VOLUME 01 ISSUE 02 (2026)

Journal of Waste to Value System

Utilization of Landslide-Derived Materials as Sustainable Geomaterials for Civil Engineering Applications: A Critical Review

Dusu Tassang[1]*, Ngangom Robertson[2], Talkeshwar Ray[2]

[1*]*Ph.D. Scholar, Department of Civil Engineering, Himalayan University Itanagar, Arunachal Pradesh, India*

[2]*Assistant Professor Department of Civil Engineering, Himalayan University Itanagar, Arunachal Pradesh, India*

https://doi.org/

Abstract

Landslides are among the most frequent geohazards affecting mountainous and hilly regions, particularly in the Himalayan and North-Eastern regions of India. In addition to causing loss of life, damage to infrastructure and disruption of transportation networks, landslides generate substantial quantities of displaced soil, weathered rock, gravel, boulders, sand and fine-grained materials. These materials are commonly treated as waste and are removed from affected locations and disposed of along roadsides, river channels, low-lying areas or designated dumping sites. Such practices may create secondary environmental problems, including blockage of drainage systems, river sedimentation, degradation of agricultural land, landscape disturbance and increased transportation-related emissions. At the same time, the construction sector requires enormous quantities of natural soil and aggregates for road construction, embankments, backfilling and other geotechnical works. This situation provides an opportunity to convert landslide-derived materials from a post-disaster waste stream into a locally available construction resource.

The present paper critically examines the potential utilisation of landslide-derived waste as a sustainable geomaterial for civil engineering applications. The proposed framework considers the identification, collection, segregation, processing, characterisation and engineering utilisation of landslide materials. Potential applications include road embankment construction, subgrade and sub-base layers, backfilling behind retaining structures, structural fill, slope regrading, drainage layers, erosion-control works and selected concrete or pavement applications where the material satisfies relevant technical requirements

A circular-economy-based management framework is proposed in which suitable landslide materials are recovered and reused near the source, thereby reducing dependence on virgin aggregates and minimising disposal requirements. However, direct reuse without adequate geotechnical and environmental assessment may introduce risks related to variability, contamination, excessive fines, poor drainage and long-term instability. Therefore, material-specific classification and application-specific performance criteria are essential. The study concludes that systematic utilisation of landslide-derived waste has considerable potential to reduce disposal burdens, conserve natural resources and support sustainable infrastructure development in mountainous regions. Further experimental investigation, field trials, life-cycle assessment and development of standardised acceptance criteria are recommended for large-scale implementation.

Keywords: *Landslide waste; Sustainable geomaterials; Waste utilisation; Himalayan region*

1. INTRODUCTION

Landslides represent one of the major natural hazards affecting mountainous and tectonically active regions across the world. The occurrence of landslides is generally associated with the interaction of geological, geomorphological, hydrological and anthropogenic factors. Prolonged rainfall, earthquakes, weathering, steep terrain, geological discontinuities, toe erosion, road cutting and changes in land use can significantly influence slope instability. In the Himalayan region, the combination of young and highly fractured geological formations, steep topography, intense monsoonal rainfall and extensive infrastructure development creates particularly favourable conditions for landslide occurrence. Site-specific investigations along Himalayan road corridors have demonstrated that road-cut slopes can exhibit low shear strength and inadequate factors of safety, requiring engineering intervention for stabilisation.

The consequences of landslides extend considerably beyond the immediate failure of a slope. A landslide can obstruct highways, damage bridges and drainage structures, bury agricultural land, affect settlements and interrupt communication and transportation systems. Following a landslide event, large quantities of displaced materials have to be removed to restore road connectivity and maintain safe traffic movement. The resulting material commonly consists of a heterogeneous mixture of soil, rock fragments, gravel, cobbles, boulders and organic matter. Depending on the geological and geomorphological setting, the material may also contain a substantial proportion of clay, silt and weathered rock.

At present, landslide-derived material is predominantly considered a waste product of disaster management and road maintenance. The material is often transported to nearby disposal locations or dumped along valley sides and drainage channels. Although such practices may provide an immediate solution for clearing transportation routes, uncontrolled disposal can generate secondary environmental and geotechnical problems. Dumped debris may obstruct natural drainage, increase sediment delivery to rivers, affect aquatic ecosystems and create additional unstable slopes. Furthermore, the transportation of large volumes of debris over considerable distances increases fuel consumption, project expenditure and greenhouse-gas emissions.

The conventional approach of disposing of landslide material is therefore inconsistent with the emerging principles of resource efficiency and circular economy. The waste hierarchy increasingly promotes reduction, reuse and recycling before final disposal. In disaster management, reuse and recycling of recovered materials can conserve natural resources, reduce landfill requirements and lower the environmental and economic burden associated with debris transportation and disposal.

At the same time, the construction industry is one of the largest consumers of natural resources. Road construction, embankment development, slope modification, foundation works and drainage infrastructure require considerable quantities of soil and aggregates. The extraction of natural aggregates from quarries and riverbeds can result in ecological disturbance, landscape modification and depletion of finite resources. Consequently, the utilisation of locally available alternative materials has become an important component of sustainable construction.

The concept of using waste materials as construction resources is not new. A considerable body of research has investigated the utilisation of construction and demolition waste, industrial by-products, mining waste, agricultural residues and recycled aggregates in civil engineering. Studies have demonstrated the potential of processed waste materials in road bases, sub-bases, embankments, concrete, pavement systems and other geotechnical applications. Recent research has further emphasised that waste materials can replace virgin resources in several infrastructure applications, although variability in material properties and the absence of uniform acceptance criteria remain important challenges.

However, an important distinction exists between conventional industrial or construction waste and landslide-derived waste. Construction and demolition waste generally originates from known materials such as concrete, brick, asphalt, mortar and masonry, whereas landslide material is a naturally occurring but displaced geological material. Its characteristics depend strongly on the parent rock, weathering grade, soil formation, slope morphology, landslide mechanism and hydrological conditions. Consequently, landslide-derived material cannot be assumed to possess uniform engineering properties. For this reason, the term “landslide waste” in the present study refers primarily to the excess soil, weathered rock, granular material, rock fragments, boulders and associated debris generated during landslide occurrence and subsequent clearance operations. The term does not imply that all landslide materials are inherently unsuitable for engineering use. Rather, it highlights the need to assess whether the material can be safely recovered and converted into a useful engineering resource.

Recent research has also demonstrated that the utilisation of disaster-generated materials can provide environmental and economic benefits when reuse is prioritised over disposal. Disaster debris management studies indicate that factors such as transportation distance, preliminary sorting, temporary storage and processing requirements strongly influence the environmental and economic performance of alternative management strategies. Therefore, the feasibility of landslide waste utilisation should not be assessed solely from the perspective of material strength; logistical, environmental and economic considerations must also be incorporated.

The issue is particularly important for the Himalayan and North-Eastern regions of India. States such as Arunachal Pradesh, Sikkim, Himachal Pradesh, Uttarakhand and parts of Jammu and Kashmir experience recurrent landslide activity along major transportation corridors. In such regions, large quantities of material are generated repeatedly from the same road corridors. The repeated disposal of this material represents both an environmental liability and a missed opportunity for local resource recovery.

A systematic approach to landslide waste utilisation could therefore establish a "landslide-to-resource" pathway. Under such an approach, landslide material would be excavated, segregated, tested and classified according to its engineering properties. Coarse rock fragments could potentially be processed as aggregate, granular materials could be considered for embankment or sub-base applications, and suitable soil fractions could be used as engineered fill or subjected to stabilisation. Materials failing to meet direct-use criteria could potentially be improved using mechanical blending or stabilising agents such as cement, lime, fly ash or other suitable additives.

2. BACKGROUND AND CONCEPT OF LANDSLIDE WASTE

2.1 Definition of landslide-derived waste

A landslide involves the downslope movement of soil, rock or a combination of both under the influence of gravity. The material generated or displaced during such events may remain within the landslide body or may be transported further downslope. During emergency restoration and road-clearing operations, a portion of this material is excavated and removed from the affected site.

For engineering purposes, the excavated material may be classified into:

1. Boulders and large rock fragments
2. Coarse gravel and cobbles
3. Sand and granular soil
4. Silt and clay fractions
5. Highly weathered rock
6. Organic and vegetative debris
7. Mixed heterogeneous material

The proportion of these components varies considerably from one landslide to another. Therefore, a classification system based on particle size, mineralogy, weathering and engineering behaviour is required before reuse.

3. NEED FOR UTILISATION OF LANDSLIDE WASTE

The motivation for utilisation can be broadly divided into environmental, technical and economic considerations.

3.1 Reduction in disposal requirements

The disposal of landslide material requires temporary or permanent dumping locations. In mountainous areas, suitable disposal sites are scarce because of steep topography, limited available land and environmental sensitivity. Reusing the material close to the generation site can significantly reduce the quantity requiring disposal.

3.2 Conservation of natural aggregates

Road and infrastructure development requires large quantities of aggregates. Reusing suitable landslide-derived rock and granular material can reduce dependence on quarry materials.

3.3 Reduction in transportation distance

Because landslides commonly occur along roads, the material is already located near infrastructure projects. If technically suitable, the material can be processed and reused within the same project corridor. This can reduce hauling distance, fuel consumption and transportation costs.

3.4 Environmental protection

Uncontrolled disposal may cause sedimentation of rivers, blockage of drainage channels and secondary slope instability. A controlled utilisation strategy can reduce these impacts.

3.5 Circular economy

The conversion of landslide debris into construction material changes the management philosophy from "remove and dump" to "recover, process and reuse". This is consistent with the wider circular-economy approach in civil engineering.

4. CHARACTERISATION REQUIREMENTS FOR LANDSLIDE WASTE

Before utilisation, the material should undergo systematic laboratory and field characterisation.

4.1 Physical characterisation

Important physical properties include:

- particle-size distribution;
- specific gravity;
- natural moisture content;
- bulk density;
- particle shape and texture;
- percentage of fines;
- degree of weathering;
- absorption and porosity for coarse material.

Particle-size distribution is particularly important because it determines whether the material is suitable for embankment, subgrade, drainage or aggregate applications.

4.2 Index properties

For soil-dominated landslide material, the following properties should be evaluated:

- liquid limit;
- plastic limit;
- plasticity index;
- shrinkage characteristics;
- soil classification.

Materials containing excessive clay or highly plastic fines may require stabilisation before use in pavement or embankment applications.

4.3 Compaction characteristics

The Standard Proctor or Modified Proctor test can be used to determine:

- Maximum Dry Density (MDD);
- Optimum Moisture Content (OMC).

Compaction characteristics are essential for assessing suitability as engineered fill, embankment material and pavement subgrade.

4.4 Shear strength

Direct shear and triaxial tests should be conducted to determine:

- Cohesion, (c);
- Angle of internal friction,
- Peak and residual strength;
- Stress-dependent behaviour.

These parameters are particularly important when landslide material is proposed for slope reconstruction or retaining-wall backfill.

4.5 Bearing capacity and pavement-related properties

For road applications, the following properties should be considered:

- California Bearing Ratio (CBR);
- resilient modulus;
- aggregate impact value;
- aggregate crushing value;
- Los Angeles abrasion value;
- soundness;
- water absorption;
- Flakiness and elongation indices.

The material should be compared against the applicable requirements of relevant Indian road and geotechnical standards.

5. POTENTIAL CIVIL ENGINEERING APPLICATIONS

5.1 Road embankments

One of the most promising applications of landslide-derived material is road embankment construction. Large quantities of material are frequently generated during landslide clearance along mountainous highways. If properly classified and compacted, suitable granular and coarse materials can be incorporated into embankments.

However, highly plastic soils, organic-rich materials and unstable mixtures should not be used without treatment.

5.2 Subgrade and sub-base

Granular landslide materials may potentially be used in pavement subgrade and sub-base layers after appropriate processing. The suitability should be established through CBR, gradation, compaction, durability and drainage tests.

Research on recycled materials has demonstrated that alternative waste-derived aggregates can be successfully incorporated into pavement base and sub-base systems when their engineering properties satisfy application-specific requirements.

5.3 Backfilling behind retaining walls

Well-graded granular landslide materials can potentially be used as backfill behind retaining structures. The principal requirements should include:

- Adequate shear strength;
- Low compressibility;
- Suitable gradation;
- Adequate drainage;
- Limited fines;
- Compatibility with the drainage system.

The use of highly compressible or poorly draining landslide material should be avoided.

5.4 Structural and non-structural fill

Selected landslide materials may be utilised as engineered fill in:

- Site development;
- Road widening;
- Approach embankments;
- Landscaping;
- Low-height platform construction;
- Restoration of excavated areas.

5.5 Drainage layers

Clean coarse rock fragments and gravel can potentially be used in:

- Sub-surface drainage;
- Toe drains;
- Filter layers;
- Drainage trenches;
- Erosion-control systems.

However, particle-size compatibility with filter criteria should be verified before implementation.

5.6 Slope reconstruction

Instead of transporting all excavated material away from the landslide site, suitable material can potentially be reused in engineered slope reconstruction.

This approach may involve:

1. Removal of unstable material;
2. Segregation of suitable and unsuitable fractions;
3. Benching of the slope;
4. Placement of selected material;
5. Controlled compaction;
6. Surface drainage;
7. Erosion protection;
8. Vegetation or bioengineering measures.

This approach converts waste management into an integrated slope-restoration strategy.

6. PROCESSING AND TREATMENT OF LANDSLIDE WASTE

Direct utilisation may not always be possible. Processing may therefore include:

6.1 Screening

Screening can separate:

- Oversized boulders;
- Coarse aggregate;
- Gravel;
- Sand;
- Fines.

6.2 Crushing

Large rock fragments can be crushed to produce graded aggregate. The resulting aggregate should subsequently be tested for strength, durability and shape.

6.3 Mechanical blending

Materials with excessive fines can potentially be blended with coarser material to obtain a suitable gradation.

6.4 Stabilisation

Fine-grained landslide soil may be improved using:

- Lime;
- Cement;

Fly ash;
Ground granulated blast-furnace slag;
Other suitable stabilising agents.

The selection of stabiliser should be based on soil mineralogy, plasticity and strength requirements.

6.5 Moisture conditioning and compaction

For earthwork applications, appropriate moisture conditioning followed by controlled compaction is essential.

7. ENVIRONMENTAL CONSIDERATIONS

Landslide waste should not automatically be considered environmentally harmless simply because it originates from a natural geological process. Materials may become mixed with:

Road construction debris;
Concrete fragments;
Bituminous material;
Fuel or oil;
Domestic waste;
Vegetation;
Contaminated soil.

Therefore, source segregation is important.

Environmental assessment should consider:

pH;
Electrical conductivity;
Soluble salts;
Heavy metals where contamination is suspected;
Organic contaminants where anthropogenic sources are present;
Leachability;
Sediment-release potential.

Disaster debris management guidance similarly emphasises segregation and evaluation before reuse because different debris streams may require different treatment and management pathways.

8. PROPOSED LANDSLIDE WASTE UTILISATION FRAMEWORK

A practical framework for the utilisation of landslide-derived materials in mountainous regions should follow a systematic, sequential approach from landslide identification to long-term performance monitoring. The process begins with landslide identification, where the location, extent, type, geological setting and approximate dimensions of the landslide are determined using field investigations, remote sensing, GIS and available historical information. This is followed by a preliminary site investigation to assess the geological and geotechnical conditions, drainage characteristics, degree of weathering, slope stability and the general nature of the displaced material. Once the site conditions are established, quantity estimation is carried out to determine the approximate volume and mass of material generated and the proportion that may potentially be recovered for engineering use.

The next stage involves material segregation, in which the landslide debris is separated into boulders, rock fragments, gravel, sand, silt, clay, organic matter and any anthropogenic waste. Such segregation is important because different material fractions possess different engineering characteristics and may require different applications or treatment methods. The segregated materials are subsequently subjected to laboratory characterisation, including particle-size distribution, specific gravity, Atterberg limits, compaction characteristics, permeability, shear strength, CBR and relevant aggregate-quality tests. Based on the measured properties, the material is then subjected to engineering classification to determine its potential suitability for applications such as embankment construction, road subgrade and sub-base, retaining-wall backfill, drainage layers, structural fill and erosion-control works.

Materials that do not directly satisfy the requirements of the intended application may undergo processing or treatment, including screening, crushing, grading, mechanical blending or chemical stabilisation using suitable additives such as lime or cement. The treated material is then subjected to an application-specific suitability assessment, in which its engineering properties are compared with the relevant technical requirements and design criteria. Materials satisfying the required criteria can subsequently be utilised through field implementation, involving appropriate placement, moisture conditioning, compaction, drainage provision and construction quality control. Finally, performance monitoring should be undertaken to evaluate settlement, deformation, erosion, drainage behaviour, strength and overall stability during the service period. This systematic framework transforms landslide-derived material from a disposal problem into a potential construction resource while

ensuring that its utilisation is governed by engineering performance, environmental safety and long-term stability.
Overall, the framework follows a simple principle:
Identify → Investigate → Quantify → Segregate → Characterise → Classify → Process → Assess → Utilise → Monitor
This approach ensures that landslide-derived material is not simply dumped as waste, but systematically evaluated and converted into a safe and sustainable construction resource.

9. APPLICATION-BASED CLASSIFICATION FRAMEWORK

A practical classification may be proposed as follows:

Material category	Typical characteristics	Potential application
Large boulders	High strength, low weathering	Rock protection, gabions, toe protection
Strong crushed rock	Good durability	Aggregate, sub-base, pavement applications
Well-graded granular soil	Good compaction and drainage	Embankment, structural fill
Sandy material	Moderate permeability	Backfill, drainage/filter applications
Silty soil	Moderate/low drainage	General fill after assessment
Clayey soil	High plasticity/compressibility	Stabilised fill, landscaping
Highly weathered rock	Variable strength	Engineered fill after testing
Organic/mixed waste	Poor engineering behaviour	Generally unsuitable for structural applications

This classification should be considered a conceptual framework rather than a replacement for project-specific testing.

10. ECONOMIC AND SUSTAINABILITY BENEFITS

The economic feasibility of landslide waste utilisation depends largely on the balance between processing costs and avoided disposal and material procurement costs.
Potential benefits include:

- Reduced purchase of natural aggregates;
- Reduced transportation of imported construction materials;
- Reduced disposal costs;
- Reduced requirement for dumping areas;
- Reduced environmental disturbance;
- Local employment opportunities;
- Shorter material supply chains.

The environmental benefits may be particularly significant where the alternative involves transporting debris over long mountainous routes. Studies on disaster debris management have shown that transportation distance and processing strategy can substantially influence both environmental and economic performance.
Evidence from the broader recycling sector also demonstrates that replacing disposal with material recovery can produce environmental benefits through reductions in land occupation, energy consumption and greenhouse-gas emissions. Indian case studies of C&D waste recycling have reported environmental advantages over landfilling under several scenarios.

11. CHALLENGES AND LIMITATIONS

Despite the potential benefits, several challenges must be addressed before widespread implementation.

11.1 Material variability
Landslide material can vary substantially over short distances. Consequently, a single laboratory sample may not represent the entire debris mass.
11.2 Presence of excessive fines
High fines content may reduce drainage and strength and increase susceptibility to moisture-related deterioration.
11.3 Weathering
Highly weathered rock can degrade during crushing, compaction and subsequent service.
11.4 Contamination
Material mixed with anthropogenic waste requires additional environmental testing.
11.5 Lack of standards
Unlike conventional aggregates and established recycled materials, there is currently limited standardised guidance specifically addressing landslide-derived construction materials.
The broader waste-utilisation literature identifies material variability, technical uncertainty, economic considerations and lack of standardisation as major barriers to large-scale implementation.
11.6 Seasonal availability
Most landslides in Himalayan regions occur during the monsoon period. Large quantities of material may therefore become available over a relatively short period.
11.7 Risk of reactivation
Material excavated from an active or recently failed slope should not be reused without considering the geological stability of the source area.

12. CONCLUSIONS

Landslide-derived material is traditionally regarded as a waste product requiring immediate removal and disposal. However, the large volume of soil, rock, gravel and granular material generated during landslide events represents a potentially valuable local source of geomaterials. The conversion of this material from waste to construction resource can provide environmental, economic and engineering benefits, particularly in mountainous regions where transportation distances are long and natural aggregate resources are under increasing pressure.
The review indicates that landslide-derived materials may potentially be used in road embankments, engineered fills, subgrade and sub-base layers, retaining-wall backfills, drainage systems, slope reconstruction and erosion-control works. Coarse and durable rock fractions may have particular value as aggregate after suitable processing, whereas fine-grained or highly plastic materials may require stabilisation before engineering utilisation.
However, the suitability of landslide waste cannot be established solely from its visual appearance or geological origin. Comprehensive characterisation of particle size, plasticity, compaction, strength, permeability, durability and environmental compatibility is essential. The heterogeneous nature of landslide deposits also necessitates representative sampling and material classification.
A sustainable management strategy should therefore adopt a hierarchy of assessment → segregation → processing → testing → utilisation → monitoring rather than indiscriminate disposal. This approach is consistent with the broader principles of circular economy and sustainable infrastructure development.
India's evolving regulatory framework is also moving towards greater emphasis on waste utilisation and resource recovery, although the current construction-and-demolition framework specifically excludes waste generated by natural disasters, indicating that landslide-derived material requires a carefully defined regulatory pathway rather than being automatically treated as conventional C&D waste.
For Himalayan states such as Arunachal Pradesh, where landslides repeatedly disrupt road networks, the concept of landslide waste utilisation may be particularly valuable. Local reuse could reduce the demand for virgin construction materials, decrease transportation requirements and minimise environmentally damaging dumping practices.
Future research should therefore focus on developing a scientifically validated classification system for landslide-derived materials, establishing application-specific engineering criteria, conducting field-scale demonstrations, and quantifying environmental and economic benefits through life-cycle assessment. Such efforts can transform landslide management from a predominantly disposal-oriented activity into a resource-recovery and circular-construction strategy.

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