VULNERABILITY REDUCTION (STORMPROOFING) AND DAMAGE REPAIRS USING BEST PRACTICES ON LOW-VOLUME ROADS

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ABSTRACT

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Many millions of dollars are spent annually on storm damage repairs worldwide. Natural disasters are a recurring threat to life and infrastructure today. The frequency and intensity of disasters is increasing. Major storm events commonly lead to widespread flooding, road washouts, numerous failed bridges and culverts, and large and small scale slope failures, particularly on low-volume roads.

Fortunately many measures can be undertaken to reduce the vulnerability and prevent or minimize the damage caused by storms. This can be considered Storm Damage Risk Reduction, or "storm proofing" a road. For storm damage prevention, planning for major storm events, sound engineering analysis, the use of roads Best Management Practices, and the application of mitigation measures are needed.

Storm damage risk reduction first involves an assessment of any given road, the natural setting, the value of the road, traffic use, and design standards. Roads in areas of high risk, in steep terrain, areas subject to flooding, and those most important should be prioritized for preventative work.

Measures to reduce the risk of road damage include keeping the road well maintained and the drainage system functioning; using frequent cross-drain structures; preventing stream diversion; minimizing debris in channels; keeping slopes well vegetated; etc.

1. INTRODUCTION

The frequency and intensity of natural disasters appears to be increasing, likely due to Global Climate Change and related effects. They represent a recurring threat to life and infrastructure worldwide today. In the Western United States at least 5 major storm events have occurred in the past forty years. In 2004 three major storms hit North Carolina in a row, causing widespread devastation and $50 million in damage. Hurricanes in the Caribbean and monsoons or typhoons worldwide are becoming more intense and destructive. Hurricane Katrina in 2005 was a "monster". Hurricane Mitch in 1998 and Hurricane Stan in 2005 did extensive damage in Central America and Mexico. Recent record floods in Pakistan and Australia have had locally devastating effects. Roads, and particularly low-volume roads, are typically impacted by flooding, reducing their serviceability at a time they are needed the most, Closure or damage to rural roads presents a major hardship to local populations, hinders disaster relief efforts, and results in costly damage and associated repairs.

Disasters come from a variety of natural events. These include tropical storms and hurricanes, earthquakes, landslides, volcanoes, fires, tsunamis, and wind storms and tornadoes. By far the most common and significant damage to roads comes from inundations and flooding caused by hurricanes, monsoons, tornadoes, or tropical storms. Storm events have lead to widespread flooding, inundation of roads on floodplains and washouts near streams (see Figure 1), numerous failed bridges and culverts, and slope failures.

Figure 1 - A road washout due to poor road location on a floodplain.

Many measures can be undertaken to reduce the vulnerability of and prevent or minimize the damage caused by storms, but it does require planning, road maintenance, the application of preventative measures, and the use of roads engineering Best Management Practices. Also a great deal of experience has been gained in the cost-effective repair of damaged roads, including improved drainage, increasing capacity of culverts and bridges, and slope stabilization measures.

Vulnerability to natural hazards can be defined as the extent to which people will be harmed and property will be damaged from that hazard. These hazards impact humans, property, communications and transportation networks, and the social fabric of communities. The greatest vulnerability occurs in areas with the greatest population, where the most infrastructure has been built, where road use is the highest, and where the local population is dependent on a single route. The greatest vulnerability results from possible prolonged delays for many people with lack of access to markets, high loss of infrastructure, and lack of alternative routes (OAS/USAID, 1997) [1]. Rural roads are not typically considered critically important, but they can impact large rural areas, and they are a part of the transportation system that can be "storm-proofed" in many areas for relatively low cost. Local authorities as well as donor and private volunteer organizations (PVOs) have confirmed that the rehabilitation and repair of local infrastructure that provides basic services to rural, isolated populations is a top priority (CARE Nicaragua, 2000) [2].

Storm damage assessments, for both repairs and assessing vulnerability, have involves a subjective process of working with local communities to identify their highest priorities and support, combined with objective inventory of the transportation system, road use, and identification of hazards, the most vulnerable sites on roads, risk and consequences of failure, and repair alternatives. Most needed work can be specified on simple work lists with needed site information and site-specific repair or reconstruction recommendations.

Planning before a disaster occurs and actions during a storm event include issues such as having good inventories of the transportation system and knowing alternatives to use in case of closures; knowing the ”weakest link” in the transportation system and how to work around it or being prepared for temporary repairs; and having a system of communication in-place that functions during a disaster.

Physical measures to reduce the vulnerability of roads include good design, preventative design measures and upgrading of facilities, and preventative maintenance. Some of the measures commonly used include the following:

- Keeping the road well maintained and the drainage system functioning;
- Keeping ditches and bridges free of excessive vegetation;
- Keeping adequate vegetative cover on soil slopes;
- Adding a reinforced dip or armoring for overflow protection on undersized culverts;
- Using stream diversion prevention dips to prevent washouts down a road;
- Adding trash racks to drainages carrying woody debris;
- Pulling back marginally stable or loose fill slope material;
- Planning for “storm damage patrols” to inspect roads during storms; etc.

Storm damage repair corrective measures have included closing and relocating roads; improving roadway surface drainage; repairs or replacement of bridges, culverts and fords; and a wide variety of slope stabilization measures including use of horizontal drains, buttresses, reinforced fills, lightweight fills, and mechanically stabilized earth (MSE) and gravity retaining structures.

In some cases, the only alternative is to rebuild a road knowing the road will likely fail in the future, but only if it is determined that the road is absolutely necessary, changing the location of the road is not an option, and known hazards cannot economically be mitigated. The probable frequency of replacement should be evaluated to justify the repair investment in a known geologic hazard area. Road standard and investment should be minimal in these high-risk areas.

2. PLANNING AND PREPARATION

Disasters and major storm events will happen! The only question seems to be when, where, and how often, and unfortunately these answers are unknown! Thus to minimize the damage and impacts of natural disasters, countries or agencies need to plan and be prepared for disasters and reflect such events in their design and maintenance practices.

Steps that can be taken to be prepared for storm events and reduce the impact of storm damage include the following:

- Have a transportation inventory and identification of major routes;
- Inventory points of great risk or vulnerability;

- Identify alternative transportation routes;
- Have maintenance equipment available;
- Keep temporary bridges on hand (like Bailey bridges);
- Organize storm damage patrols;
- Keep maps available and a system of communication that functions during storms.

Adequate communications during a disaster is critical for coordination of services, reporting damage and areas of local emergencies, and planning repair measures. In August, 2005 when Hurricane Katrina hit the Gulf Coast region and New Orleans, many of the local communication systems for relief efforts were inoperable because of lack of power and lack of access to bring in generators and fuel. Communications between command centers and the field was accomplished by runners. Thus a reliable communications system is needed.

Additionally a disaster response organization must be in place, such as one based upon the Incident Command System (ICS) [3]. Key individuals must know their responsibilities and drills should be held periodically so that all members of the command and operations know their jobs before and during a disaster. Have redundancy in the system to compensate for missing individuals.

3. RISK ASSESSMENT

Two different levels or types of risk assessment can be undertaken. The assessment principally discussed herein is determining where to do risk reduction work and spend limited funds before any major storm strikes. The other assessment period is after a major storm where storm damage exists and assessment must be done to repair the sites and reopen road systems, and which projects will be repaired first. Some considerations are similar. For post-disaster assessment work, repair priorities have dominantly been based upon road use and standard of the road, with the most heavily used and important roads receiving top priority. Other factors influencing project priorities include land manager priorities; opportunities for road closure or re-routing; right-of-way conflicts; watershed, legal, and sensitive species issues; and funding limitations. The actual assessment work is typically accomplished by engineers working with other resource specialists such as hydrologists or geologists on an interdisciplinary team, as well as coordination with local governments.

Disaster assessment prior to an event requires deciding where to apply risk reduction measures. This involves a large number of considerations. These include watershed geology and condition, geographic location of the road, local and historic storm patterns, shape and orientation of the watershed, soil types and characteristics, road location on the slope, slope steepness, road standard, as well as other factors. Thus roads that have the greatest risk of failure and causing damage can be identified.

The orientation of a watershed and its hillslope characteristics control how that watershed will respond to severe storms and what stresses a road may encounter during storm events. For instance, watersheds that are aligned with the storm track respond greater to storm inputs than watersheds that are perpendicular to the typical storm track. Other watershed scale factors that determine the risks faced by a road system are related to watershed condition. These include land use, past and current, that affects how the watershed handles runoff generated during storm events and the nature of sediment generated by runoff, and road density. At the smaller scale, site conditions pose a number of threats to a road system. These include: unstable slopes; local land use or disturbances such a harvest units or fire; stream densities; proximity to stream channels, wetlands and floodplains; the site specific morphology at stream crossings; micro-topography such as bedrock outcrops and slope breaks; road grade, cut and fill slope materials; road switchbacks and stacked roads on the slope; road position on the hillslope; and roadside vegetation.

Two components of storm damage risk must be evaluated to help selection of the appropriate treatment. First there is the risk of failure component. This is the risk, related to the various factors noted above, that a road feature may fail or be damaged during a storm event. The second component is the actual value at risk. The resource or road component that would incur damage is part of the risk equation that determines the amount of resources and the level of risk that is tolerable. There is the value of the infrastructure itself (loss of or damage to road components that impair or prevent use of the road until repaired). These require the expenditure of funds to repair the infrastructure. There are also environmental values, such as the importance of protecting water quality, maintaining aquatic habitat in a stream, or protecting riparian plant communities that are impacted by stream migration or scour. There may be long term consequences to some of these resources.

Last, the consequences of failure must be evaluated. What happens to the material if a roadway fill fails? If the material travels a short distance downslope and comes to rest in the forest or on a river terrace, the harm would be less than if that debris entered a critical area such as a high water quality stream or damages a road below. The likely final location of the failure material is important to determine the risk tolerance for the site. Once these items and conditions are identified, an assessment of the level of acceptable loss can be determined. Downslope factors that should be evaluated in order to predict the disposition of the failure material include the following:

- Topography and presence of broken slopes with terraces or benches to catch material, versus steep straight slopes that deliver directly to water or wetlands;
- Distance downslope to valuable resources;
- Volume of material that would travel the distance;
- Downslope resources that are affected and their resilience to impacts;

4. APPLICATION OF BEST MANAGEMENT PRACTICES

Roads engineering Best Management Practices should be regularly applied in road management to reduce the impact of storm damage, to lessen environmental damage and water quality degradation, and lessen impacts of road delays, closures, and repair costs. Since roads are a critical part of rural infrastructure, they need to be built, protected, and maintained as well as possible with appropriate design standards and mitigation measures. The application of Best Management Practices helps to achieve these goals. They also help guarantee a reasonable level of needed quality in design practice and for water quality protection, and they reduce the risk of damage during storm events.

Best Management Practices are an integral part of road planning, design, and maintenance that builds in a certain level of quality into the road. A road built using Best Practices will likely be well located, minimize ground disturbance, be well drained, and surfaced appropriately to control loss of surfacing material. The road also has appropriately selected and designed drainage crossing structures with adequate storm flow capacity, stable cut and fill slopes, has effective erosion control measures, and it is regularly maintained. All of these measures help reduce or prevent storm damage. Much of this information is outlined and summarized in the USAID/US Forest Service publication titled *Low-Volume Roads Engineering-Best Management Practices Field Guide,* by Keller and Sherar, 2003 [4].

5. STORM DAMAGE RISK REDUCTION (STORM-PROOFING)

A variety of planning and design tools are available to rural roads managers and engineers to help "storm-proof" a road and reduce the risk of damage to the road from storms. Note that no roads are totally "storm proof", but their risk of damage or failure can be reduced. These measures include:

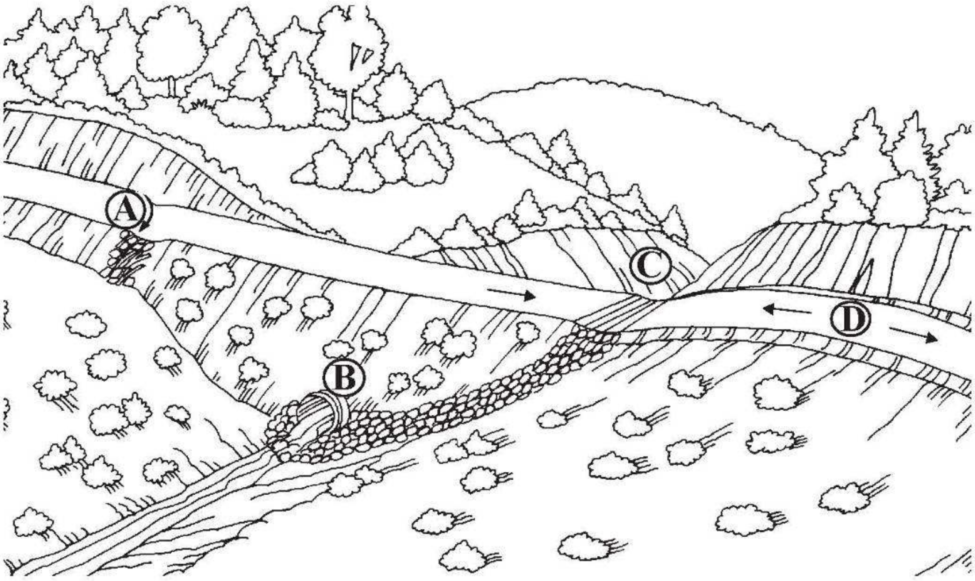
- Preventative maintenance;
- The application of Engineering Best Management Practices;
- Simple, minor road improvements;
- Major retrofits or mitigation work as needed.

A list of specific recommendations, or "Best Practices", is presented below. In general several lessons have been learned regarding rural road function during major storm events. Road drainage or drainage crossing designs with overflow protection will reduce damage to the road; surfaced roads generally hold their shape better and maintain drainage patterns better than unsurfaced roads; well installed culverts reduced the frequency of failure; using fords rather than culverts further reduces the risk of failure; and full bench construction with minimal fills reduced the incident of slope failures (Copstead and Johansen, 1998) [5].

For road stream crossings, studies have indicated that damage and risk can be reduced both by increasing the crossing structure (culvert) capacity, and by decreasing the consequence of overtopping (Furniss, et al, 1998) [6]. Figure 2 shows a road badly damaged by a simple culvert failure caused by plugging and overtopping. Culvert capacity and installation can be improved, and plugging potential decreased, by sizing pipes to limit the headwater depth to culvert diameter ratio (Hw/D) to less than 1. In watersheds with a lot of channel debris, the Hw/D ratio should be as low as 0.7.

Other measures include using culverts as wide as the natural active channel width; aligning the culvert with the natural stream channel; repairing damaged culvert inlets; and by keeping a well vegetated stream channel margin. The document *Designing Watercourse Crossings for Passage of 100-year Flood Flows, Wood, and Sediment*, by the California Division of Forestry [7] discusses key measures useful to prevent culvert failure. The consequences of overtopping, failure, and stream diversion can be minimized, particularly on rural roads, by keeping the fills as small as possible; by constructing fills with coarse material and compacting the fill material; by using concrete headwalls on culverts; and by avoiding stream diversion with use of berms or armored dips to insure that any water that overtops the structure stays on-site in the natural channel (Furniss, et al, 1997) [8]. Figure 3 shows a stream diversion prevention dip installed in the road at a stream crossing with a large fill.

Figure 2 - A washed out rural road due to a plugged and overtopped culvert and lack of overflow protection.



(A) Roadway Cross Drain (Dip)
(B) Culvert
(C) Overflow Protection Dip
(D) High point in the road profile

Figure 3 - Overflow dip protection and diversion prevention at a fill stream crossing.

The work needed to reduce risk of damage and failures can be identified in the field on a "work list", where the specific item, site conditions, and description of work are listed by station or kilometer along the road. Figure 4 presents an example of a simple work list form used in Honduras that is useful to document needed work along a road. Most identified items of work involve improving roadway surface drainage to avoid water concentration and having well designed drainage crossing structures. Other common items of work include road surface stabilization, slope treatments or needed retaining structures, and erosion control measures.

Location, Station or MP	**Road Width m.**	**Road Grade %**	**Cross-Slope %**	**Code**	**Work Description**
D1 (MP 0.0)			0		Intersection with P1 at Saddle
	4+1RL	0-18			Inslope Road to Ditch, Clean Ditch
D2					Install 24" Pipe & Drop Inlet, Drain Left
		11-12			Outslope Road, Reshape Rough Road Surface
D3 (MP 0.1)			15		Construct Dip, Drain Left
		3			Outslope Road
D4					Clean Existing Timber Culvert
		3			Inslope Road to Ditch
D5					Excavate Inlet Basin for Timber Culvert
	3.5+1RL	+3--3	35		Inslope Road and Reshape Ditch
D6					Replace Damaged Timber Culvert with an Armored Dip
		+3--3			Reshape Road and Ditch
D7			15		Construct Dip, Drain Left
		3 -5			Inslope Road, Reshape Ditch
D8 (MP 0.35)			20		Existing Timber Bridge Marginal—Eventually Replace with an Armored Ford
	3.5+1RL	7			Inslope Road, Reshape Ditch
D9			15		Replace Plugged Existing Timber Culvert With Culvert or Dip (Lower Grade 45 cm)
		2-10			Outslope Road and Construct 3 Dips, Drain Left
D10			25		Construct Dip, Drain Right
		10-16			Smooth Existing Roadway--Alternative-Relocate Road between D10 & D11
D11			15		Construct Dip Left
	3.5+1RL	6			Outslope Road
D12 (MP0.7)			0		At Gentle Saddle—Road OK
		2-5	10		Outslope Road, Construct 6 Dips between D12 & D13

Figure 4 – Example of a simple work list from a storm damage project (Desvio Sabana Hoyosa).

Some “stormproofing” considerations and measures applicable to low-volume roads include the following:

- **Identify areas of historic or potential vulnerability**. Areas of historic or potential vulnerability, such as geologically unstable materials or slopes, areas subject to flooding, or areas of high volcanic or seismic hazards should be identified, with mapping or the use of existing hazard maps, to assess the potential risk of that area, avoided if possible, or the hazard considered in design.

- **Avoid local problematic and high risk areas**. Local problematic areas and poor road locations should be avoided whenever possible to reduce risk or reduce the cost of construction and repairs. Common problematic areas include steep slopes (over 60-70%), landslides, avalanches, rock-fall areas, wet areas, saturated soils, highly erosive soils, rock outcrops, etc. Avoid or minimize construction in narrow canyon bottoms or on flood plains of rivers that will inevitably be inundated during major storm events.

- **Use appropriate minimum design standards**. Road standards, and particularly road width, should be minimized as low as possible and yet satisfy traffic safety and the needs of the road user. Minimum standards will result in less earthwork, lower cuts and fills, and less surface drainage structures, all of which reduce risk of damage or failure during disasters. Structures, however, should not be underdesigned!

- **Incorporate relevant appropriate technology**. Apply current appropriate technology to improve planning, design, construction, and repair practices. This includes the use of GIS and GPS technology; geosynthetics for filters, separation, and reinforcement; mechanically stabilized earth retaining structures; current riprap sizing criteria for bank stabilization; biotechnical slope stabilization and erosion control measures, etc.

- **Minimize changes to natural drainage patterns, both surface and subsurface**. Changes to natural drainage patterns and crossings to drainages are problematic and should be avoided or minimized. Drainage crossings are expensive, so they must be well designed. Changes to natural drainage patterns or channels often result in environmental damage, substantially increased costs, or higher risk of failures.

- **Use simple, positive, frequent roadway surface drainage measures**. Good roadway surface drainage, frequent cross-drains, crown, inslope or outslope roads (see Figure 5), and rolling road grades should be provided so that water is dispersed off the road frequently and water concentration is minimized. Outslope roads whenever practical and use rolling dip cross-drains for surface drainage rather than a system of ditches and culverts that require more maintenance and can easily plug during major storm events. Few rural roads are built with adequate surface drainage and this concentrated water causes the majority of damage. Failed cross-drain culverts are very common after major storm events.

- **Properly install and size culverts**. Improperly installed or undersized pipes are two of the most common reasons for pipe failure during storms. Improper alignment, excessive headwater elevation, excessively wide inlet areas, and inadequate capacity all contribute to pipe plugging and subsequent failure. Headwalls greatly improve the resistance of culvert to failure during overtopping.

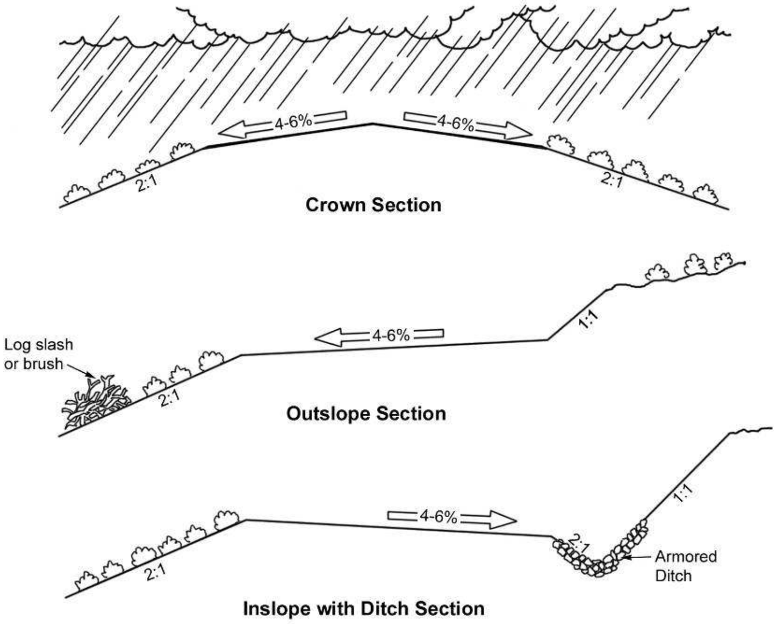


Figure 5 – Road surface drainage options to remove water off the road surface.

- **Use simple fords or vented low-water crossings**. Simple fords or vented low-water crossings should be used as often as appropriate for small or low-flow stream crossings on low-volume roads, instead of culvert pipes that are more susceptible to plugging and failure (see Figure 6). Protect the entire wetted perimeter of the structure, protect the downstream edge of the structure against scour, and provide for fish passage where needed. Fords are particularly useful in streams and drainages that carry a lot of debris or that have debris slides in the watershed.

Figure 6 - A concrete slab low-water ford, with high flow capacity, used as an alternative to a large culvert or bridge.

- **Perform scheduled maintenance**. Scheduled maintenance should be performed, as scheduled, at a regularly planned frequency, to be prepared for storms. Insure that culverts have their maximum capacity that ditches are cleaned, and that channels are free of debris and brush than can plug structures. Keep the roadway surface shaped to disperse water rapidly and avoid areas of water concentration. There is usually insufficient time to do the routine work as a storm is approaching.

- **Keep cut and fill slopes relatively flat.** Cut and fill slopes should generally be constructed as flat as possible, and well covered (stabilized) with vegetation, to minimize instability problems as well as minimize surface erosion. Over-steep slopes contribute to failures during storm events and earthquakes. Well-cemented but highly erosive soils may best resist surface erosion with near-vertical slopes that minimize the surface area exposed to erosion. Avoid “sliver fills” by using full bench construction on steep slopes. Also avoid rock foundations that dip near-parallel to and out of the cut slope.

- **Use deep-rooted vegetation.** Deep-rooted vegetation should be selected and used for erosion control and biotechnical stabilization on slopes to help “anchor” the soil and reinforce structures using root strength, as well as to promote slope stability. A mixture of good ground cover plus deep-rooted vegetation, preferably using native species, should be used to minimize deep-seated mass instability as well as offer surface erosion control protection. Brush layering and live stakes (see Figure 7) are common treatments to help stabilize slopes.

Figure 7 – Live stakes used in a shallow unstable area to help stabilize the landslide. Use plant types that grow deep roots!

- **Protect bridges against scour**. Bridges and major hydraulic structures should be located in narrow sections of rivers and in areas of bedrock or coarse, rocky alluvium whenever possible. This is to avoid scour problems, to reduce the need for center piers in the active stream channel, and to provide a good foundation for the bridge. Many bridge failures are caused by scour of mid-channel piers. Fine, deep alluvial deposits (fine sand and silt) that are scour susceptible and problematic should be avoided. Alternatively, scour prevention measures or deep foundations should be used as needed.

- **Add armored overflows to critical bridges and culverts**. Critical bridges and culvert structures can often be retrofitted with armored overflow areas near the structure to withstand overtopping, or have a controlled "failure" point that is easy to repair. This is particularly desirable if a bridge approach berm or fill has partially blocked a flood plain. Alternatively over-sizing the structure and allowing for extra freeboard on bridges will maximize capacity and minimize risk of plugging. Avoid natural channel constriction!

- **Reinforce structures placed on marginal foundation materials.** Retaining structures, structural foundations, and slope stabilization measures should be placed into bedrock or firm, in-place material with good bearing capacity to minimize foundation failures. Structures placed on shallow colluvial soils or on loose fill material to avoid deep excavation have a high risk of failure from scour, bearing capacity failure, or global instability, particularly during natural disasters. Reinforce marginal foundations with grouting, soil nailing, deep rooted vegetation, etc.

A comprehensive treatment of the main hazards impacting roads, particularly landslides, earthquakes, floods, and snow avalanches, and both methods of hazard evaluation and methods of repair and mitigation, are presented in *Natural Disaster Reduction for Roads* (PIARC, 1999) [9]. The conclusions and recommendations presented in this paper augment this information and are generally basic, simple and cost effective measures particularly applicable to low-volume roads. Also the document *Road Storm Damage Risk Reduction Guide,* by Ketchison and Keller (in Publication) [10], presents a comprehensive treatment of most of the risk reduction measures available for low-volume roads.

6. ORGANIZATION AND SUPPORT DURING/AFTER THE DISASTER EVENT

As a storm damage event is occurring, or immediately after the event, some organization and preparation can help minimize the consequences or the impact of the event. Disasters are chaotic, so a disaster plan and organization must be in place **before** the event, so that it can function **during and after** the event!! As the storm approaches, during the event, and immediately after the event, various functions can be performed to minimize the impact of the disaster. These include:

- Storm damage patrols to inspect roads, unplug culverts, or block off unsafe areas;
- Public notification of evacuation routes;
- Evacuations of high risk or flooding areas;
- Implementation of ICS
- Emergency repairs of some roads and opening temporary roads;
- Media information of the event and conditions.

The Incident Command System, or “ICS” as it is known it the United States, is an on-scene incident management concept that has been developed over years of firefighting and is a useful and flexible system applicable to all disaster situations. It consists of an Incident Commander and a Staff responsible for operations, logistics, planning, safety, information, and administration. It can communicate with the various agencies and groups involved, and coordinate local rescue and repair efforts. It is a flexible system that can respond and grow to meet the needs of the event or disaster (ICS-Incident Command System- eTool, 2007) [3].

Storm damage patrols can be a useful function as the storm hits to unplug culverts and ditches as much as possible and minimize damage, to place barriers across closed roads, to report damage as it is encountered, and to help direct local rescue efforts. The storm patrol can be providing real time communications and information to the command center.

7. COMMON STORM DAMAGE REPAIR MEASURES

Once storm damage has occurred, a wide variety of repair measures can be used. Each requires good engineering judgment and a perspective to prevent similar damage in the future, similar to risk reduction measures. The most common type of storm damage repair work has involved various aspects of drainage. These include:

- Installing significant additional cross-drainage structures for road surface drainage, including rolling dips (see Figure 8), lead-off ditches, and pipe cross-drains;
- Repairing or replacing and up-sizing the pipes;
- Replacing a culvert pipe with a low-water crossing (simple or vented) type structure;
- Replacing, raising, or adding additional scour and erosion armoring to bridges; and
- Moving the road away from the stream, or adding stream bank armoring.

Figure 8 - A rolling dip cross-drain used to divert water off the road surface, as well as drain the ditch.

Instability problems, the other common type of damage, have been the result of debris flows and torrents, massive deep seated landslides, shallow debris slides that shear off the soil profile, and local cut and fill slope failures. These instability problems are often exacerbated due to previous fires in the area, streams at the toe of a slide, and human changes to the landscape such as roads and removal of the native forests. In evaluating damage, it is imperative to understand the site geology and mechanism of failure that caused the damage, and to design an appropriate fix with the cause in mind. Fixes used have included:

- A wide variety of retaining walls, particularly mechanically stabilized earth (MSE) structures;
- Reinforced fills using geogrid and geotextile reinforcement;
- Use of deep patch technology (see Figure 9) developed by the Forest Service for road shoulder repairs (Wilson-Musser and Denning, 2005) [11];
- Building a lightweight fill over a large, deep seated landslide;
- Building a reinforced dip to convey debris in a debris chute over a road, or installing catchment or deflection structures;
- Installing horizontal drains or other drainage measures in a large landslide;
- Using vegetative or biotechnical slope stabilization measures; and
- Moving or closing the road.

As mentioned previously, if the only alternative is to rebuild a road knowing the road will likely fail in the future, then the investment should be minimal, and made only after considering all other alternative and after a thorough study of the site.

Figure 9 – A deep patch road shoulder repair using geogrid to reinforce a failing “sliver” fill slope.

CONCLUSIONS

Closure or damage to rural roads can present a major hardship to rural populations, particularly during a time of disaster. Considerable experience has been gained in the assessment of storm damage to rural roads, risk reduction measures, subsequent repairs, and implementing measures to reduce the vulnerability of the road system to future events, both in the United States and in Latin America.

Storm damage assessment for both assessing vulnerability and implementing repairs should involve a process of working with local communities to identify their highest priorities and support, combined with objective inventory of the transportation system, road use, and identification of hazards and repair options. Needed work can be specified on simple work lists and with site-specific designs.

Many planning, location, design, and maintenance measures exist that can greatly reduce the risk and vulnerability of low-volume roads. Most measures involve avoiding problematic areas, having adequate designs, or controlling drainage in a positive manner. The Reference list provides a number of useful publications regarding storm damage prevention and repair.

As a result of work done in the aftermath of many major storm events, and a long-term look at disaster mitigation for rural roads, a couple key conclusions emerge. First is the importance of local or community involvement in this work, particularly in developing countries. The local people are knowledgeable about local conditions and resources, they are the shareholders in this work and the people impacted by a disaster, and they are the beneficiaries of measures taken to prevent or minimize the severity of a disaster. They are also the people who can make it happen, with or without government support and despite the politics behind so many programs.

The second key issue is the value of practical, cost effective, and preferably simple solutions to disaster prevention that will be accepted and used. Simple, very cost- effective measures that can prevent or minimize storm damage include minimum road widths, frequent and well disbursed road surface drainage, use of rolling dips and fords, measures that prevent the diversion of streams down a road, use of relatively flat cut slopes that will not fail, and well vegetated areas for both slope stabilization and erosion control.

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