Performance of slope stabilization trials on the road network of Laos

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Abstract: Landslides pose significant hazards on the road network of Laos. These landslides frequently block access and occasionally result in the subsidence or loss of the carriageway. Several slope stabilization trials focusing on the use of bioengineering techniques and low-cost engineering measures were implemented in 2007 and 2008. Heavy rains in 2018 caused numerous landslides on the road network and a review was undertaken of the performance of the slope stabilization trials sites implemented ten years earlier. The outcome has proved very positive overall and vindicates the efforts made to understand the causes and mechanisms of the observed slope failures and the ground conditions that pertained. The outcomes of this research have been used to strengthen practice in Laos, and further afield, and to provide a valuable basis for future practice.

Received 23 March 2020; revised 3 April 2020; accepted 6 April 2020

Expansion of the trunk road network and the connectivity of rural areas are seen as investment imperatives in most developing countries. Improved road access is considered to be a major contributor to economic development and the improvement of livelihoods (Warr 2010; Faiz et al. 2012; Hearn 2015; Sewell and Desai 2016; Hearn and Shakya 2017; Tanga et al. 2017). Large parts of the world’s mountains lie in developing countries and many mountain areas experience seasonally distributed rainfall that can trigger landslides and flood hazards (e.g. Hearn 2011a). Landslides, in particular, lead to recurrent road closures that can require costly reinstatement as well as socioeconomic losses due to intermittent access. Road authorities often have insufficient funds to prevent landslides from occurring and some are unable to respond swiftly and effectively when they do occur. An affordable and sustainable approach to slope management has so far eluded many road authorities when confronted with these hazards.

The UK Department for International Development (DFID) has invested considerable effort in the development and application of best practice techniques for sustainable slope management in rural access road corridors in developing countries. Much of the earlier work was carried out in Nepal and Bhutan (e.g. Howell et al. 1991; Hearn and Lawrance 1997; Howell 1999; Hearn et al. 2003). In 2006, DFID commenced a three-year research project in Laos aimed at strengthening slope management practices in the country and developing and adapting the techniques pioneered in Nepal for use in the Indochina region. Several sites were selected for bioengineering and low-cost engineering trials and the performance of these works can now be assessed, some ten years after their implementation.

Landslides and mountain roads

Landslides are an unfortunate fact of life when it comes to the management of transport infrastructure and the safety and livelihood of rural communities in mountain areas. Factors that control the stability of slopes along mountain roads can be broadly divided into those that condition instability and those that trigger it. Among the conditioning controls are the steepness of natural slopes, the geometry of cut slopes, the structure, strength and permeability of the underlying rocks and the depth and composition of soils. Triggering factors are usually transient and include the distribution of rainfall and the groundwater condition on any given slope at any given time, the presence of toe erosion, whereby river scour removes support to the slopes above, seismic acceleration during earthquakes, and the effects of changes in land use and engineering practices. To varying degrees, all of these factors play a part in the stability of roadside slopes in Laos.

Road construction techniques have come in for a lot of criticism in recent years as far as landslide activity is concerned. Well-engineered roads have carefully selected alignments (Hearn 2015), earthworks that are designed to suit the rock and soil conditions exposed, drainage and scour protection works that control rainwater runoff, and retaining walls to: (1) avoid excessive excavations; (2) support otherwise unstable slopes above; and (3) facilitate road construction across difficult ground conditions below (Hearn 2011b). However, even the most well-designed and constructed mountain roads are affected by landslides, especially following the passage of high-intensity cyclonic rainfall. Most of these landslides are shallow and occur in overburden soils, leading to temporary road closures. Deep-seated landslides, usually involving rock, are less frequent. These can present recurrent hazards that prove extremely difficult to stabilize or mitigate.

Landslides occurring on the slope below the road are often triggered by erosion below culvert outlets, the reactivation of previously failed soil or first-time failure in fill and spoil material due to saturation from rainfall or road runoff. Although some of these problems can be resolved using periodic and emergency maintenance, others require engineering geological investigations to sufficiently define ground conditions for robust design purposes (Hearn and Hart 2020).

Landslides and the mountain road network of Laos

Geography and geological background

Laos is a landlocked country (Fig. 1) with a population of 6.5 million in 2015, a GDP growth rate of 7% per annum.
and an economy that is the thirteenth fastest growing in the world (AIIB 2019). Its land area extends over 236 800 km², of which >75% can be described as hilly or mountainous (Fig. 2), with elevations of up to 2800 m above sea-level. The average annual rainfall generally ranges between 1500 and 2500 mm, although some areas receive in excess of 3500 mm. Much of this rainfall occurs between the months of May and October and is associated with tropical depressions, storms and typhoons. Forest covers most of the mountainous regions and, although some areas are still being progressively cleared for timber and agricultural purposes, many
upland watersheds are seeing forest becoming re-established through government efforts to limit slash-and-burn agriculture and shifting cultivation.

The regional geology is the outcome of >400 myr of plate convergence, accretion, subduction and volcanic arc formation, resulting in multiple episodes of orogeny and mountain-building, the creation of fold–thrust belts and igneous intrusions (e.g. Metcalfe 2013). The outcrop pattern is complex and consists of a wide range of rock types, including fine- and coarse-grained sedimentary sequences, low- to high-grade metamorphic rocks, and lavas and plutonic rocks, predominantly granite and granodiorite. The rock masses are typically closely-jointed, often intensely folded and faulted, and are sometimes deeply weathered on the surface. Transported soils are common and are derived from the gradual processes of hillslope denudation as well as rockfall and landslide deposits that accumulated as the contemporary landscape evolved.

The country is highly vulnerable to climate-related disasters (OECD 2017), particularly floods and landslides (Fig. 3), which cause annual losses of 3–4% of the GDP (AIIB 2019). Although landlocked, Laos is still periodically affected by typhoons that penetrate across Vietnam from the South China Sea.

**Road network**

The Ministry of Public Works and Transport (MPWT) is responsible for the development and management of the road network. This network currently consists of slightly more than 50,000 km of roads, divided into National, Provincial, District, Urban, Rural and Special roads, of which National Roads account for c. 7500 km (MPWT 2018). Less than 20% of the entire network is made from asphalt or double bituminous surface treatment; the remainder consists of gravel or earth roads. According to the OECD (2017), Laos has the lowest ratio of sealed road length to total road length and the lowest quality of transport infrastructure of 11 countries in South East Asia. However, the mountain road network never carries >5000 AADT (annual average daily traffic),

**Fig. 3.** Landslides, floods and debris-strewn river beds were common outcomes of the heavy rains that affected large parts of the country in 2018.

**Fig. 4.** A large rock slide blocked this section of road in 2018 and caused heave to the pavement and gabion retaining wall.
with a significant proportion of this network receiving <1000 vehicles per day and therefore qualifying as low-volume roads.

Landslides pose significant hazards to the management of the road network (Fig. 4). Figure 5 shows the range of slope hazards that commonly affect mountain roads in Laos. By far the most frequent are shallow (up to 1–2 m) slope failures that occur within roadside cut slopes and the slopes above. These result in partial or complete blockage to roads, causing disruption to traffic, sometimes for several hours. In extreme cases this disruption can last for days where landslides are numerous and/or there is limited earth-moving plant available to clear them. 2018 was a particularly wet year in Laos, with several rain gauge stations recording their highest annual rainfall ever. This triggered numerous shallow landslides in the mountainous north and NE of the country, with one 60 km length of road, for example, experiencing >250 small landslides that required more than US$ 0.5 million in emergency work to clear. Landslide reinstatement costs accounted for between 30 and 90% of the 2018 emergency budgets in the six provinces occupying the north and NE of the country.

Where large and recurrent landslides occur above the road, a common response is to remove as much of the unstable material as
possible through slope excavation rather than to attempt stabilization. This is often successful if the topography allows excavations to daylight, but can lead to much more serious problems if the slopes above are steep and long, if excavations are cut too steeply and if the geological conditions are unfavourable.

Slope failures below the road are less numerous, but their effects on long-term road serviceability can be much greater. As shown in Figure 5, these failures can involve instability in both fill and natural slopes and the outcome can range from cracking and deformation to the pavement to large-scale subsidence and loss of the carriageway (Fig. 6). Below-road slope failures are usually more difficult to resolve because they often require expensive geotechnical investigations before any design options can be assessed. Retaining walls are sometimes constructed to provide short-term support, but these tend to fail in the medium to long term as a result of inadequate foundations or a design that does not take full account of the ground conditions. Alternatively, sections of road are realigned through excavation into the cut slope to avoid slope instability below. This usually provides only temporary relief and, again, can trigger slope problems above.

**SEACAP 21 research programme**

**Background**

The South East Asia Community Access Programme (SEACAP) consisted of a series of research projects sponsored by DFID in the low-volume road sector during the 2000s. It focused on the need to provide low-cost and sustainable solutions to the transport needs of local communities. SEACAP 21 was a research project established to examine how landslide hazards could be mitigated on the road network of Laos, including measures to strengthen the capacity of the MPWT to manage them. The project was divided into four components that covered the design and implementation of slope improvement and landslide reinstatement works, the training of road engineers within the public and private sectors, the strengthening of university curricula in geotechnical engineering applications and feasibility studies to examine the economic basis for proactive investment in slope management initiatives (Hearn et al. 2008; Hunt et al. 2010; Hearn and Hunt 2013).

Slope stabilization trials were implemented at 13 sites along National Road 13 North between Vang Vieng and Luang Prabang and the adjacent section of National Road 7 (Fig. 1) and were divided into two phases: Phase 1, bioengineering works; and Phase 2, geotechnical engineering works. A budget of US$ 250 000 for civil works was provided by a World Bank credit under the Road Maintenance Program and US$ 25 000 was provided by SEACAP for geotechnical ground investigations.

**Phase 1 bioengineering works**

Bioengineering is the use of vegetation, either alone or in conjunction with small-scale and low-cost engineering structures – such as surface drains, trench drains, dry stone walls and revetments – to reduce shallow (usually up to 1 m depth) slope instability and erosion on slopes. When properly designed, vegetation structures can, themselves, perform the function of surface drainage and soil retention; plant roots play a part in increasing the shear strength of soils and promoting soil suction (Howell 1999; Hearn et al. 2011). Table 1 summarizes the engineering functions that different planting techniques can fulfil and Figure 7 shows diagrammatically how they are implemented.

Three experimental sites between Vang Vieng and Luang Prabang were selected for bioengineering works. All three were the locations of shallow slope instability above and below the road. Most of the techniques summarized in Table 1 and illustrated in Figure 7 were applied. The works commenced just prior to the 2007 wet season and were substantially complete by the end of the year. Plants were selected that were familiar and acceptable to local farmers and were grown in dedicated nurseries. Bioengineering specifications and layout drawings formed the basis of a contract

<table>
<thead>
<tr>
<th>Technique</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear grass-planting: rooted slips of large grasses planted in lines. Slips are made by splitting out clumps to give small sections of root and shoot. Lines are horizontal (dry, well-drained soils), vertical (moist, poorly drained soils) or diagonal (variable moisture soils)</td>
<td>The best and quickest way to create surface vegetation cover on a steep, bare, predominantly soil slope</td>
</tr>
<tr>
<td>Brush layers: woody cuttings from shrubs or small trees are arranged in lines in shallow trenches vertically across slopes formed in unconsolidated debris. These can be installed on slopes up to about 1V:1.25H</td>
<td>Effective on almost all soil slopes up to 2V:1H</td>
</tr>
<tr>
<td>Wattle fences: fascines of long woody cuttings placed horizontally in shallow trenches across slopes. Can be installed on slopes up to about 1V:1.25H. After burial, they put out roots and shoots, forming a strong line of vegetation</td>
<td>Robust protection and shallow reinforcement of the surface soil</td>
</tr>
<tr>
<td>Truncheon cuttings: large woody cuttings from trees inserted upright at intervals in slopes formed in deep and/or loose debris</td>
<td>Most shrubs tolerate shade, so this method can often be used under tree canopies where grasses will not grow</td>
</tr>
<tr>
<td>Tic-tac-toe cuttings: large woody cuttings from trees inserted upright at intervals in slopes formed in deep and/or loose debris</td>
<td>Less disturbance to the slope than brush layers, so they can be installed on steeper slopes</td>
</tr>
<tr>
<td>Live-check dams: small check dams with structural elements made from the woody cuttings of trees are placed at intervals in erosion gullies</td>
<td>In certain locations, palisades can be angled to provide drainage</td>
</tr>
<tr>
<td>Tree-planting: potted seedlings from a forest nursery are planted at intervals across a soil slope</td>
<td>Form an immediate barrier that traps debris</td>
</tr>
<tr>
<td>Wattle fences: fascines made of woven branches are used to retain small volumes of debris, forming mini terraces</td>
<td>Low-cost, flexible structures to reduce concentrated erosion</td>
</tr>
<tr>
<td>Palisades: woody cuttings are planted in lines across the slope, usually following the contours. This can be done on a wide range of sites up to about 1.75V:1H</td>
<td>Limited disturbance to the slope</td>
</tr>
<tr>
<td>Fascines: bundles of long woody cuttings placed horizontally in shallow trenches across slopes. Can be installed on slopes up to about 1V:1.25H. After burial, they put out roots and shoots, forming a strong line of vegetation</td>
<td>Can be used on weak, unconsolidated materials</td>
</tr>
<tr>
<td>Cables: palisades of large woody material on slopes that are still in the process of forming</td>
<td>Restoration of a forest mix of trees in the long term</td>
</tr>
<tr>
<td>Brush layers: woody cuttings from shrubs or small trees are arranged in lines in shallow trenches horizontally across slopes formed in unconsolidated debris. These can be installed on slopes up to about 1V:1.25H</td>
<td>A rapid temporary measure on slopes with loose surface debris</td>
</tr>
</tbody>
</table>

Table 1 Engineering functions of different bioengineering techniques (modified from Hearn et al. 2011, reproduced with permission of the Geological Society, London)
with a local contractor, who was given training and close supervision while implementing the works during the 2007 wet season.

**Bioengineering illustration A**

Figure 8 shows the slope condition at one of the Phase 1 sites in 2007, 2008 and 2018. Instability in the cut slope in 2007 had extended into the cultivated slope above and could potentially have placed an electricity pylon at risk. Following a topographic survey and detailed site inspection, a combination of slope-trimming, the removal of loose debris, grass- and shrub-planting, and a surface drainage system was designed and implemented. Shallow failure and gully erosion were occurring in loose spoil material below the road at this location as well. This was addressed using live-check dams, grass-planting and brush-layering. The layout of the designed...
works is shown in Figure 9. The slope condition in 2018 (Fig. 8) shows how well the trial performed at this location: dense vegetation growth is providing good surface protection. The cost of these works, covering a total area of c. 3500 m², amounted to US$ 18 700 in 2008. Using 2019 unit rates, this cost amounts to US$ 22 800.

**Bioengineering illustration B**

Another of the bioengineering trial sites is illustrated in Figure 10. At this location, slope-trimming, re-profiling, mortared masonry composite revetment, brush-layering and grass-planting were used to address shallow instability in the cut slope, while truncheons were planted to help stabilize the slope below the road (Fig. 11). As Figure 10 shows, substantial progress in slope protection had been achieved during the passage of only two wet seasons (2007 and 2008). In 2018 the slope was well-vegetated and stable, although a small area of slope erosion had appeared at one end of the site (not visible in the photograph). The total cost of the works, covering an area of c. 2200 m², amounted to US$ 13 500.

**Phase 2 geotechnical engineering works**

Most of the ten geotechnical trial sites related to ground movements below the road. The main causes of these problems included stream erosion and scour below culvert outlets, seepage of road runoff into slopes and the headward regression of landslide and erosion scars. Each of these locations was subject to a site investigation consisting of topographic mapping, engineering geological mapping and ground investigations. The shallower slope failures were investigated using trial pits, including the use of a dynamic cone penetrometer to assess the founding conditions for retaining walls. Drill holes were used to supplement trial pits at sites of deeper instability and/or where trial pits could not be excavated deeply enough for foundation investigations.

At three locations, the engineering geological mapping showed that cracking close to the edge of the road, or settlements to the road itself, were the result of ground movements occurring over much larger areas than the confines of the road and adjacent slopes. Slope monitoring schemes at two of these locations, comprising surface monuments and inclinometers, yielded such slow rates of movement that it was decided the high cost of stabilization would not be justified in view of the anticipated low cost of ongoing road maintenance. Investment in stabilization at these sites would have been unaffordable for the SEACAP project and would have been inconsistent with the intention of yielding low-cost solutions. Instead, drainage improvements were implemented and, in 2018, the situation had not become significantly worse at either site.

At the third location, the rates of ground movement were evidently much faster: the entire road had subsided in 2008 by up to 1 m over a distance of 50 m as a result of the failure of the slope below. Site investigations led to the design of a 6 m high masonry wall to retain the road fill with a foundation beneath the depth of movement. Design drawings and bills of quantities were prepared for the wall and ancillary works, but before these could be implemented the road authority had realigned the road into the hills, thus placing it outside the zone of active movement (Fig. 12). In 2018 this movement had regressed to the point that the realigned outside shoulder of the road was beginning to fail. Although the realignment option may have been significantly cheaper in the short term, a road-retaining wall will eventually be required to protect the road from the regressive ground movements that have inevitably continued.

Remedial designs at the six other geotechnical sites comprised improved slope and roadside drainage, retaining walls, scour...
protection works and the use of reinforced concrete slope surfacing. Standard details and site-specific designs were prepared, existing construction specifications used by the MPWT were strengthened to accommodate the slope works, and a local contractor was procured and supervised during the 2007–2008 dry season.

The reinforced concrete slope surfacing trial was used to halt the progress of erosion and shallow failure affecting a 20 m high slope below the road formed in weathered rock. Prior to 2008, the road had been realigned into the hillside above in an attempt to allay the effects of the regressing scar. The application involved the removal of loose and unstable rock, smoothing of the rock face and fixing of a reinforcing mesh that was nailed and grouted into the slope, onto which a 50 mm thick layer of concrete was applied by hand. Careful detailing of the design was required and specifications developed in Hong Kong and the Philippines were adapted to suit the ground conditions and contractor capabilities in Laos. As far as the authors are aware, this was probably the first time the technique had been used in the road sector of Laos and, as Figure 13 shows, the outcome has been successful. The area of slope covered was c. 1100 m² at a total cost in 2008 of US$ 9300. Using 2019 unit rates, the cost would be US$ 11 000.

Figure 14 shows one of several sites where masonry retaining walls were used as the main means of road reinstatement. In each case, the founding levels were determined from geotechnical investigations. To illustrate the construction costs, three of these walls were c. 6 m in height with unit costs at 2019 prices amounting to a little over US$ 1000 per metre run. This rate includes the cost of excavation and safe disposal, filter fabric, structural backfill, a subsoil drain behind the heel of the wall, mortared masonry and grass-planting for erosion protection on the slope immediately below the toe of the wall. During a training course for road maintenance engineers that took place in 2019, the general view was that these costs were significantly higher than the walling costs normally incurred. However, it was also agreed that there was little point in building structures with inadequate foundations or without the required quality control, particularly as there are several cases of retaining wall foundation failure along the road network.

Two of the geotechnical sites had not performed as intended when they were observed in 2018. The main exception concerned a location where culvert outlet protection works had been built in 2008, consisting of reinforced concrete chutes, cascades and stilling basins and the reconstruction of the masonry culvert headwall that provided support to the adjacent road fill. According to local accounts, a failure in the cut slope adjacent to these works had blocked the road in 2017 and caused ponding of road runoff, creating a small lake across the road. Eventually this lake over-spilled the retaining wall and washed out most of these structures, including the retaining wall itself. Although this is a disappointing outcome, it is the result of events beyond the design scope of the original structures. A reinforced concrete headwall has been
Fig. 10. Bioengineering illustration B: slope condition before, during and after implementation of bioengineering works at a site of cut slope instability.

Fig. 11. Bioengineering illustration B: layout of the bioengineering works shown in Figure 10.
constructed in their place and a concrete covering has been applied to the slopes below, in a similar manner to the 2008 trial described earlier. In the second exception, the works constructed in 2008 above the road were entirely excavated as the road was realigned to avoid a large landslide triggered below the road in 2018. Apparently, the trial site had performed well until it had to be removed to make way for realignment.

Fig. 12. Realigned road (behind the trucks) with benched excavation into the hillside and active ground movement associated with the landslide in the foreground (date of photograph 2008).

Lessons learnt from the SEACAP 21 slope stabilization trials

In general, the outcome of the SEACAP 21 trials has been very positive. The bioengineering works have performed well and this reflects the importance of investing sufficient time and effort to ensure that:

Fig. 13. Slope condition before (2007), during (2008) and after (2018) the construction of hand-applied reinforced concrete coverings to an unstable weathered rock slope below the road. RC, reinforced concrete.
the design matches the ground conditions;
the plants selected are appropriate for the soils and drainage conditions and will have the required function;
the site is properly prepared;
quality control is maintained throughout the planting process; and
the completed works are carefully monitored during the first years of growth to identify and rectify any adverse developments, including the replacement of under-performing plants and any changes to the drainage regime on the slope.

With respect to the last point, it will usually take three to five years in the subtropics to establish full vegetation cover. During this time the slope will need to be protected from grazing and there will need to be a plan in place, agreed with local farmers, to ensure they manage their own land above the cut slope in a way that does not adversely affect the stability of the site. The greatest success has been achieved with the planting of grasses in diagonal lines (i.e. at 45º to the direction of the maximum slope) and in the use of shrubs grown from cuttings rather than from seedlings, as the former tend to produce a mass of fine strong roots most suitable for soil reinforcement.

Fig. 14. Slope condition before (2007), during (2008) and after (2018) construction of a masonry retaining wall at a site of slope failure below the road.

Fig. 15. Use of bioengineering techniques to help stabilize and control erosion on slopes adjacent to and below retaining walls.
Attention to detail in the design and construction of geotechnical engineering works has enabled them to remain stable and perform as required. The preparation of engineering geological maps proved crucial in assessing the extent, mechanisms and causes of ground movement, and close inspection of the exposures in trial pits meant that the ground conditions could be defined adequately for design purposes. Confirmation of the bearing capacities and foundation depths for masonry retaining walls and quality control during construction, especially with respect to the mortar content and block interlock, are among the main reasons why these walls have remained robust after ten years of service.

It should be noted that, although the description and discussion in this paper have treated bioengineering and geotechnical engineering techniques separately, bioengineering was applied as either primary or ancillary works to almost all the trial sites (Fig. 15).

Uptake and sustainability of the SEACAP 21 research outputs

Extensive field and classroom training formed important components of the SEACAP 21 project (Scott Wilson 2009). This culminated in the production of a slope maintenance manual (Hunt et al. 2008) and a slope maintenance site handbook (Hunt et al. 2009), both produced in English and Lao. The former has been incorporated into the latest version of the MPWT road design manual (MPWT 2018) and elements of it have found their way into manuals developed in other parts of the world, most notably in Africa. Through the Research for Community Access Partnership, DFID continues to sponsor research in the rural access sector in South Asia and Africa and is in the process of developing a guideline for the use of bioengineering and low-cost slope stabilization measures to enhance roadside slope stability in Uganda (Hearn et al. 2019). The findings from Laos form a useful background to this work.

Despite the progress made by the SEACAP 21 research project, the part played by engineering geology and geotechnical engineering in the routine and emergency management of roadside slopes in Laos remains limited. The MPWT does not currently have personnel sufficiently trained in these subjects and this, together with the limited maintenance budgets available, means that the engineering response to landslides is almost always reactive and, understandably, limited in scope to the need to reinstate access to traffic as quickly as possible. These are probably the main reasons why some below-road measures, particularly retaining walls, are not always performing effectively.

The MPWT is currently hosting the Climate Resilient Road Planning and Asset Management project, which includes the mapping of landslide and flood vulnerability along the Laos road network. This project has also trained road maintenance engineers in landslide investigation and slope management, using the SEACAP 21 trial sites as part of the field demonstrations. These demonstrations involved discussions that focused on engineering geology and the need to avoid building retaining walls without confirmed foundation stability. The potential value that bioengineering has to offer slope management and erosion control was also fully-appreciated. With the SEACAP 21 bioengineering trial sites costing between US$ 6 and 7 per square metre, compared with cement-based systems at over ten times the price, the economic case for its wider use in protecting bare slopes and landslide scars from erosion and further instability appears self-evident.

Conclusions

The Laos slope stabilization trials have demonstrated how low-cost techniques can be effective in the remediation of shallow slope instability and erosion on roadside slopes in this country. The vast majority of landslides that affect the road network are small and involve shallow failures in soil and weathered rock on the slopes above the road. These are treatable using grass- and shrub-planting, fascines and palisades, often in combination with small-scale engineering works, such as masonry revetments and surface drainage measures. Although bioengineering can also be used effectively in below-road situations, most of the locations remedied by SEACAP 21 involved the use of retaining walls and substantial protection works for drainage outlets. These structures require levels of investment that may be atypical of normal practice on low-volume roads, but the trials demonstrate how it is important to ensure that all engineering interventions are fit for purpose and that investments are not wasted by an inadequate appreciation of the ground conditions.

Author contributions

GJH: conceptualization (equal), formal analysis (equal), funding acquisition (lead), investigation (equal), methodology (equal), writing – original draft (lead), writing – review and editing (equal); JH: formal analysis (equal), investigation (equal), methodology (equal), project administration (equal), writing – review and editing (supporting); TH: conceptualization (equal), formal analysis (equal), investigation (equal), methodology (equal), project administration (equal), writing – review and editing (equal).

Funding

The SEACAP 21 project was sponsored by the Department for International Development. The World Bank provided funds for the civil works element of the project. The preparation of this review has been funded by UKaid from the UK Government through the Research for Community Access Partnership. The opportunity to examine the SEACAP 21 trial sites in 2018 was provided by the lead author’s role in the Climate Resilient Road Planning, Asset Management Support and Capacity Building project undertaken by Sweco in association with Lao Transport Engineering Consultant and the Lao Consulting Group, with funding provided by the Nordic Development Fund, supported by the World Bank, the European Investment Bank and the European Union.

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