7091-Roads and landslides in Nepal: How development affects environmental risk

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Abstract. The number of deaths from landslides in Nepal has been increasing dramatically due to a complex combination of earthquakes, climate change, and an explosion of road construction that will only be increasing as China's Belt and Road Initiative seeks to construct three major trunk roads through the Nepali Himalaya. To determine the effect of informal roads on generating landslides, we measure the spatial distribution of roads and landslides triggered by the 2015 Gorkha earthquake and those triggered by monsoon rainfalls prior to 2015, as well as a set of randomly located landslides. As landslides generated by earthquakes are generally related to the geology, geomorphology and earthquake parameters, their distribution should be distinct from the rainfall-triggered slides that are more impacted by land use. We find that monsoon-generated landslides are almost twice as likely to occur within 100 m of a road than the landslides generated by the earthquake and the distribution of random slides in the same area. Based on these findings, geoscientists, planners and policymakers must consider how roads are altering the landscape, and how development affects the physical (and ecological), socio-political and economic factors that increases risk in exposed communities.

1. Introduction

On 29 and 30 July 2015, during the first monsoon season after the Mw=7.8 Gorkha earthquake, a dramatic cloudburst triggered landslides that killed 29 people in Nepal's Western Region (**BBC, 2015**). These deadly landslides and many others like them are not solely the result of intensified rainfall associated with climate change (**Bharti et al., 2016)**, but a complex intersection of socio-economic factors with a highly-altered physical landscape where informal, non-engineered roads regularly fail during the annual monsoon season (**Petley et al., 2007**). This problem will become more acute as China's Belt and Road Initiative (BRI) aims to expand trade into Nepal, India and beyond via a series of trans-Himalayan corridors which traverse some of the world's most geomorphically-complex terrain (**Bhushal, 2017**). This expanded transportation network will have unintended effects on the surrounding landscapes as villages seek to link to these lines with roads constructed and maintained with severely limited resources, putting them more at risk of landsliding.

Figure 1. Informal, rural roads in Sindhupalchok District, Nepal. (Top left) Earth-moving equipment is hired by villagers to expand footpaths into roads that bring goods and services to isolated locations. (Top right) There are 5 primary modes of potentially damaging mass movements caused by informal road construction- a) debris flows from excavated material stored on the downslope side of the road; b) Deeper seated landslides that are accommodates by poor road drainage; c) Shallow failures close to the road caused by oversteepened road cuts that can be mitigated by planting; d) Shallow landslides caused by oversteepening that include potentially stabilising roots from vegetation; e) Deeper seated failures below root zone related to road cuts. (Bottom left and right) Without proper engineering (slope gradients, drainage, etc.), landslides are triggered on these rural roads during heavy monsoonal rains, damaging land, structures, and roads, and endangering human lives and livelihoods.

Many villages in the Middle Hills region of rural Nepal are connected by simple footpaths that limit social and economic opportunity. As the nation continues developing, communities hire heavy machinery (funded in large part by remittances sent to rural villages) to expand these pathways into vehicular roads for better access to markets, educational opportunities, and healthcare (**Fig. 1**). The resulting informal roads often create landslides by undercutting slopes, providing pathways for water to seep into potential slide planes, and producing debris that is easily mobilised during heavy rainfall (e.g. **Sidle et al., 2006**). Landslides disrupt the transportation networks that bring much needed goods and services to and from rural communities, damage agricultural lands in regions where subsistence farming is the norm, and cause scores of deaths every year (**DesInventar, 2016**), all counteracting the sought after developmental gains.

To better understand the link between the development that will follow the BRI and geomorphic risk, we examine the relationship between roads and landslides in the Sindhupalchok district of

Central Nepal (**Fig. 2**). The 2015 Gorkha earthquake heavily impacted Sindhupalchok, where over 95% of the houses were severely damaged and over a third of the deaths occurred here (**ReliefWeb, 2017**). The earthquake also generated thousands of co-seismic landslides in this district (**Gnyawali and Adhikari, 2017; Fig. 2a**), many of which intersect rural roads. By comparing the geographic distribution of slope failures generated before and during the Gorkha earthquake with a randomly-distributed suite of landslides, we present compelling evidence that landslides associated with informal roads are a significant and often overlooked geomorphic agent and may compromise the development trajectory in villages that sought to gain from the road construction. Based on these results, we show that this mode of failure should be carefully considered in studies of landslide distribution and development planning, especially as the BRI extends the road network through the Himalaya.

2. Methods

To help determine the significance of roads in the generation of landslides, we compare the landslides present before the Gorkha earthquake with those triggered by the earthquake itself. Implicit in this comparison is that the landslides present before the earthquake were mostly generated by monsoonal rains on poorly drained, oversteepened roadcuts that concentrate water and facilitate failure (see **Petley et al., 2007**). Landslides generated by the earthquake, however, respond more to the geomorphology of the landscape more than the human-altered features, degree of weathering of the bedrock, and proximity to the deepest part of the earthquake rupture zone (**Roback et al., 2018**). If there is a strong spatial correlation between the roads and either set of landslides, we can begin to better understand how important these roads are in altering both the physical and social landscapes.

There were on the order of 20,000 landslides generated by the Gorkha earthquake (**Gnyawali and Adhikari, 2017; Roback et al., 2018**), of which 8,238 were in Sindhupalchok and are considered in this study alongside 139 discrete slides present before the earthquake. The landslide inventories we used was created by manually digitizing the bare earth-landslide scars in Google Earth from high resolution satellite images, at an eye altitude of 500 meters, correspondingly minimum detected landslide area being around 20 square meters (**Gnyawali and Adhikari, 2017**). The post-earthquake landslides inventory consists of scars observed in the image between April 25 (main -shock day) to May 25, 2015, during the dry season before the monsoon rains in June. Similarly, the pre-earthquake landslides inventory consist of the landslides identified in the area before April 25, 2015. Many of the slides were ground truthed with field observations. The vast majority of slides involve the regolith with very few deep-seated failures that involve the bedrock. It is not feasible to determine if the failures involve bedrock from the satellite imagery alone.

The distribution of the earthquake-generated landslides is similar to that generated by other earthquakes- the primary controls are related to proximity to earthquake rupture zone and peak ground acceleration, as well as the physical characteristics of the topography including aspect, slope, curvature and bedrock geology (**Gnyawali and Adhikari, 2017; Roback et al., 2018**). The majority of landslides (7,230 or 86%) occur in two soil types- the better developed, agricultural humic cambisols (CMu), and the less-productive eutric regosols (RGe) that occur in higher, more arid zones (**Dijkshoorn and Huting, 2009**; **Fig. 2a**). Of the 7,091 earthquake-triggered landslides, 2,687, or 38% are in the RGe soil type, whereas only 35 of 139 (25%) pre-earthquake landslides occur in this soil type. The remaining 104 monsoon-triggered landslides in the CMu are in the area with more agricultural development, and hence more exposed communities and roads.

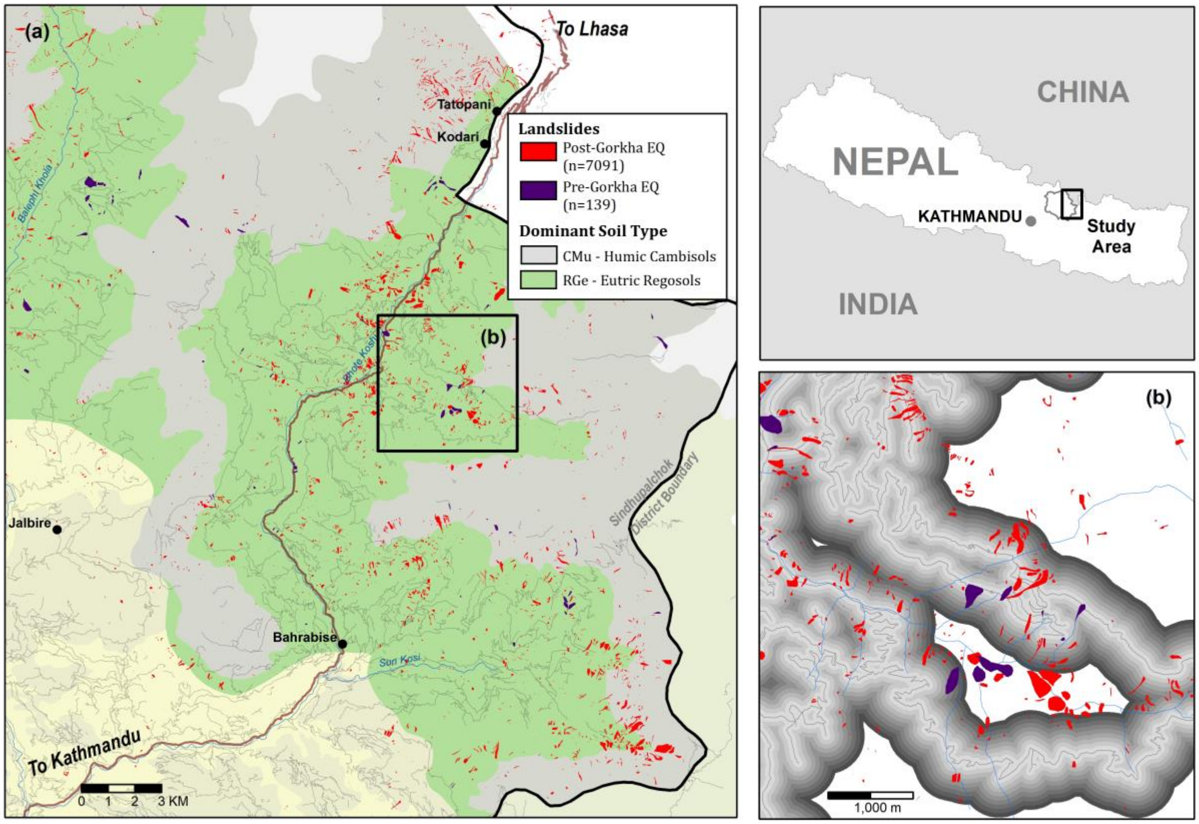

Figure 2. Roads and landslides in Sindhupalchok district, Nepal. (a) The Arniko Highway that runs between Kathmandu and Kodari at the Chinese border was heavily impacted by the 2015 Gorkha earthquake, and a dense network of informal, rural roads grows out of this main trunk road (**OpenStreetMap Contributors, 2017**). The red polygons mark the location of landslides generated during the earthquake, and the blue polygons were the landslides that were present before the earthquake (2014). Most landslides correspond with the CMu (humic cambisol) soil type as mapped by **Dijkshoorn and Huting (2009)**, however there is a higher percentage of earthquake-generated failures in the RGe (eutric regosols) soils. (b) We place buffers at 50 m intervals along the roads that can support a vehicle in the study area to determine the distribution of landslides within a given distance from the road.

To determine the spatial relationship between the landslides and roads, we sought to determine how many of the slides were in close-proximity to roads, suggesting a causal relationship. If more landslides of either class occur closer to the roads than the random distribution, then it would suggest that the existence of the roads predisposes the landscape to failure. If, however, the existing landslides match the randomly generated ones, then the presence of roads has little effect on landslide risk. First, we randomly distributed 7,091 earthquake-generated landslides and 139 monsoon-triggered slides over the map area covered by the CMu and RGe soil types using the same distribution of surface areas as the actual landslides (**Fig. 2a**). The pre-earthquake landslides have a normal distribution that is slightly skewed, perhaps due to undersampling of smaller slides limited by the satellite resolution (**Stark and Hovious, 2001**), whereas the co-seismic landslides follow an expected power law distribution (**Guzzetti et al., 2002**; **Fig. 3, inset**). We repeated this spatial randomisation process with a Monte Carlo simulation of 10 runs for each landslide dataset with arbitrary locations to ensure a good stochastic spread. Using the existing road network (**OpenStreetMap Contributors, 2017**), we filtered out the smallest trails and footpaths, leaving only tracks that had been improved and could likely support a vehicle. Finally, created nine buffers at 50 m intervals normal to the road, and counted the number of landslides that intersect the buffer at the given distance (**Fig. 2b**).

3. Results

Our observations from the field suggest a strong spatial correlation between roads and landslides, however as we are often traveling on roads, our sampling may be quite biased. By using satellite data and limiting the analysis to the soil types that might support agriculture at higher elevations and where the majority of the shallow-seated landslides are located, we observe a strong signal that demonstrates the genetic relationship between development, roads, and landslides in the areas that have the most farms, villages and roads.

In this district, we found that nearly 50% of the 139 pre-earthquake landslides occur within 100 m of a road, whereas only 20-25% of the 7,091 landslides generated by the earthquake are within 100 m of a road and overlap completely with the randomly-generated landslides from both triggering mechanisms (rainfall and earthquakes; **Fig. 3**). Stated differently, there are twice as many monsoon-generated landslides near roads than the earthquake generated landslides, and twice as many than in a randomly located suite of slides with the same area distribution. The monsoon-triggered landslides cover a total area of 1.9 km^2 (1.2 km^2 in CMu and 0.7 km^2 in RGe) whereas the earthquake-triggered slides represent 18.4 km^2 (9.8 km^2 in CMu and 8.6 km^2 in RGe) and the average area for the monsoon-triggered slides (13,670 m^2) is much larger than the earthquake-triggered slides (2,590 m^2).

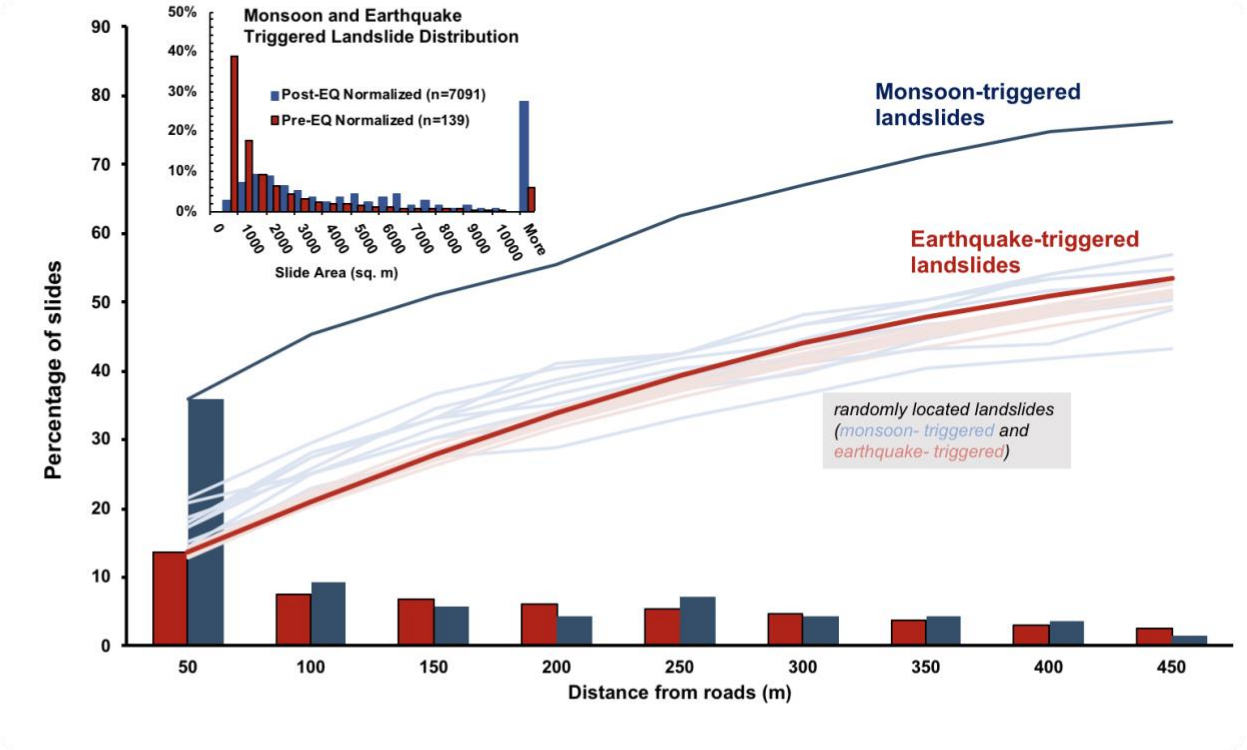

Figure 3. Distance from roads of earthquake, monsoon and randomly-generated landslides. Histograms show the distribution of landslide areas before and after the 2015 Gorkha earthquake. The grey lines represent the cumulative percentage of randomly-located landslides that occur within a given distance from a road, whereas the red line represents the percentage of earthquake-generated landslides (n=7,091) that occur with distance from roads, and the blue line represents the percentage of monsoon-generated landslides (n=139) that occur with distance from roads. These data demonstrate that roads are a significant generator of landslides.

Borrowing from the fractal literature (e.g. **Brown, 1987**), we might expect to see a noticeable kink in the trend of the cumulative number of slides at increasing distances from the road that would correspond to a, “crossover length”, or in this case, a critical distance from the road where the number of landslides begins to decrease. This tell-tale bend in the curve is not clear in the data, possibly due to resolution issues of the satellite data, as evidenced by the high number of slides within 50 m of the road. The trend, however, is not linear- If we had a random distribution of roads across the landscape in addition to the randomly distributed landslides, we would expect to see a linear increase in the cumulative number of landslides with distance from the road. What we notice, however, is that there are less slides further away from the roads than would be expected, suggesting that the roads might be in locations that are predisposed to failure, such as near valley bottoms or ridge tops.

Many of the roads in Sindhupalchok indeed follow the major river valleys (Bhote Koshi, Sun Koshi, Balephi Khola, Indrawate and Melamchi) as well as the smaller, steep ravines that are carved into the ridges. As many landslides occur in the inner gorges of these valleys, the data might reflect this bias. However, as suggested by the distance of the randomly placed landslides from the road, the landscape is being altered by a process that is well outside of the natural variation, and observations and failure modes strongly suggests that roads are the responsible for this marked increase in slide occurrence. Regardless, as many settlements are located near these water sources, the risk to villages and transportation networks remains significant.

4. Discussion

Informal rural roads are causing dramatic changes in the physical and social landscapes of the Middle Hills region of Nepal. Although the number of slides generated by monsoon rains is vanishingly small when compared to the vast number of slides triggered by the Gorkha event, they nonetheless have a substantial impact on the physical and social landscape. We show that there are twice as many landslides in the more developed areas (with its good agricultural soils and vast network of informal roads) than there would presumably be if the roads were better engineered. This concentration is due in part to the productive CMu soils in this part of the Middle Hills, along with deforestation for agriculture that likely leads to more shallow-seated landslides. Because the population in this region will soon be impacted by the improved BRI trunk road, expansion of the informal, rural transportation network is likely to grow, triggering more monsoon-rains driven failures and property loss, transportation network disruptions, and mortality.

While there are numerous factors that control where landslides occur, our data strongly suggest that the mechanism of failure is influenced by the presence of a road and gives us an idea of how important these anthropogenically-controlled slides are in shaping the landscape. It is well known that the risk of roadside failures is heightened during the monsoonal rains because of slope oversteepening on the uphill side of the road and the deposition of excavated debris on the downhill side that is easily mobilised during heavy rainfall events (accentuated by runoff from the road). This combined road-rainfall effect is more acute than earthquake- generated failures in terms of percentage, if not total numbers.

These road-related failures will also impact the sediment delivery system. While this snapshot of monsoon-induced slides is small compared to the earthquake, the average size is larger and it is important to consider this additional material in annual budget calculations based on current river sediment load, and over longer periods of time. There are many new hydropower schemes following the BRI trunk road development, and they will be forced to contend with this additional sediment burden.

The societal impact of these additional landslides is devastating and threatens to impede development for thousands of people in Nepal. **Petley et al. (2007)** show a 6-fold increase in landslide fatalities between 1992-2002, a time period marked by increased rainfall that culminated when 1.4 m of rain fell in July 2002 alone, resulting in 325 landslides that caused 455 deaths. **Figure 4** shows that between 2004 and 2006, the total number of rainfall and landslide deaths decreased significantly, but the annual fatality rate of 5.3 additional deaths occurring each year during the Maoist insurgency (1996-2006) increased dramatically to 9.4 more deaths every year following the ceasefire (**DesInventar, 2016**). This increase in death rate closely corresponds with a 55% increase in length of the road network (19,150 km to

27,120 km; **MoF, 2016**) funded in part by a 12-fold increase in foreign direct investment after the cease-fire. Nearly a third of the earthen and gravel roads developed as feeders to the main arteries prior to the insurgency, and now these informal roads represent over half of the roads in Nepal (**MoF, 2016**).

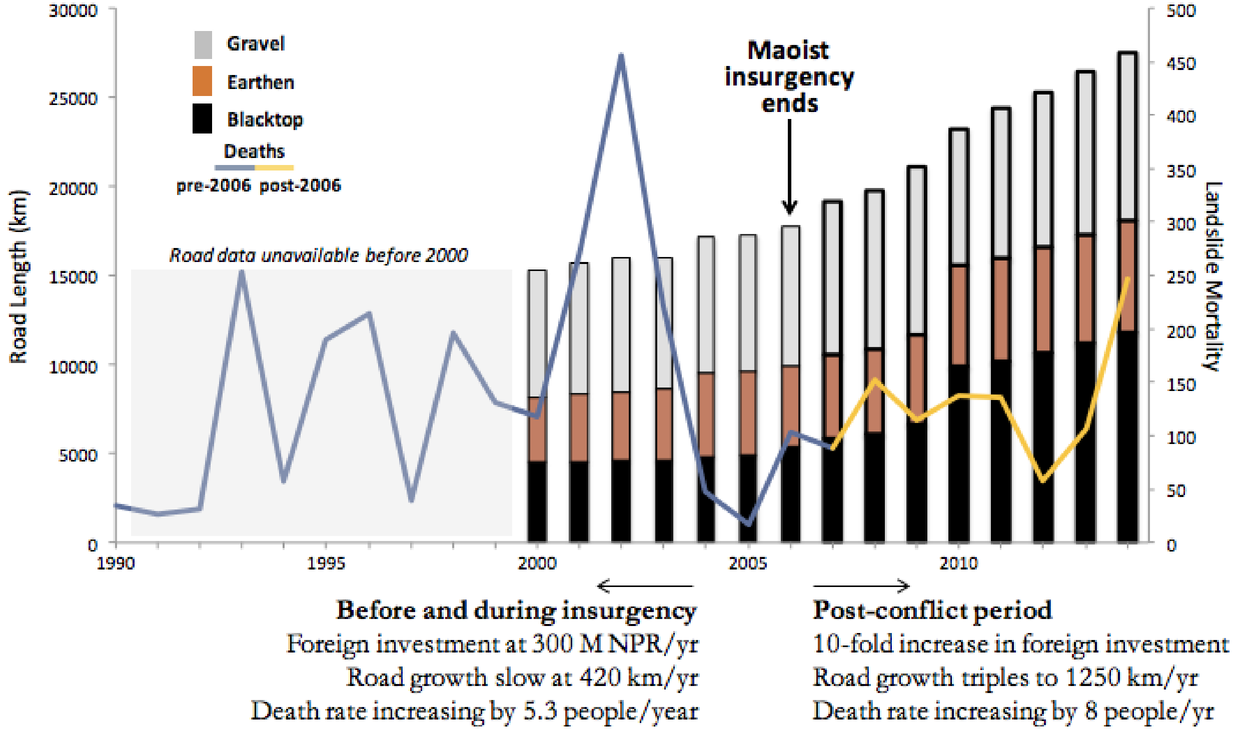

Figure 4. Following the 10-year Maoist insurgency against the Nepali government, foreign direct investment increased dramatically, funding nearly half of the Strategic Road Network and Local Road Network development (**MoF**, 2016). The resulting growth in the length of the road network closely followed the increase in mortality from landslides (**DesInventar**, 2016), many of which are associated with roads in the Middle Hills.

China's BRI fits well with the Nepali government's long-term development strategy to promote road development (**Murton, 2016; The Economist, 2017**). While the trunk roads constructed by the Chinese over the Himalaya are well-engineered, the concern lies in the informal roads that connect marginalised villages. With the onus of construction and maintenance of rural roads in the hands of local communities and politicians, scarce funds needed for road maintenance compete with the need for investment in other sectors. **Leibundgut et al. (2016)** found that the economic impact of rural roads around Phewa Lake, Kaski district of western Nepal amounted to $117,287 USD/year in maintenance costs, forecasted to rise to $192,000 USD/year by 2030 with the current rate of road construction. Considerations of more sustainable "Green roads" that take into account local engineering geology and best practices in design, construction and maintenance (**Hearn and Shakya, 2017**) are outweighed by local communities negotiating with limited funds, short-term political agendas and ease of access to heavy equipment.

5. Conclusions

The landslides generated by the 2015 Gorkha earthquake provide an opportunity to compare the distribution of ‘natural’ failures with those triggered by humans in a landscape heavily modified by informal road construction. By comparing earthquake-generated failures with those caused by monsoonal rains beforehand as well as a suite of randomly located landslides, we show that there are likely to be twice as many monsoon-generated landslides in terrain with poorly-constructed roads than would be present without roads. While these slides do not represent a much of a change in the physical systems during any given year, over time, their impact cannot be ignored. The socio-economic landscape, however, is being severely impacted by this explosion of informal roads to the point where it is hindering the development that the roads sought to bring and killing too many people in the process. Landslides in the Anthropocene are no longer simply a function of geomorphology and climate as poorly-built roads are rapidly changing the landscape.

Better engineered roads will lead to more sustainable economic development, but these roads come with a price. Although foreign investment aids construction, maintenance costs fall on impoverished communities who must decide between access and basic services. Green solutions such as plantings on metastable hillslopes are more economically sustainable and can be implemented by community members with minimal training. There is little that can be done to control the climate, but economically feasible and environmentally sound adaptations will reduce losses in resources and lives.

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