes inclined and horizontal planes of deep valleys and high mountainous terrains (Wang et al., 2019). Tedious manual post-extraction corrections are needed to make the slope unit acceptable (Cheng & Zhou, 2018; Wang et al., 2020).

After revised*: (*Page 3, lines 4-1) -Manuscript

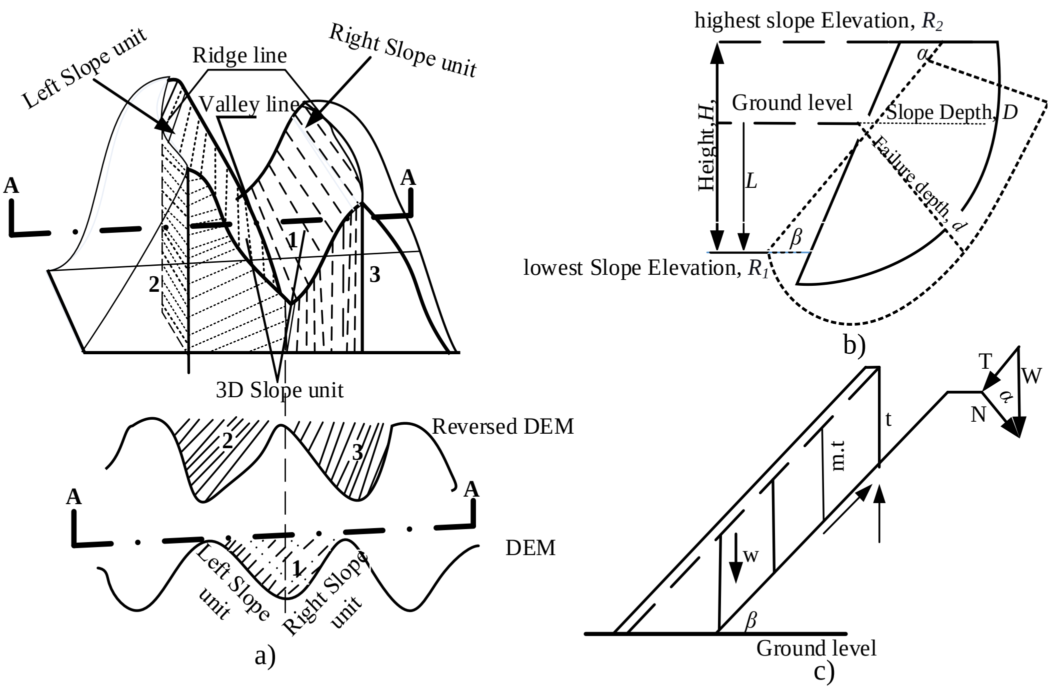

Fig. 1 Slope Unit and slope types a)*3D* diagram of slope unit definition from the hydrological method (reverse DEM=DEM rotated by 180along the horizontal plane *A*-*A*). The number 1 represents a sub-watershed obtained from the DEM data, and the numbers 2 and 3 represent the watersheds obtained by reverse DEM calculations, b) *2D* view of circular slope failure model under static and failure mode, where β is the slope angle with ground and α is the slope angle of failure. c) *2D* View of Slope in Plane Failure Mode, where w is the weight of soil mass, *L* is the length, and t is the depth of the slope.

The term conventional has been removed from the revised manuscript.

However, the conventional method is also the same as the hydrological method and involves manipulations in *GIS*, including flow direction, flow accumulation, calculations, and catchment delineation. The *DEM* is reversed, and the procedure is repeated. the two catchments are merged to end the slope unit extraction method (Cao et al., 2011). The term mechanical slope unit extraction has also been replaced with "a new slope unit extraction method" in the revised version of the manuscript

iii) Structure

The structure of the manuscript might not be as expected by the reviewer. However, the topic under consideration and the procedure involved justify the process used (Tsai et al., 2019). The structure is as follows:

Introduction, framework for the proposed methods, case study (study area), method implementation and data, sensitivity (results and validation), and conclusions.

Comment 2: I am quite surprised to see that there is no landslide inventory or a specific earthquake the authors examined but still the manuscript is evolving around earthquake-induced landslides. I still do not understand how this could be possible. I might have missed something because of the reasons I mentioned above. However, taking this possibility aside, I do not understand the rationale of the manuscript. If there are no landslides triggered by earthquakes, the whole premise of the manuscript is just hanging in the air. I was planning to provide comments in detail for the entire manuscript but after realizing these issues mentioned above, I cut it short because, with all due respect to the authors' labor on the manuscript, I have to say those small revisions would not be adequate to make it publishable. Still, below I've included some of my line-by-line suggestions.

Response: Thank you very much for your constructive comments.

Ghana has had a series of earthquakes since 1615. The highest intensity of the Earthquake in Ghana is *IX*, with a maximum magnitude of 6.8mw on the *MSK* Scale, recorded in 1862 (Ambraseys & Adams, 1991). Ghana is a third-world country and does not have a substantial earthquake-induced landslide database. However, Ghana experienced rockfalls in the Aburi mountains in 2019 (myjoyonline. com).

" Landslide scare hit residents of Weija-Kasoa ridge in Ghana after a torrential rain which caused some minor landslide in the area (myjoyonline.com 24th May 2022). Because "Weija-Kasoa ridge" sits on a very active fault (Romanche-transform fracture zone), which has been seismically active since 1788 and reactivated on 25th June 2020 with an earth tremor having magnitude 4.2. This indicates that Ghana is prone to earthquake-induced landslides in the immediate or near future. So, in this study, since Ghana doesn't have a solid earthquake-induced landslide database, the authors used the displacement method to predict the possibility of earthquake-induced landslides in Ghana. The probably failed inventories from the displacement maps are used to validate the proposed slope unit and displacement method in Ghana.

Comment 3: Lines 17-18: "Landslides occur on slopes and have been the rationale behind making earthquake-induced landslides and seismic engineering a scientific and national demand". It is not clear what you mean here.

Response: Thank you very much for your question. The sentence has been reviewed in the revised version of the manuscript (Page 1 Lines 21-23) to read as "Landslides mainly occur when acting forces exceed the strength of earth materials that composes a slope, and its evaluation provides general insight into future earthquake-induced landslides based on medium and long-term predictions of earthquake distribution to provide a possible mitigation measure to control its impact on life and properties”.

Comment 4: Line 18: “its evaluation provides general estimates of future earthquake-induced landslides” Do you mean the evolution of earthquake-induced landslides? What do you mean? Or are you referring to the evolution of techniques that we use to assess landslide hazards or something? This line is not clear. Please revise and express it in a clearer way

Response: Thank you very much for your question. We mean to say that, evaluating already occurred landside is a means of acquiring insight into probable future occurrences of landslide (at the same or different location) to provide a means of mitigating the occurrence or curb its impact on life and properties.

Comment 5: Line 21: You can still examine historical landslide catalogs and address some research questions even today, right? What do you mean? Do you think it is not an old fashion approach?

Response: Thank you very much for your question. We mean to say that, evaluating already occurred landside is a means of acquiring insight into probable future occurrences of landslide (at the same or different location).to strategize means of mitigating future occurrences if possible or curb their impact on life and properties.

Comment 6: Lines 22-23: “current scientific and engineering stability analysis models” What are you referring to? Could you please be more specific?

Response: Thank you very much for your question.
In the early days, there wasn't the availability of physical-based modeling for landslide analyses. Therefore statistically-based methods based on historical landslide distribution were usually applied to hazard zonation. However, in recent times engineering approaches (i.e., physically-based modeling) with the application of slope stability analysis models have been intensively studied and used to analyze landslides (e.g., Jibson and Keefer, 1993).

After revised: (Page 2, Line 1-3)- Manuscript,

Statistically-based methods based on historical landslide distribution were typically used in the early days for hazard zonation. However, the engineering approach (i.e., physically-based modeling) with the application of slope stability analysis models has recently been intensively studied and used to analyze landslides.

Comment 7: Line 24: “The statistical method” Are you referring to a statistically-based method developed to assess landslide susceptibility? What sort of method are you referring to? Please be more specific. Also, from lines 24 to 28, you do not say "such as" each and every time. You can just say, for instance: multivariate statistics (i.e., Logistic Regression, *LR*; Atkinson & Massari, 1998) Btw, I also noticed that you do not refer to, for instance, the logistic regression later on in the text. If this is the case, you do not need to indicate the abbreviation either

Response: Thank you very much for your constructive comment.

After revised: (Page 2 Line 4-7)- Manuscript

"The statistical method" Are you referring to a statistically-based method
We are referring to statistically-based methods, instead of statistical methods, and have been corrected throughout the revised manuscript.

After revised: Lines 24 to 28, have been revised on Page 2 Line 4-7 – Manuscript

The statistically-based method could be bivariate (Chung & Fabbri, 2012; Chung & Fabbri, 2003; Dai & Lee, 2002; Wubalem, 2020), a multivariate method (Atkinson & Massari, 1998; Polykretis et al., 2019), Artificial Neural Network (*ANN*) method (Ortiz & Martínez-Graña, 2018; Tsangaratos & Benardos, 2014; Vakhshoori et al., 2019) or Machine Learning Techniques (*MLTs*) (Tien Bui et al., 2012; Youssef & Pourghasemi, 2021; Kavzoglu et al., 2014).

Comment 8: Line 29: "The robustness of the statistical method is, however, suspect". Of course, there is no perfect model. But you cannot say that "The robustness of the statistical method is, however, suspect". Based on what? You can be critical for sure and mention some uncertainties, but not like this. Please revise the line.

Response: Response: Thank you very much for your constructive comment.
We agree with your comment. Following the reviewer's comments, the sentence has been deleted from the manuscript

Comment 9: Line 29: "statistical method generates landslide maps" What do you mean? Do you mean "landslide susceptibility maps"? You are resisting saying what we are really talking about. Susceptibility? Hazard? Or something else?

Response: Response: Thank you very much for your constructive comment.

We mean to write that," hazard maps generated by the statistically-based method" are obtained from a combination of maps generated by different control points, which are assumed to be independent of each other. The sentence has been revised on Page 2 Lines 8 - 9. of the manuscript as,

After revised: **(Page 2 Lines 8 to 9) - Manuscript**

Hazard maps generated by some of these Statistically-based methods are obtained from a combination of maps generated using control points, whose predictive variables suffer from multicollinearity.

Comment 10: Lines 29-31: "Because the statistical method generates landslide maps by using a combination of maps generated by different control points that are assumed to be conditionally independent of each other, thus questioning its accuracy". What does this mean now? I have a hard time following the logic behind your argument. You are saying they? Then please say it clearly. Btw, I would say this is quite a minor issue among many others regarding the statistically-based method and actually, there are ways to deal with this issue in the literature. If you would like to be really critical, you should come up with better arguments/stronger. Also, are you sure that these papers support your argument (e.g., Youssef & Pourghasemi, 2021). Or these are the examples that you think that they are clearly representing the problem you mention.

Response: Response: Thank you very much for your constructive comment.
We agree with your comment. Following the reviewer's comments, the sentence has been revised on page 2 Lines 8-12 of the manuscript to read

After revised: **(Page 2 Lines 8-12) – Manuscript**

"statistically-based methods assume that landslide controlling factors are conditionally independent of each other (e.g., Youssef et al., 2016). Hazard maps generated by some of these Statistically-based methods are obtained from a combination of maps generated using control points, whose predictive variables suffer from multicollinearity. The multivariate statistically-based methods are also suitable for large and complex areas. However, the method's robustness highly depends on the database used for the analysis. And only conditionally identical to those in the database can be predicted (Tien Bui et al., 2012; H. Y. Tsai et al., 2019)".

We think multicollinearity among independent variables usually results in less reliable statistical inferences and, in this case, produces a hazard map that reflects the actual condition of a study area. Although using independent variables that are not correlated or repetitive when building multiple regression models that use two or more variables may solve this situation, an oversight could cause multicollinearity. This is why we see this as a drawback of the statistical method. Also, with the multivariate statistically-based methods, only conditionally identical data to those in the database can be predicted, meaning an unidentical database cannot be predicted, which also adds to the drawbacks of the statistical method.

Comment 11: Lines 31-32: "Recent engineering earthquake induced landslides and displacement analysis (Rathje et al., 1998; Jibson & Keefer, 1993; Saygili, 2008)" these do not sound "recent" to me. Btw, please rewrite the line, there is no such thing called "engineering earthquake induced landslides". Also, "analysis" should be "analyses".

Response: Response: Thank you very much for your constructive comment.

Recent was used in the sentence because the engineering method for landslide analyses is more contemporary compared to the statistically-based method. The sentence has been revised on page 2 lines 12-14 of the manuscript to read,

After revised: (Page 2 Lines 12-14) – Manuscript

"Engineering methods for earthquake-induced landslides and displacement analyses are done using the sliding block displacement method, which is a compromise in complexity between simple pseudo-static analysis and complex numerical simulation engineering methods."

Comment 12: Line 34: "Newark Rigid Dynamic Block Model" should be "Newmark's sliding block method". Please do the same corrections through the text.

Response: Response: Thank you very much for your constructive comment.

We agree with your comment. Following the reviewer's comments, the term 'Newmark Rigid Dynamic Block Model', has been corrected and rewritten as

"Newmark's sliding block method", throughout the manuscript.

Comment 13: Lines 34-36: "The precision of the Newark Rigid Dynamic Block Model cannot be misconstrued, as it produces a stronger correlation between the estimated sliding block displacement and the mapping location of the earthquake-triggered landslide". Please do not say "cannot be misconstrued" out of blue and please support your argument by citing the literature. This is quite a subjective statement I would say. As there is no perfect machine learning technique to assess the spatial distribution of landslides, the same is also valid for their physically-based counterparts. If you would like to list the pros and cons of both approaches, you have to do it in an objective manner. Btw, this may not be even required because I still do not understand where you want to go from here. Do we really need to list all these here? Are these relevant for this paper? There is a large literature associated with both approaches and no need to destroy or glorify one of them compared to the other. However, if you would like to do this then do it properly. For instance, how accurately can you identify geotechnical parameters to run a regional-scale landslide susceptibility/hazard analyses?

Response: Response: Thank you very much for your constructive comment.

We agree with your comment. Following the reviewer's comments, the comment has been revised on Page 2 Lines 17 -20 of the manuscript as below,

After revised: (Page 2, Lines 17 -20) – Manuscript

Newmark's sliding block method produces a stronger correlation between the estimated displacement and the mapping location of the earthquake-triggered landslide, making it a good engineering method suitable for predicting earthquake-induced landslides.

Comment 14: Line 38: Why is that the final stage?

Response: Response: Thank you very much for your constructive comment.

We agree with your comment. Following the reviewer's comments, the sentence "final stage" has been deleted from the manuscript.

Comment 15: Line 39: "achievable through slope mapping units". Please first tell us what the slope unit is and why you prefer working with it. Also, please prefer using either "Slope units" or "mapping units" not both

Response: Response: *Thank you very much for your constructive comment.*

The research has made two proposals, first is a displacement method that considers the effect of depth in its analysis. The proposed displacement method is being applied on a regional scale. Therefore, the area must first be divided into sampling units of landslide hazard zones in which every landslide influence factor can be allocated. And these landslide hazard zones are termed mapping units. The popular mapping units in landslide hazard assessment include grid cells, slope units, etc. (unit). According to hydrological theory, a "slope unit" is considered a watershed defined by ridge and valley lines and is used to divide spaces into smaller regions for easy analysis. Slope units are usually extracted from a digital elevation model (*DEM*) using geographic information system (*GIS*) software (Wang et al., 2019).

As Xie et al. (2003) highlight, slope units can represent natural slope topographic boundaries in their natural conditions because it uses naturally marked units of slope to represent natural landscape events. This makes the slope unit the best method for landslide hazard zonation. The research proposed a new slope unit extraction method to solve slope heterogeneity and boundary effects associated with the hydrological slope unit extraction method. (Note: The revised version of the manuscript has omitted the conventional method because its delineation is similar to the hydrological method).

Comment 16: Line 40: You started using susceptibility (e.g., in line 39) and hazard (e.g., in line 40) terms and which is ok but do not use them as if you can use them interchangeably. They are not the same thing, right?

Response: Response: Thank you very much for your constructive comment.

We agree with your comment. Following the reviewer's comments, we admit that susceptibility and hazard maps aren't the same and cannot be used interchangeably in the manuscript. Susceptibility has been changed hazard throughout the manuscript (except places not applicable).

Comment 17: Line 42: "slope unit model" there is no model, just slope units. Also, if you are referring to slope units, it is more appropriate to cite papers that proposed slope units, not the ones that only used them based on available sources

Response: Response: Thank you very much for your constructive comment.

We agree with your comment. Following the reviewer's comments, we have realized that *both slope unit and grid cells are neither models nor methods, we have taken note and made the necessary corrections throughout the manuscript. Some of the publications cited in the manuscript propose slope units* (e.g. Cheng & Zhou, 2018; Wang et al., 2019, 2020; Tsai et al., 2019; Xie et al., 2003)

***After revised*:** **References**

Cheng, L., & Zhou, B. (2018). A new slope unit extraction method based on an improved marked watershed. MATEC Web of Conferences, 232, 1–5. https://doi.org/10.1051/matecconf/201823204070

Wang, K., Zhang, S., DelgadoTéllez, R., & Wei, F. (2019). A new slope unit extraction method for regional landslide analysis based on morphological image analysis. Bulletin of Engineering Geology and the Environment, 78(6), 4139–4151. https://doi.org/10.1007/s10064-018-1389-0

Tsai, H. Y., Tsai, C. C., & Chang, W. C. (2019). Slope unit-based approach for assessing regional seismic landslide displacement for deep and shallow failure. Engineering Geology, 248(January 2018), 124–139. https://doi.org/10.1016/j.enggeo.2018.11.015

Xie, M., Esaki, T., Zhou, G., & Mitani, Y. (2003). Geographic Information Systems-Based Three-Dimensional Critical Slope Stability Analysis and Landslide Hazard Assessment. Journal of Geotechnical and Geoenvironmental Engineering, 129(12), 1109–1118. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:12(1109)

Comment 18: Line 44: "(Xie et al., 2003)" please remove the parentheses

Response: Response: Thank you very much for your constructive comment.

We agree with your comment. Following the reviewer's comments, the parentheses have been removed on page 3 line 1. And the sentence reads

***After revised*: (Page 3, Line 1-3) - Manuscript**

As highlighted by Xie et al., (2003), a limitation of the grid-cell mapping unit method is its inability to represent natural slope topographic boundaries in their natural condition because it uses artificially marked cells of a block to represent the natural landscape event

Comment 19: Line 48: "the best mapping unit for earthquake-induced landslide and displacement analysis" Do you mean it is the best mapping unit specifically for earthquake-induced landslides? Why is that? How about rainfall-triggered landslides?

Response: Response: Thank you very much for your constructive comment.

We used the sentence "the best mapping unit for earthquake-induced landslide and displacement analysis" precisely because this study focuses on earthquake-induced analysis, including external factors (for instance, soil properties). These external factors are also influenced by rainfall. As such, we thought it would be too bold to make such a statement. However, Following the reviewer's comments, the sentence has been revised on page 3, lines 4-6 of the manuscript to read,

***After revised*: (Page 3, Line 4-6) – Manuscript**

According to hydrological theory, a "slope unit" is considered a watershed defined by the ridge and valley lines and is used to divide spaces into smaller regions for easy analysis, making the method more related to the geological environment, hence the best for landslide and displacement analysis.

Comment 20: Line 48: "The slope unit method" Slope unit is not the method but the output of some landscape partitioning methods which you haven't mentioned yet.

Response: Response: Thank you very much for your constructive comment. We agree with your comment.

The sentence "slope unit method" is a mistake on the part of the authors; we meant to write, "The slope unit extraction method proposed." However, the sentence has been removed from the revised manuscript.

Comment 21: Lines 51-54: Please separately cite the corresponding paper of each method you mention.

Response: Thank you very much for your constructive comment.
The corresponding paper for the hydrological slope unit extraction method has been accordingly cited in the revised manuscript (Mesut et al., 2011).

After revised: **References**

Mesut, T., & David, F., (2011). GeoRisk 2011. Delineation of slope profiles from Digital Elevation Models for landslide hazard analysis © ASCE 2011 403. GeoRisk 2011, 403–410. doi:10.1061/41183(418)87.

Comment 22: Lines 62-63: “The conventional watershed method for slope unit extraction” Please be specific and cite corresponding papers.

Response: Response: Thank you very much for your constructive comment.

The conventional slope unit extraction method involves delineating a catchment from DEM in ArcGIS software. The procedure is repeated for an invented DEM. The two catchments are merged to end the procedure for slope unit delineation. With the hydrological slope unit extraction method, the method for the extraction of the slope unit involves delineating a watershed from a DEM, then reversing the DEM to delineate another watershed. The two watersheds are merged to end the extraction of the slope unit.
The conventional slope unit extraction method follows the same trend as the hydrological slope unit extraction method but for minor details.
The conventional slope unit extraction method has been removed from the revised manuscript. And the hydrological slope unit extraction method has been cited in answer to question 24.

Comment 23: Line 68: “The application of the framework is validated in Ghana.” Which earthquake is that?

Response: Response: Thank you very much for your constructive comment.

The application of the framework for the slope unit extraction method and the displacement of slopes is validated in Ghana.
Although Ghana does not have a strong landslide database, however, has had a series of earthquakes, as shown in the table below.

Using the proposed slope unit extraction and displacement methods, these earthquake histories (table below) were used alongside the geological parameters and soil material properties to predict Ghana's vulnerability to future landslide hazards.

After revised: **Page 36 - Manuscript**

Table 1 Earthquake Record of Ghana indicating earthquake parameters

No.	Year	Magnitude (M_l)	Intensity (I_n)	Surf. Mag. (M_s)	Source
1	1615				Ambrasey's and Adams, 1986, NNA
2	1636	5.7	IX	North Axim	Ambrasey's and Adams, 1986, NNA
3	1788	5.6		Accra	British Geological Survey, BGS
4	1862	6.8	IX	Accra	Ambrasey's and Adams, 1986, NNA
5	1858	4.5		West of Accra	Ambrasey's and Adams, 1986, NNA
6	1871	4.6	VI	Accra	Ambrasey's and Adams, 1986, NNA
7	1872	4.9	VII	Accra	Ambrasey's and Adams, 1986, NNA
8	1879	5.7		Accra	Ambrasey's and Adams, 1986, NNA
9	1906	6.2	VIII	Ho	Ambrasey's and Adams, 1986, NNA
10	1907	5.0		Accra	Ambrasey's and Adams, 1986, NNA
11	1939	6.5	IX	Accra	Ambrasey's and Adams, 1986, NNA
12	1948	4.0		Accra	Ambrasey's and Adams, 1986, NNA
13	1964	4.7		Near Akosombo	Akoto and Anum, 1992, AKO
14	1969	4.8		Offshore	United State Geological Survey, USG
15	1997	4.7		Accra District	Internal Seismological centre, ISC
16	1992 - 2002	1-3	IV	Ho, Accra	Ambrasey's and Adams, 1986, NNA
17	1615	4.0		Accra	Ambrasey's and Adams, 1986, NNA

Comment 24: Line 70: "The impact of cohesion c is negligible, therefore neglected" In which context? You did not say anything about the landslides you examined. You can keep this statement for your method section and better explain it there

Response: Response: Thank you very much for your constructive comment.

First, the study predicted the possibility of landslide hazards in Ghana using the country's current geological parameters, soil properties, topography, DEM, and earthquake histories. In the study by Jibson & Keefer (1993), *a* threshold displacement of 5-10 cm is deemed reasonable, and 5-10 cm indicates a failure. This study is used to determine possible landslide inventories in Ghana and is used to validate the study. *The manuscript initially neglected the effect of cohesion in the analysis. Still, upon further reflection,* the rigid and flexible method has been modified to include cohesion as presented in the manuscript Page 7, (Lines 5-30)]. We initially ignored the effect of cohesion because, according to Biondi et al. (2007), consideration for the effect of pore water pressure during stability analysis of slope is usually done for cohesionless soil materials. As such, this study decided to base the displacement analysis on designing for the worse possible condition. Thus, neglecting the effect of cohesion. However, after further consideration based on the reviewer's comment, the study omitted the idea of neglecting the effect of cohesion in its analysis. And has included the effect of soil cohesion in the determination of the F_s, hence including the effect of cohesion in the displacement analysis as stated on Page 7 of the manuscript

Comment 25: Lines 71-72: I did not understand what you mean here.

Response: Response: Thank you very much for your constructive comment.

71-72 reads, " The paper also underlines the possibility of the proposed model for displacement analysis of shallow and deep slope failures considering the pore water pressure during the computation of the factor of safety F_s."

The general idea behind the study is to propose a new slope unit delineation method. The delineated slope unit extracted is used alongside Newmark's sliding block displacement method to predict landslide hazards in Ghana. Newmark's sliding block method is useful for the rapid prediction of a seismic-induced landslide. Still, it always considers the defined slope units to be infinite sets of grids, hence having definite depth (usually less than 3m).

However, Rathje & Antonakos, (2011) pointed out that ground motion parameters for displacement analysis on a regional scale can be altered to consider both shallow and deep failure due to their interaction with the sliding soil material. Therefore, this study decided to alter the sliding block method by Zhang et al. (2019) to overcome the problem of defining slope displacements as an infinite sliding block with shallow depth to consider it a finite failure slope with depth above 3m.

We realized that if the slope displacement is above 3m, then there is a need to consider the effect of underground water pressure when determining the factor of safety Fs (a measure for determining the slope's stability).

The F_s method is altered from the regular one in Eq.1 proposed by Jibson & Keefer, (1993) to the adjusted one in Eq. 2, which is applicable for deep failure.

$$F_s = \frac{\tau_{ss}}{\tau_{st}} = \frac{c + \sigma \tan \varphi}{\tau} \quad (2)$$

where *c* is the cohesion, σ is the effective stress, τ is the shear stress component parallel to the failure surface, and φ is the rock's friction.

$$F_s = \frac{c + (\gamma - m\gamma_w) d \cos\beta \tan\varphi}{\gamma d \sin\beta}[1 - r_u] \quad (5)$$

where m is the percentage of failure thickness saturated. Eq. (1) is primarily suitable for an infinite slope because the F_s for infinite slopes are not dependent on the slope's depth d but rather the *c*, φ, and β. The approach could also be used to compute the F_s for a finite slope by adding the effect of pore water pressure ($1 - r_u$) Eq. (2).

In this situation, the sentence means the slope displacement method can be used for finite and infinite grids depending on the F_s method. *The sentence has been revised*

After revised:* *(Page 14, Line 20-21) - Manuscript

"The proposed displacement model applies to infinite and finite slope failures considering the effect of pore water pressure during the F_s computation *for finite slopes*".

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