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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Calculation of coseismic displacement from Lidar data in the 2016 Kumamoto, Japan, earthquake" *by* Luis Moya et al.

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Thank you very much for your insightful review. We consider your comments and suggestions in order to improve our manuscript. Details for each comment are addressed below.

General comments: The authors present a study that calculates the coseismic displacement of the recent Kumamoto earthquake from Lidar data and compares the results with the outcomes of alternative approaches based on strong-motion data. The manuscript is well written, scientifically sound and the topic is timely and certainly of interest for a wider group of readers in disaster risk management. I have, however, some comments and questions throughout the paper. Mainly, I suggest to improve the introduction, the discussion and conclusion chapters of the paper. For these reasons,

I recommend the manuscript for publication in NHESS after minor revision.

Specific comments:

COMMENT FROM REFEREE:

Introduction: I strongly suggest to add more references and a more in-depth review of the state-of-the-art. In particular more emphasize should be given in presenting other studies that use Lidar and/or strong-motion data to estimate coseismic displacement. Based on this and the review of work that has been done related to this particular earthquake, it would be important to highlight the need for this study and the added-value that it can bring to the scientific understanding of the earthquake. I also suggest to remove the paragraph related to a general definition of Lidar which does not add much to the content.

Author's response:

The referee is right to point out that more review of the state-of-art is necessary. We have extended the introduction by referring previous publications. We basically added publications related to the use of Lidar data to ground deformation, the use of only post-earthquake Lidar data, and the few cases where there was available pre- and post- earthquake data. We also emphasize the additional information that could be acquired from Lidar data. About to the general definition of Lidar, since NHESS journal gathers readers from various disciplines, we believe that the definition of Lidar would be useful to an uninitiated reader

Author's changes in manuscript:

The extended information in the introduction was added from page 2, line 10 to page 3, line 32, as follows: "The airborne Lidar technology is an integrated system consisting of a Global Navigation Satellite System (GNSS), an Inertial Navigation System (INS) and a laser scanner, which sends pulses of laser light towards the ground and records the return time for calculating the distance between the sensor and the ground surface (Lillesand et al., 2004). Lidar has many applications in earthquake engineering, such as landslide detection (Jaboyedoff et al., 2012), and extraction of building features (Vu et al., 2003; Vu et al., 2009). Lidar data have been used in estimating ground displacement as well. Muller and Harding (2007) used the elevation of uplifted marine terraces mapped in the Lidar data to estimate the source parameter of the A.D. 900 Seattle fault earthquake. Sahakian et al. (2016) used Lidar data, in combination with other technologies such as seismic reflection, to identify a previously unmapped right-lateral strike-slip fault located in the Salton sea, California, U.S. They used the Lidar data to constrain the onshore deformation. Usually, only post-event Lidar data is available; thus, the coseismic displacement detection is limited to the identification of distortions of line features such as roads. Li et al. (2016) detected an offset of car tracks produced during the 2014 Mw 6.9 Yutian earthquake, Tibetan Plateau, by visual inspection. Chen et al. (2015) extracted two topographic profiles from Lidar data collected after the 1999 Mw 7.1 Hector Mine earthquake, California. The profiles were parallel to the fault-line and located on either side of the fault in order to estimate the slip during the earthquake. There are few cases in which Lidar data both before and after an earthquake were available. The first case was in the 2010 Mw 7.2 El Mayor-Cucapah earthquake. Oskin et al. (2012) performed a simple difference of elevation to estimate the surface rupture; however, they did not consider the horizontal displacement. Two more earthquake events: the 2008 Mw 6.9 Iwate-Miyagi earthquake and the 2011 Mw 7.1 Fukushima-Hamadori earthquake were monitored by Lidar data acquired before and after the event. Then Nissen et al. (2014) estimated the 3D displacement using the Iterative Closest Point (ICP) algorithm (Nissen et al. 2012). Their results showed a coherent displacement but with high level of noise in the horizontal component. Cross-correlation technique has been used successfully to monitor movements. Duffy and Hughes-Clarke (2005) applied cross-correlation to monitor the movements of sea–floor dunes using bathymetry data. Liu et al. (2011) extracted the shifts of vehicles between the panchromatic and multispectral QuickBird images, which were taken with a time lag of approximately 0.2 seconds, and then they estimated the vehi-

cles' velocity. Liu and Yamazaki (2013) calculated the crustal displacement during the 2011 Mw 9.0 Tohoku earthquake by estimating the shift of undamaged buildings using the cross–correlation coefficient between the TerraSAR–X intensity images taken before and after the earthquake. Borsa and Minster (2012) evaluate the potential use of cross-correlation using Lidar data by applying a synthetic slip to the Lidar data of the southern San Andreas fault and then their result could recover the synthetic slip. Duffy et al. (2013) also used a pair of Lidar data taken before and after the 2010 Mw 7.1 Darfield, New Zealand earthquake to calculate the horizontal coseismic displacement. Measurements of the coseismic displacement in the near field is of great importance because it can be used to locate the source and to understand the rupture process. Wang et al. (2013) inverted the coseismic displacement calculated from GNSS and strong-motion stations to modulate the earthquake source of the 2011 Mw 9.0 Tohoku earthquake. Earthquake source inversion methods have become important in the last years because of its potential for forecasting tsunamis (Melgar and Bock, 2013). The GNSS devices calculate positions and nowadays it is used for continuous monitoring of the earth crust. Strong-motion devices record acceleration or velocity, and in most of the cases, a baseline correction is required before estimating the correct displacement time history because the baseline is shifted as a result of several factors such as ground rotation and rocking movements of the instrument. The displacement time history can be calculated precisely if the six components, three translational and three rotational, are recorded (Graizer, 2010). However, the displacement time history is often estimated by a double integration of only the translational components with respect to time. Up to now the source of errors and the rotation components cannot be quantified and only empirical methods have been proposed in the past to reduce the effect of the baseline shift and retrieve a reliable displacement time history. One of the first method was proposed by Iwan et al. (1985), in which a bilinear function is used to estimate the velocity trend caused by the baseline errors. Several modifications of this approach have been proposed. Wu and Wu (2007) defined the bilinear function in an iterative process in a way that the displacement time history best fits a ramp function. Later, Wang et al. (2011) also proposed an iterative procedure; but they used a step function to constrain the displacement time history. Moya et al. (2016) used a pair of strong-motion records that were closely located and perform a simultaneous correction of both records. Although there have been a great improvement and deployment of GNSS and strong-motion networks, even the densest network, either GNSS or strong-motion, has a low spatial resolution. For instance, the nationwide GNSS network of Japan has one station in an about 20-km interval. Thus, for an earthquake of moderate magnitude, where the coseismic displacement is concentrated in a narrow area, it is difficult to depict the spatial pattern of coseismic displacement. SAR satellite images offer a better spatial resolution, but it requires a pair of images with the same viewing condition to calculate the coseismic displacement to the line-of-sight (LOS) of radar. More pairs of SAR images from different views, which are not very realistic, are required to obtain 2.5 D or 3D coseismic displacement. Another use of coseismic displacement comes up when the effects of an earthquake in the near field are estimated using remote sensing techniques. It is necessary to consider the permanent displacement if an automatic change detection is applied to extract collapsed buildings or quantify the mass movement in landslides."

COMMENT FROM REFEREE:

Page 4, line 1: I suggest to move the references to Liu et al 2011 and Lie and Yamazaki 2013 to the introduction.

Author's response:

In accordance with the referee's comment, we have moved the references to the introduction.

Author's changes in manuscript:

The references are located between page 2, line 31 to page 3, line 1, as follows: "...Liu et al. (2011) extracted the shifts of vehicles between the panchromatic and multispec-

tral QuickBird images, which were taken with a time lag of approximately 0.2 seconds, and then they estimated the vehicles' velocity. Liu and Yamazaki (2013) calculated the crustal displacement during the 2011 Mw 9.0 Tohoku earthquake by estimating the shift of undamaged buildings using the cross–correlation coefficient between the TerraSAR–X intensity images taken before and after the earthquake...."

COMMENT FROM REFEREE:

Page 4, line 23: The pixel resolution would be "increased" if you resampled from 50 cm to 10 cm. A few more words on the applied convolution method would be desirable.

Author's response:

The referee is right to point out this mistyping. We apologize for it.

Author's changes in manuscript:

In page 6, line 8-11, as follows: "...The pixel resolution was increased from 50 cm to 10 cm by using the cubic convolution method, where a bicubic function is fitted using 4x4 pixels neighborhood and used to estimate the intermediate values. The subpixel size was decided based on the computational effort that is required to detect the peak value of the correlation coefficient..."

COMMENT FROM REFEREE:

Page 5, line 31: "Lidar data are capable..." I suggest to move this paragraph into a separate discussion section.

Author's response:

In accordance with the referee's comment, we have moved this paragraph to a new section.

Author's changes in manuscript:

The paragraph has been moved to page 9, lines 13-17.

COMMENT FROM REFEREE:

Page 7, line 17-24: Suggest to move this paragraph into a separate discussion section.

Author's response:

In accordance with the referee's comment, we have moved this paragraph to a new section.

Author's changes in manuscript:

The paragraph has been moved to page 9, lines 7-12.

COMMENT FROM REFEREE:

Discussion: Please add a separate discussion section that clearly outlines the limitations and benefits of the applied method, and compares the results with findings of other studies (linked to studies introduced in the introduction section).

Author's response:

In accordance with the referee's comment, we added a new section where we addressed the suggestions.

Author's changes in manuscript:

The new section is located at page 8, line 26: "6 Discussion Our result could recover the spatial distribution of the three-dimensional (east-west, north-south, and up-down) coseimsic displacement and validated the fault line drawn by the GSJ (Error! Reference source not found., 8 and 9). From the evaluation of the parameters used, the results were found to be highly sensitive to the window size. Basically, it is crucial that the windows have to cover several features, such as buildings, trees and different topography, in order to obtain a clear peak value in the correlation coefficient (Error! Reference source not found.c). This issue was our main concern in agricultural fields because large areas have uniform elevation. In this study, a constant window size

was used; however, if the land use information is available, different window sizes can be applied. For instance, in urban areas the window size can be smaller than that for agricultural lands. Therefore, one limitation of the method is the required window size because the larger the window size, the lower the spatial resolution of coseismic displacement. Comparing our result with the InSAR satellite images published by the GSI, our result provides the 3D coseismic displacement; while the InSAR results provide only the displacement to the line-of-sight. But concerning about the area coverage, satellite sensors can cover a larger area than airborne Lidar sensors do. The slips calculated from our results are very close to that obtained from the field observation for most cases (Error! Reference source not found. and 15). It is observed that in the majority of the cases our results are greater than the measured ones. We believe that the main reason for this is that the type of soil is cohesive in this area. Cohesive soils have the ability to exhibit large plastic deformation that depends on the water content and, as can be seen, the area is mostly used for agricultural purposes where the soil has high water content. Thus, the surface rupture measured in the field might not be the total slip. The largest differences between the GSJ survey and the Lidar results are observed in the profiles 'op' and 'qr'. Lidar data are capable of extracting other types of information. Error! Reference source not found. Error! Reference source not found.shows two areas: one with collapsed buildings and the other where a landslide occurred. Error! Reference source not found. also shows the change in elevations between the DSMs after removing the horizontal coseismic displacement. As can be observed, the large change in elevations implies that a building collapsed or a landslide occurred. Therefore, with proper thresholds, these phenomena can be detected automatically. This issue will be discussed in a future publication."

COMMENT FROM REFEREE:

Conclusions: Some more relevant conclusions would be desirable. For example, on the basis of your study, would you be able to say if it is worth to do the expensive Lidar surveys or would the other available sensor data have been enough to estimate the coseismic displacement to a sufficient degree? On the basis of this, what are the implications of your study on a better understanding of the earthquake physics? Is Lidar just a another data source to be used or does it make a difference with respect to the other data source that have been available for this event?

Author's response:

In accordance with the referee's comment, we extended the conclusion section where we addressed the suggestions.

Author's changes in manuscript:

The additional information of the conclusions section is located at page 9, line 30: "…The detailed information of coseismic displacement is indeed useful to constrain the focal mechanism of the event. Recall that the GSI's preliminary report estimated a slip of about 24 m in the source zone during the 2011 Mw 9.0 Tohoku earthquake from an inversion method using the inland GEONET station records. However, later Sato et al. (2011) observed a coseismic displacement of 23 m at the ocean bottom and pointed out that this information could better constrain the focal mechanism. Thus, our results, which records higher coseismic displacement than the one recorded from GNSS stations, would improve the source estimation. However this issue is out of the scope of this paper and will be addressed in a future publication. As mentioned before, there are only few cases in which Lidar data before and after an earthquake are available. The main reason is a high cost of Lidar surveys. However, this technology can be used properly for a specific region of interest, such as along fault lines. For instance, the B4 project (Bevis et al., 2005) collected Lidar data of the southern San Andreas and San Jacinto faults in southern California in order to have a pre-event Lidar data for future earthquakes"

Technical corrections:

COMMENT FROM REFEREE:

Page 1, Line 24: Suggest to rephrase sentence to: "This Kumamoto earthquake sequence triggered secondary effects such as landslides and liquefaction, and caused extensive damage to lifeline systems, buildings, bridges and transportation structures."

Author's response:

In accordance with the referee's comment, we have changed the statement.

Author's changes in manuscript:

Page 1, line 24

COMMENT FROM REFEREE:

Page 4, line 32: "…vertical axis shows is used for the number…" remove "is used for".

Author's response:

The referee is right to point out this mistyping. We apologize for it.

Author's changes in manuscript:

The words "is used for" was removed from the sentence. Page 6, line 19 "…vertical axis shows the number …"

COMMENT FROM REFEREE:

Page 6, line 6: Add a reference to Fig. 1 to the statement that there are no Geonet stations in the area.

Author's response:

Adding the reference make the sentence clearer. We appreciate the referee for this suggestion.

Author's changes in manuscript:

Page 7, line 20: "Unfortunately, there is no GEONET station in this study area (Error!

Reference source not found.). . .”

COMMENT FROM REFEREE:

Page 6, line 19: Suggest to replace second “because” by “as a result of”.

Author’s response:

In accordance with the referee’s comment, we have changed the statement. Please note that this paragraph have been moved to the introduction section, where we added more detail about displacement from acceleration records.

Author’s changes in manuscript:

Page 3, line 12: “. . .because the baseline is shifted as a result of several factors. . .”

Please also note the supplement to this comment:
http://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2016-315/nhess-2016-315-AC1-supplement.pdf

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