Simplified approach to rapidly predict road blockages caused by co-seismic landslides

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ABSTRACT

The 2016 Kaikōura earthquake triggered tens of thousands of landslides leading to several road blockages which isolated the population in Kaikōura and disrupted the transport services across the South Island. The prediction of these road blockages is complex as it requires a landslide model as well as a runout concept. This can be time consuming if the assessment covers a larger network such as the New Zealand State Highways. Based on a geospatial model and a buffer approach, a simplified method is developed to enable rapid calculation of the probability of road blockages caused by co-seismic landslides. The development involves high-resolution New Zealand specific datasets and different buffers to capture the areas around the network that contribute to the blockage. Comparing the estimates with the observational data shows that the simplified method achieves a high prediction accuracy (0.81). However, it tends to overestimate the road blockage hazard in several places. Despite the limitations, the method allows for a rapid identification of road sections that might be affected by landslides of future earthquakes and helps to support emergency planning and response.

1 INTRODUCTION

On 14 November 2016, a M_W 7.8 earthquake hit the South Island of New Zealand, involving the rupture of multiple faults both on- and offshore (Kaiser et al., 2017). Besides coastal uplift and deformation, the event triggered over 29,000 landslides (Massey et al., 2020). Several sections of State Highway 1 and the Main North Line (railway) were blocked north and south of Kaikōura, isolating the local population and disrupting the transport services across the South Island (Davies et al., 2017, Sitzia, 2021). Figure 1 presents the spatial distribution of the peak ground velocity (PGV) (ShakeMap, USGS (2016)) and the location of the observed road blockages along State Highway 1 (NZTA, 2017). The 2016 Kaikōura earthquake demonstrates the impacts of landslides affecting the transport networks and emphasizes the importance of understanding co-seismic hazards on a national level.

The prediction of earthquake triggered landslides blocking infrastructure networks requires two steps: First, the landslide probability needs to be calculated for a specific ground shaking scenario. Second, a runout concept needs to be developed to identify source areas that may lead to a blockage. The runout concept

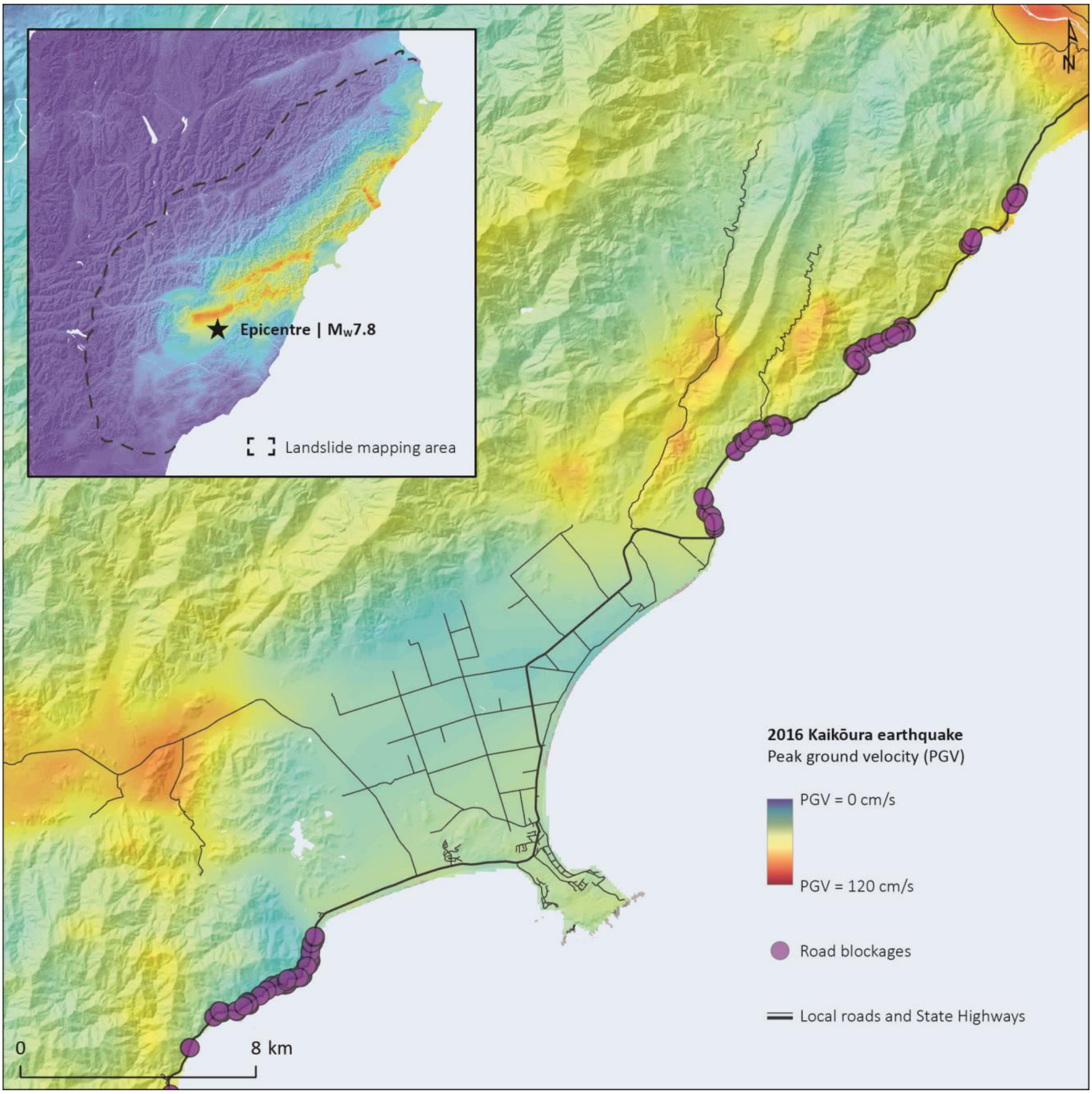

Figure 1: Spatial distribution of PGV as well as location and size of the road blockages triggered by the 2016 Kaikōura earthquake. The inset shows the location of the earthquake epicentre and the landslide mapping area by Tanyaş et al. (2022).

usually considers the surrounding topography and the distance between the road segment and the landslide source area. Existing approaches include for example the method by Robinson et al. (2016), using the horizon line (surrounding skyline from an observer point) in a 1 km radius around points generated along the network (500 m spacing). The mean landslide probability is assessed within the horizon line and assigned to the network point. Another example is the method by Robinson et al. (2018), calculating the reach angle which equals the inverse tangent of the elevation difference between the top of the landslide scar and the toe of the deposit divided by the horizontal distance between these points. Due to the complexity of the runout concept, the estimation of the road blockage probability can be time consuming or require the network fragmentation (e.g. point spacing along roads where the road blockage is estimated) to be reduced.

This paper presents a simplified approach to predict road blockages caused by co-seismic landslides, aiming for a rapid calculation while providing high-resolution outputs. Using a New Zealand specific model to calculate the landslide probability for the 2016 Kaikōura earthquake, the aggregated estimates based on different probability percentiles and buffer radii around the road network are assessed to identify the model with best prediction performance.

2 METHODOLOGY

This section describes the methods and datasets used to calculate the landslide probability as well as the road blockage probability. In addition, the statistical measures to evaluate the prediction performance are introduced.

2.1 Landslide probability

A geospatial landslide model is used to calculate the landslide probability. Nowicki Jessee et al. (2018) developed a global model using peak ground velocity (PGV) in cm/s, slope in degrees, compound topographic index (CTI, indicates potential soil wetness), lithology and land cover. Previous research replaced all explanatory variables (except PGV) with New Zealand specific datasets and performed a regression analysis based on the landslide inventory of the 2016 Kaikōura earthquake. Compared to the global approach, the adjusted model offers a better spatial accuracy due to the higher resolution of the geospatial datasets (25 m) and more updated information of the region specific datasets (Lin, 2022). The landslide probability (P) is calculated by:

$$P = 1 / (1 + e^{-X}) \tag{1}$$

where X is a function of the explanatory variables:

$$X = -6.5 + 1.05\, ln(PGV) - 0.11\, slope + c_1\, lithology + c_2\, land\ cover - 0.06\, CTI + 0.05\, ln(PGV)\, slope \tag{2}$$

Since lithology and land cover are nominal, each category is assigned an individual coefficient (Lin, 2022). More details including the references for the datasets as well as the coefficients for lithology (c_1) and land cover (c_2) are provided in the DATA section at the end of the paper. The geospatial model is preferred over other statistical models as it provides a higher output resolution (e.g., Kritikos et al. (2015)) and allows for a rapid calculation (aside from PGV, no event specific information such as the distance to the nearest ruptured fault (e.g., Massey et al. (2020)) is required).

2.2 Road blockage probability

The landslide probability calculated by the geospatial model is used to estimate the road blockage probability by aggregating the probability values across a buffer area around a network point. The buffer area is a simplified representation of the potential source area across which the debris accumulates leading to a road segment blockage. In order to find the buffer area with the highest prediction potential, different radii (R ranging from 100 m to 1,500 km in 100 m increments) are compared. In addition, different probability percentiles (25^{th}, 50^{th}, 75^{th}, 90^{th} and 100^{th}) are assessed.

For the representation of road network, the New Zealand Road Centrelines by Land Information New Zealand (LINZ, 2018) are used and split into segments of 100 m, which is a suitable network fragmentation for regional assessments. The road blockage probability is estimated for the centrepoint of each segment. As the locations of the observations do not perfectly intersect with the network data, road segments that are within a 100 m range of a road blockage are considered to have been impacted by a landslide. This leads to 111 impacted road segments (positive cases). All road segments that are not affected by a road blockage are considered a negative case.

2.3 Performance evaluation

To evaluate the prediction performance of each buffer radius and probability percentile, the balanced accuracy (ACC_{bal}) is calculated. The ACC_{bal} is a measure to quantify how well the approach predicts the occurrence of road blockages and is calculated by

$$ACC_{bal} = (TPR + TNR) / 2 \quad (3)$$

where TPR is the true positive rate (percentage of correctly predicted positive cases) and TNR is the true negative rate (percentage of correctly predicted negative cases) for a specific probability threshold. ACC_{bal} values usually range from 0.5 (random prediction) to 1.0 (perfect prediction), providing a quantitative measure to compare the prediction potential of unbalanced samples. ACC_{bal} is calculated for a range of probability thresholds in order to identify the optimal threshold (opt TH), which leads to the highest ACC_{bal} (max ACC_{bal}), hence, corresponds to the threshold that best distinguishes between the positive and negative cases. The opt TH can be used for the assessment of future co-seismic landslide events; for example, if the calculated probability for a road section is above the opt TH, a road blockage can be expected. To limit class imbalance and to avoid spatial bias towards the low lying local roads across Kaikōura, only segments along State Highway 1 in Figure 1 are considered in the statistical assessment, leading to 734 negative cases and a case ratio of approximately 1:8 (positive to negative).

3 RESULTS

Figure 2 presents the landslide probability calculated for the 2016 Kaikōura earthquake using the adjusted model (Eq. 1). High probabilities up to P = 1 can be found across the mountainous regions and the State Highway sections north and south of Kaikōura where the road blockages occurred. Lower values are evident across the local roads. Based on these estimates, the road blockage probability is calculated for the different radii and percentiles.

As shown in Figure 3, the max ACC_{bal} is above 0.63 across all percentiles and radii. However, the results indicate that an increase in the buffer area reduces the prediction accuracy. The best prediction performance is achieved by a radius of 200 m and the 50th

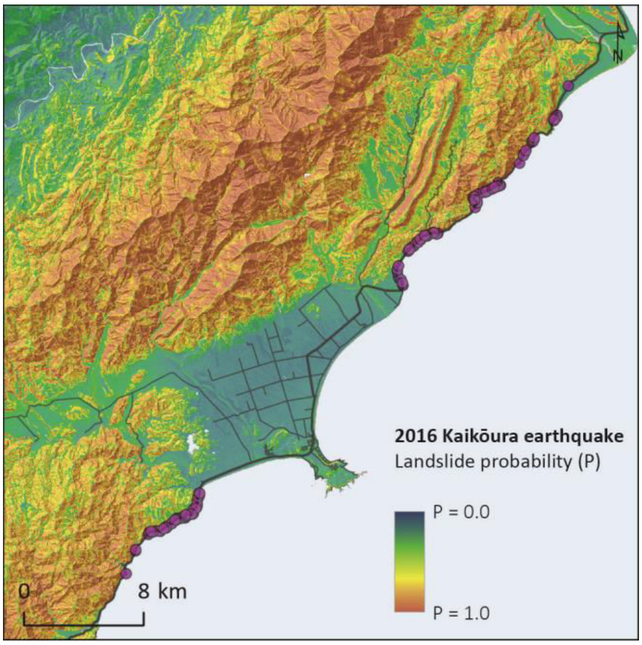

Figure 2: Landslide probability calculated for the 2016 Kaikōura earthquake and the location of the observed road blockages.

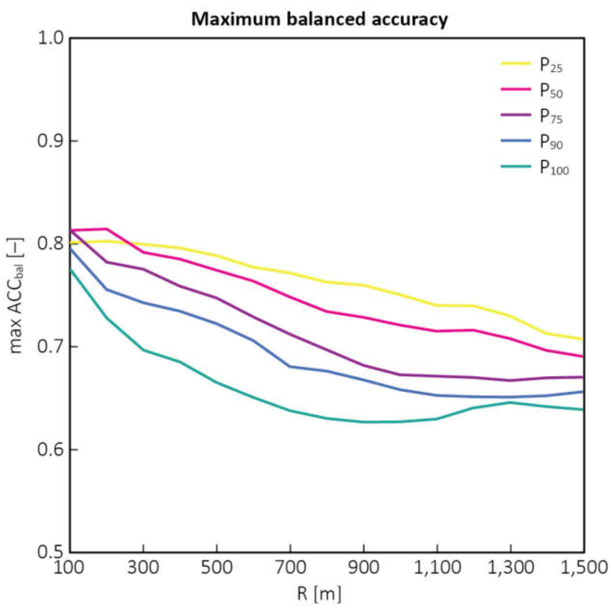

Figure 3: Maximum balanced accuracy for different buffer radii (R) and percentiles.

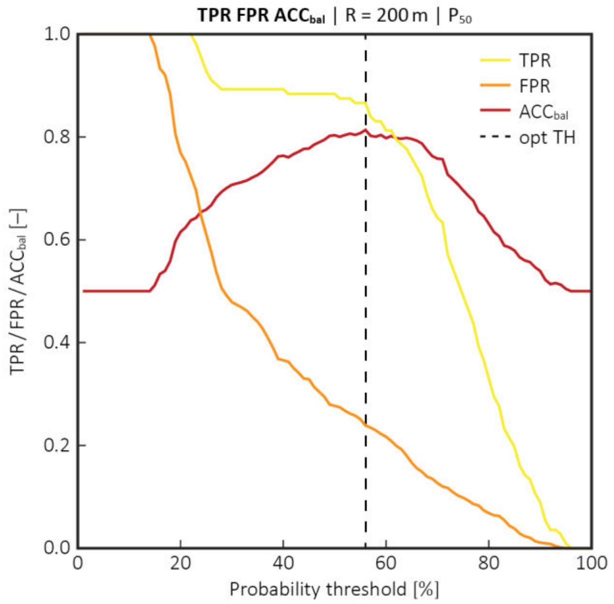

Figure 4: TPR, FPR and ACC_{bal} curves for the best performing buffer radius and percentile.

percentile, leading to max ACC_{bal} of 0.81.

For the best performing radius and percentile, the ACC_{bal} curve is plotted to further investigate the approach. In addition, the false positive rate (FPR, percentage of incorrectly predicted positive cases) and the TPR are presented in the same figure, providing further insight into the prediction performance. While a high TPR value might be more relevant for impact and risk management, a low FPR could be of interest when economic factors are important. Figure 4 shows that the approach reaches the maximum ACC_{bal} for a probability threshold of 56 % (opt TH). However, high ACC_{bal} ($\geq$ 0.80) can be found for a range of thresholds. For a more economic outcome (lower FPR), the threshold could be adjusted to a higher value (up to 65 %), for a more conservative approach (higher TPR), the threshold could be lowered to 49 %.

To better understand the prediction performance in a spatial context, a (binary) prediction map is generated using the opt TH of the best performing buffer radius and percentile. Positive cases with a road blockage probability equal or greater than the opt TH as well as negative cases with a road blockage probability below the opt TH are considered correct predictions. Overprediction relates to negative cases with a road blockage probability equal or greater than the opt TH, while underprediction describes positive cases with a road blockage probability below the opt TH. As opposed to the statistical assessment, the percentages presented in Figure 6 refer to both the State Highways and the local roads in the Kaikōura region. However, flat areas and steep areas are assessed separately. For the flat areas, which cover most of the roads in Kaikōura, a high percentage of correct prediction (96.3 %) can be found. Overprediction (2.9 %) and underprediction (0.8 %) are limited to roads entering Kaikōura from the inland and along the coast. The high number of correctly predicted road sections across the flat area is likely the result of the consistent topography leading overall low landslide probabilities (Figure 2) and road blockage probabilities. For the steep areas, which include the State Highway 1 sections along the coast as well as the inland roads north east of Kaikōura, show a larger percentage in overprediction (55.6 %) in several locations. As the landslide probability is very high along the coast, road blockages are predicted for most of the segments. The overestimation along the inland roads suggests that the approach is not able to properly capture topographic details, limiting its application across mountainous regions. Underprediction (1.2% %) is presented along the coastal State Highway sections where the flat area transitions to hilly terrain. It is likely that the calculated road blockage probability is dominated by the low estimates of the flat areas.

4 DISCUSSION

For a probability threshold of 56 % (opt TH), a buffer radius of 200 m and using the 50^{th} percentile, the approach shows a high max ACC_{bal} (0.81) and a low percentage of underprediction, which is surprising considering that topographic features are not considered in the calculation method. Although a high percentage of correct prediction is achieved across flat areas, the approach tends to overpredict in hilly environments, which could lead to uneconomic decisions, for example, when used for emergency planning or prioritising mitigation management.

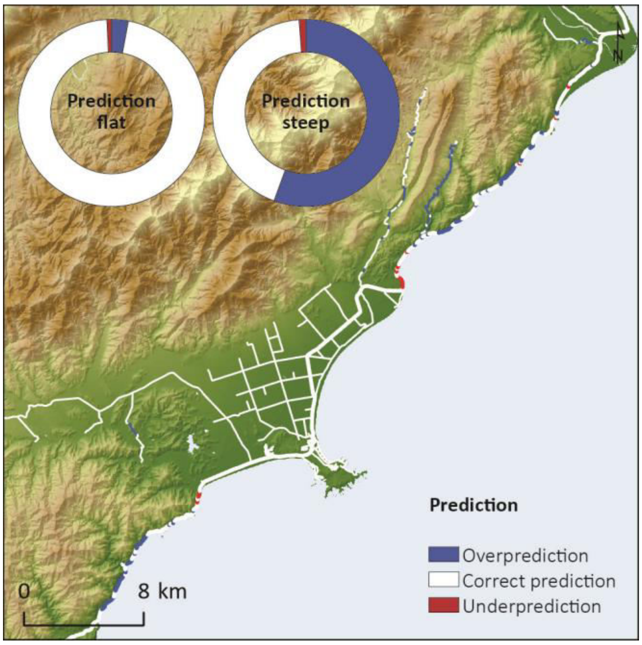

Figure 5: Prediction map for the road blockages based on the optimal threshold using the best performing buffer radius and percentile.

Aside from the restrictions related to the approach, it is important to account for the limitations and uncertainties associated with the landslide model. As the landslide model was trained on the 2016 Kaikōura earthquake, the results likely overestimate the prediction performance. In addition, the limited area covered by the sampling area of the statistical assessment (State Highway 1) might not be representative for other areas. More observational data from other earthquakes across New Zealand is required to validate the findings. Further evaluation is also essential considering that the buffer radius proposed in this assessment (200 m) is much smaller than the maximum radius used by other approach such as Robinson et al. (2016) ($R \leq 1$ km). For very large landslides, 200 m might be too small and could result in the under-estimation of landslide hazards – however, 1,000 m is excessive for very steep terrain, such as SH1 north and south of Kaikōura

Further research should also link risk mitigation and prevention efforts to the hazard assessment. For example, following the 2016 Kaikōura earthquake, additional rockfall protection was installed along susceptible State Highway sections (Sitzia, 2021), reducing the likelihood that landslide debris enters the carriageway.

5 CONCLUSION

A simplified approach to predict road blockages caused by co-seismic landslides is developed using the landslide estimates calculated by a geospatial model across a buffer area. The comparison with the observational data of the 2016 Kaikōura earthquake suggests that the 50th percentile of the landslide probability and a buffer radius of 200 m lead to the best prediction performance.

Despite limitations and the need for further development, the approach can help decision making processes regarding the risk assessment of future earthquake scenarios. The region specific datasets provide high-resolution outputs and allow for a rapid automated calculation of road blockages for both national- and regional-scale predictions.

DATA

Apart from PGV, which is retrieved from ShakeMap (USGS, 2016), all explanatory variables are available as New Zealand specific datasets. While the slope and CTI are in a raster format, defining the resolution of the model output (25 m), land cover and lithology are available as vector files. The slope is calculated from a 25 m DEM provided by Manaaki Whenua Landcare Research (MWLR, 2011). The lithology is based on the most recent version of the Geological Map of New Zealand (3rd version) (Heron, 2020) and follows the categorization proposed by Nowicki Jessee et al. (2018). The land cover is retrieved from the 5th version of the New Zealand Land Cover Database developed by Manaaki Whenua Landcare Research (MWLR, 2020) and follows the categorization proposed by Nowicki Jessee et al. (2018). CTI is calculated from a DEM as the logarithm of the specific catchment area divided by the tangent of the slope angle (Moore et al., 1991), using the same 25 m DEM data as *slope* (MWLR, 2011).

The coefficients of lithology and land cover for Equation 2 are listed in Table 1.

Table 1: Coefficients of the explanatory variables lithology and land cover.

Lithology	**Coefficient**	**Land cover**	**Coefficient**
Metamorphics	$c_1 = 0.54$	Cropland	$c_2 = -0.34$
Acid plutonic rocks	$c_1 = 0.23$	Forrest	$c_2 = -0.63$
Basic plutonic rocks	$c_1 = 0.55$	Grassland	$c_2 = -0.42$
Intermediate plutonic rocks	$c_1 = 0.47$	Shrubland	$c_2 = -0.29$
Pyroclastics	$c_1 = 0.30$	Herbaceous vegetation	$c_2 = -0.38$
Carbonate sedimentary rocks	$c_1 = 0.28$	Artificial surfaces	$c_2 = -0.11$
Mixed sedimentary rocks	$c_1 = 0.39$	Bare areas	$c_2 = -0.02$
Siliciclastic sedimentary rocks	$c_1 = 0.56$	Permanent snow and ice	$c_2 = -0.07$
Unconsolidated sediments	$c_1 = 0.93$		
Acid volcanic rocks	$c_1 = 0.45$		
Basic volcanic rocks	$c_1 = 0.44$		
Intermediate volcanic rocks	$c_1 = 0.23$		

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