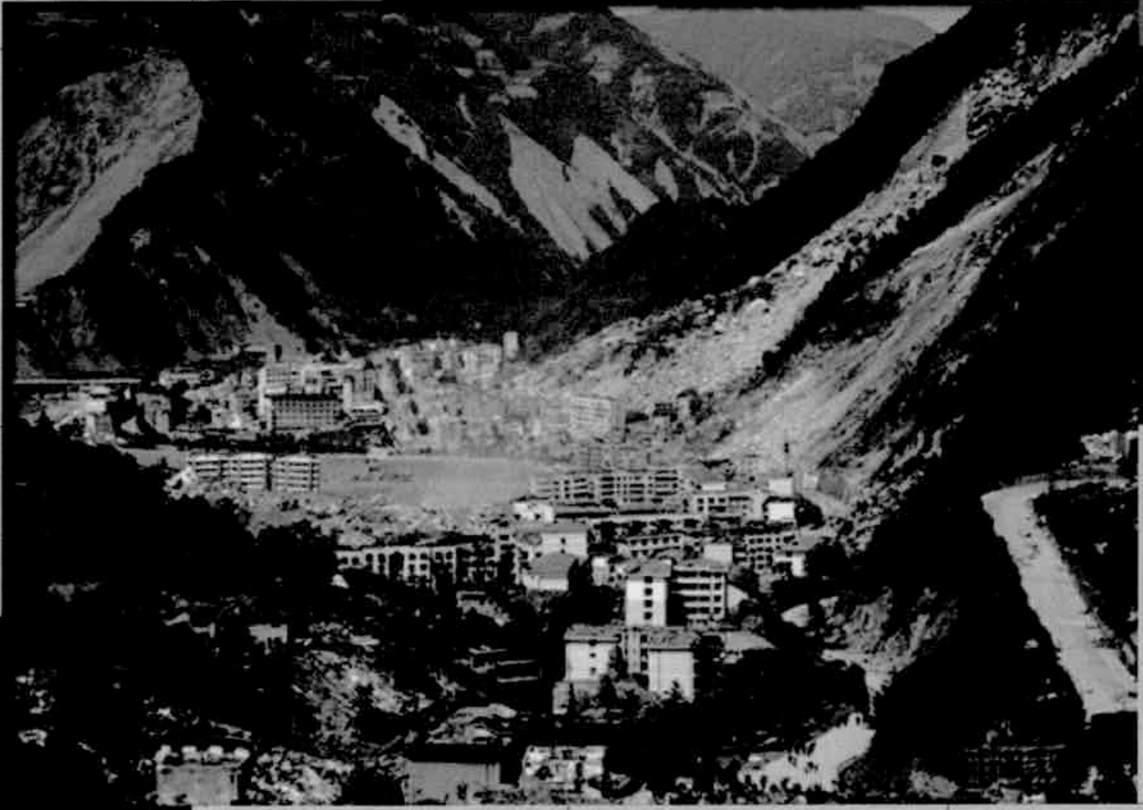
Proceedings of

The First World Landslide Forum

18-21 November 2008
United Nations University, Tokyo, Japan

Parallel Session Volume



Global Promotion Committee of
The International Programme on Landslides (IPL)

ISDR

International Strategy for Disaster Reduction

Global joint initiative by United Nations organizations, governmental organizations, non-governmental organizations, and individuals.

International Consortium on Landslides (ICL)

I symbolizes Cultural heritage at landslide risk.
C symbolizes a moving landslide mass.
L symbolizes Retaining wall to stabilize slopes.

Slight inclination of C symbolizes motion of landslide and the Consortium.

- ICL was established in January 2002 and legally registered as a non-profit scientific organization (No.1300-05-005237) in the Government of Kyoto Prefecture, Japan in August 2002.
- A full-color international quarterly journal “Landslides” was founded by ICL in April 2004. The impact factor of this journal is 0.986 for 2007.
- Approved as a scientific research organization (No.94307) eligible to apply and receive the Grants-in-Aid for Scientific Research by the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) in March 2007.
- Approved as a NGO in operational relations with UNESCO by the 176 Session of Executive Board of UNESCO in April 2007.

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Road Sediment Production and Delivery: Processes and Management

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1. Introduction

Unpaved roads are one of the most common types of man-induced disturbances. Roads induce surface runoff and can alter subsurface flow on hillslopes, and this can affect the magnitude and timing of surface runoff (Jones et al., 2000; Wemple et al., 2001). By exposing the soil surface and increasing and concentrating runoff, surface erosion can occur on each part of the road prism (i.e., cutslope, travelway, and fillslope) (Figure 1). The surface runoff from roads also can initiate gully erosion below the road prism. Roads also can increase landsliding on road cutslopes, fillslopes, and hillslopes by altering flowpaths as well as altering the strength, loading, and pores water pressures on hillslopes (Megahan et al., 2001; Wemple et al., 2001).

The magnitude and relative dominance of these different road erosion processes is driven by variations in climate, geology, physiography, road design, road construction, and road maintenance practices (Jones et al. 2000, Wemple et al. 2001). As such, there can be considerable variation in the type, magnitude, and frequency of road-related sediment production within and between regions. Hence the objectives of this paper are to: 1) describe the underlying processes of road sediment production from surface erosion and landsliding; 2) compare road sediment production rates from surface erosion and landslides in different environments; 3) compare the delivery and potential off-site effects of road-related sediment from surface erosion and mass movements, respectively; and 4) indicate the extent to which best management practices (BMPs) can minimize road sediment production and delivery from these road-related processes.

2. Sediment production from forest roads

2.1. Surface erosion from forest roads

The high infiltration rates and dense vegetative cover on most undisturbed forested hilllslopes means that surface runoff is relatively rare and hillslope erosion rates are very low. In contrast, unpaved roads can increase surface erosion rates by two or more orders of magnitude relative to undisturbed hillslopes (MacDonald and Coe, 2007). Research over the past three decades in a variety of environments has led to a relatively good understanding of road runoff and erosion processes.

Road travelways are highly compacted and have very low infiltration rates (typically less than 2-5 mm hr^{-1}). This results in the generation of infiltration-excess (Horton) overland flow even during small rainfall events. In addition, road cutslopes can intercept transient hillslope groundwater (i.e., subsurface stormflow). In some cases the interception of subsurface stormflow can account for more than 90% of the road surface runoff (Wemple and Jones, 2003).

The amount and energy of surface runoff determines the erosive force applied to the road prism by overland flow. The road prism can be broken into different process domains for surface erosion based on the interaction of flowpath length, which largely controls the amount of runoff, and slope, which is the primary control on the energy of the runoff. On road cutslopes and road fillslopes the slope can be very steep (Figure 1), but the limited slope length limits the amount of flow accumulation and hence the potential for hydraulic erosion.

The slope of the travelway is usually no more than about 10-12% in order to facilitate traffic and maximize safety, but runoff can accumulate along the travelway unless it is strongly outsloped or insloped (Figure 1). In many cases road runoff is prevented from running off the travelway by wheel ruts, and this can result in extensive rill or gully erosion on the road surface. The large volumes of water draining from longer road segments also can induce gully erosion on fillslopes or below drainage outlets.

The erodibility of the road prism varies according to the time since construction or grading, soil texture, ground cover, and traffic (Ramos-Scharrón and MacDonald, 2005). Sediment production rates for cutslopes, travelways, and fillslopes are highest immediately after road construction, with erosion rates declining rapidly within 1-2 years. Fine-textured soils are the most susceptible to surface erosion, with siltier soils producing 4-9 times more sediment than soils dominated by sand or gravel. Soils with higher rock content typically have lower erosion rates (Sugden and Woods, 2007).

Figure 1. A picture of a reconstructed outsloped native surface road on a highly erodible, weathered granodioritic hillslope in northern California, USA. The road prism is comprised of the cutslope, travelway, and fillslope, and the arrows show the potential length of overland flow for each of these pathways. Note how the rill networks on the travelway concentrate the road surface runoff before it is discharged onto the fillslope. The extensive rilling is due to poor compaction during road reconstruction.

Vegetative cover can protect the soil against surface erosion, and erosion from cutslopes and fillslopes declines over time as they revegetate. Road travelways and inboard ditches are subjected to maintenance activities such as grading, and this removes the surface cover and can greatly increase the supply of easily-erodible sediment. Grading can increase erosion rates from 70% to more than an order of magnitude relative to ungraded roads (Ramos-Scharrón and MacDonald, 2005). Surface erosion rates decline exponentially to a baseline erosion rate following initial construction or grading, and this rapid decline is due to the rapid depletion of the readily erodible material and surface armoring. Higher traffic levels increase the supply of fine material, and this is a major reason why traffic can increase sediment production rates by 2-1000 times (Ramos-Scharrón and MacDonald, 2005).

The variations in rainfall, soil texture, traffic, and other controlling factors mean that road surface erosion rates can vary over several orders of magnitude. Both empirical and physically-based road surface erosion models have been developed, and these typically include key variables such as precipitation or rainfall erosivity, road slope, road area or length, road surface slope, soil texture, time since grading, and traffic. Unfortunately it is still very difficult to accurately predict road surface erosion, and the lack of calibration and validation studies means that the models are most useful for predicting relative rather than absolute road surface erosion rates.

2.2. Landslide erosion from forest roads

Forest roads increase landsliding by disrupting the balance of driving and resisting forces acting upon and within hillslopes. As shown in Figure 2, road-related increases in landsliding are commonly attributed to: 1) oversteepening and/or overloading of downslope areas by road fills; 2) removing support for unstable hillslopes by undercutting road cutslopes; and 3) concentrating road surface runoff onto potentially unstable portions of the road fillslope and lower hillslopes (Sidle and Ochiai, 2006).

Road-induced landsliding is generally only an issue in relatively steep terrain, with most road-initiated failures occurring on hillslopes greater than 31-39° (i.e., 60-80%). In such areas landsliding from roads can exceed natural landsliding rates by 10-100 times, and most reported values in landslide-prone terranes range from 4-60 Mg ha^{-1} yr^{-1} (Sidle and Ochiai, 2006).

Cutslope failures are a common occurrence in steep areas as a result of the oversteepened hillslopes (Figure 2). By reducing the support at the toe of unstable features (i.e., undercutting), cutslopes can increase the likelihood of rotational slides. Cutslopes also expose the hillslope to weathering, which can progressively decrease the strength of the hillslope materials.

Fill material is particularly unstable when it is placed on slopes greater than 35° and on unstable landforms such as colluvial hollows and inner gorges. Fillslope failures can be largely eliminated by the more costly approach of full bench construction, but this generates a much higher cutslope.

In many cases the increase in landsliding due to roads is a result of the changes in surface runoff. The routing of concentrated road runoff onto fillslopes or hillslopes can greatly decrease their stability as a result of the additional weight and the increase in pore water pressures. Catastrophic failure of the road fill and the initiation of debris flows or landslides can occur when culverts plug or overtop during storms.

The prediction of road-related landsliding is difficult given the stochastic nature of landslide initiation, variability in road design and construction, and the inability to represent many of the causal processes for road-landslide interactions. Slope stability models such as SHALSTAB and SINMAP are useful for predicting the relative risk of failure and as landscape stratification tools. For management purposes these spatially-explicit estimates must be followed by field-based slope stability assessments to better identify and minimize the landslide risk for a specific area.

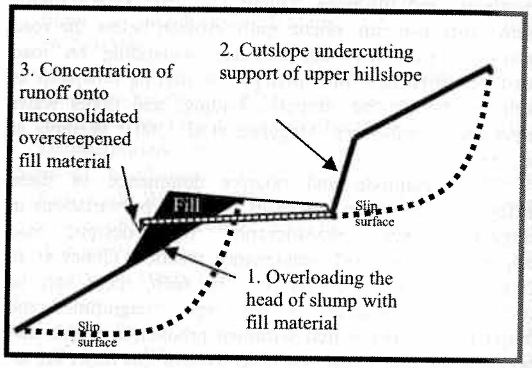

Figure 2. Schematic showing how a road increases the likelihood of landsliding.

3. Sediment delivery from forest roads

3.1. Sediment delivery from road-related surface erosion

The delivery of road-related surface erosion is of concern because it is generally fine-grained (sand sized or smaller) (Ramos-Scharron and MacDonald, 2005), and this material is particularly detrimental to many aquatic organisms (Waters 1995). Connectivity refers to the proportion of roads that drain directly to streams or other water bodies. The proportion of connected roads is strongly controlled by road location, road design, and the factors that control the amount of road runoff. In the western U.S. road-stream crossings account for 30-75% of the connected road length. It follows that road sediment delivery is highly dependent on stream density, as this affects both the number of road-stream crossings and the proximity of the roads to the stream channel network.

The delivery of road runoff and sediment to streams generally decreases as the distance between a road and a stream increases. If the road runoff is dispersed, the sediment from road surface erosion rarely travels more than 30 m on vegetated hillslopes. However, if the road runoff is concentrated into a single drainage outlet, the runoff and sediment can induce gullying and travel 3-4 times further than when it is dispersed.

The development of gullies as a result of concentrated runoff is the second most important mechanism for road-stream connectivity, as 9-35% of the total road length can be connected to the channel network via this process. Since longer road segments result in more runoff and more erosive power below road drainage outlets, roads with inadequate drainage are much more likely to induce gullies and be connected to the stream channel network that roads with dispersed or more frequent drainage.

A meta-analysis of the available data indicates that road-stream connectivity is a relatively simple function of annual precipitation and the presence of engineered drainage structures (Coe, 2006). The empirical predictive equation developed from 11 studies in different parts of the world is:

$$C = 12.9 + 0.016P + 39.5M \qquad (1)$$

where C is the percent of road length or road segments that are connected to the channel network, P is the mean annual precipitation in millimeters, and M is a binary variable with 0 representing roads with drainage structures, and 1 representing roads without drainage structures ($R^2=0.92$; $p<0.0001$). This predictive equation indicates the importance of precipitation in controlling both the amount of runoff and the density of the stream network. The binary variable indicates that well-designed roads with regular drainage will decrease road connectedness and hence road sediment delivery by at least 40%.

3.2. Sediment delivery from road-related landslides

The downstream delivery of road-induced landslides is dependent on their location relative to the channel network, road design, and the travel distance of the failure (MacDonald and Coe, 2007). Road-induced slope failures in colluvial hollows have a higher likelihood of delivering sediment to the channel network because these areas are located directly above first-order channels (Figure 3). Similarly, road-related failures in inner gorge landforms have a high probability of delivering sediment to streams because these areas are typically very steep and the slopes feed directly into the stream channels that carved these features (MacDonald and Coe, 2007). Sediment delivery is also high when flood flows overtop road-channel crossings and initiate landslides or debris flows.

Road-induced landslides deliver both fine and coarse sediment to the channel network. The episodic delivery of this sediment can induce debris fans, valley terrace formation, channel avulsion, channel aggradation, substrate fining, channel widening, and pool infilling (MacDonald and Coe, 2007). These sediment-induced changes in channel morphology can increase downstream flooding and bank erosion by reducing the channel capacity, and also can adversely affect water quality and fish habitat (MacDonald and Coe, 2007).

In summary, roads not only induce landslides at a very high rate relative to forests or clearcuts, but they also have a greater potential to deliver this sediment to the stream network. In the Oregon Coast Range in the western USA, road-induced mass failures traveled on average three times farther than in a mature forest. The combination of a much higher mass-failure rate and a higher sediment delivery means that road-induced mass failures can increase the amount of sediment being delivered to the channel network by nearly five times relative to mature forests (May, 2002).

Figure 3. Road-induced debris flows in northwest Washington state, USA. The debris flows initiated in the colluvial hollows on the upper road were triggered by road runoff, and these triggered the failures at the road-stream crossings on the lower road. The road was built prior to the implementation of best management practices and large fill volumes were placed within colluvial hollow and inner gorge landforms.

4. Management implications

The mitigation of road-related sediment production and delivery will vary according to the dominant road erosion process (Figure 4). A knowledge and understanding of these different process domains is essential to the proper selection and implementation of best management practices (BMPs), and the likely effectiveness. Without this understanding managers are more likely to treat the symptoms rather than the underlying causes.

Road surface sediment production can be readily reduced by improving road drainage, as this will decrease

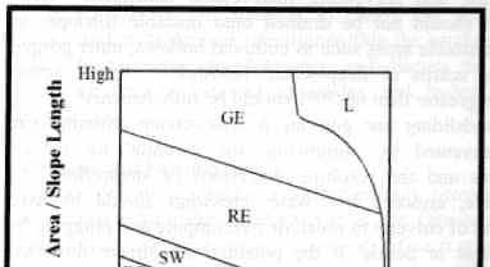

Figure 4. Conceptual process domains for rainsplash erosion (RS), sheetwash erosion (SW), rill erosion (RE), gully erosion (GE), and landsliding (L) as a function of flowpath slope and the amount of runoff as a function of flowpath area or length. The effectiveness of BMPs can be maximized by understanding and applying these process regimes.

the amount of of accumulated runoff and the erosive force applied to the road prism. Road drainage can be improved by increasing the frequency of road drainage structures such as waterbars, rolling dips, or cross-relief culverts. Outsloping the travelway is effective for decreasing flowpath length, dispersing runoff, and minimizing sediment production.

Surface erosion from roads also can be minimized by increasing the resistance of the road prism to the erosive forces of rainsplash and overland flow. Rocking the travelway can reduce sediment production by more than an order of magnitude. The addition of groundcover (e.g. mulching) to cutslopes and fillslopes can decrease sediment production (Megahan et al., 2001). Placing energy dissipators such as rocks or logging slash below road drainage outlets can greatly reduce surface erosion on fillslopes. Grading of the road travelway should be minimized, and the need for grading can be greatly reduced if adequate drainage is put in place and wet weather driving is restricted. Grading of inboard ditches also should be avoided unless absolutely necessary.

Similarly, the delivery of road surface erosion is best prevented by draining the road travelway frequently before road-stream crossings. Gully initiation below drainage outlets can be prevented by frequently draining the road and by placing energy dissipators below the outlets.

In areas dominated by road-related landsliding, road surface erosion may only represent 1-10% of the road-related sediment production. Priority in such areas should be to reduce road-related landsliding.

Slope stability problems can be minimized by: 1) reducing the length and width of roads on steep and unstable hillslopes; 2) minimizing the size of cut and fill slopes; 3) dispersing road runoff and only putting concentrated runoff onto stable hillslopes and channels; and 4) minimizing the number of road-stream crossings and carefully designing the unavoidable stream crossings. It should be clear that improving road drainage is critical to reducing and preventing road-related landslides. Road runoff should not be drained onto unstable fillslopes or onto unstable areas such as colluvial hollows, inner gorges, or the scarps of deep-seated landslides. Roads across slopes greater than 60-70% should be fully benched.

Landsliding and gullying at road-stream crossings can be prevented by minimizing the potential for culvert failures and the resulting diversions of streamflow. If possible, armored low water crossings should be used instead of culverts to preclude overtopping and plugging by sediment or debris. If the potential for stream diversion exists, an armored dip should be installed immediately below the crossing to quickly route the diverted streamflow back into the channel.

The BMPs used to mitigate road sediment production and delivery also will depend upon the resource of concern and the relative cost-benefit ratios. It should be recognized that reducing surface erosion may have immediate benefits, while efforts to reduce landsliding may not pay off until the next large storm event that could have caused a slope failure in the absence of any treatment. There also may be a substantial time lag between a reduction in sediment production and any improvement in downstream conditions (MacDonald and Coe, 2007).

5. Conclusions

Roads are important, chronic sources of runoff and sediment. This sediment is generated by both surface erosion and road-induced landslides. The surface erosion comes primarily from the road travelway as a result of rainsplash, sheetwash and rilling. Road surface erosion rates are highly variable, and depend on the contributing area, slope, precipitation intensity, soil type, soil rock content, and traffic. This sediment is delivered to the stream channel network primarily at road-stream crossings. Mean annual precipitation appears to be the primary control on road-stream connectivity.

Road-induced landslides can generate more sediment in some steep, humid areas than road surface erosion. An understanding of the process domains for road runoff and erosion is essential for reducing road sediment production and delivery. A range of best management practices have been developed to reduce road sediment production and delivery. In general it is easier to reduce road surface erosion than the number and size of road-induced landslides.

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