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Landslide-Resilient Hillside Housing: An Integrated System of Biopolymer Soil Treatment, Bio-Engineering, Micropiles and Siphon Drainage

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Abstract: ***Landslides triggered by rain repeatedly destroy homes and livelihoods on the steep, weathered slopes of the Western Ghats and other high-rainfall hill regions. The usual remedies, retaining walls and deep foundations, tend to be costly, carbon-heavy and awkward to build on remote ground, and they are normally applied one at a time even though most slope failures have several causes working together. This paper presents the concept and test plan for an integrated, low-impact housing system that deals with the soil, the slope surface, the foundation and the groundwater together. The soil is strengthened with xanthan gum, a microbial biopolymer that bonds particles and lowers permeability. The surface is protected by vetiver contour hedgerows and bamboo clumps whose roots hold the upper soil. The house stands on micropiles socketed below the potential slip surface, and a French drain with siphon pipes removes the water that raises pore pressure, without pumping. We review the literature behind each component, explain how the weakness of one measure (for example the water sensitivity of the biopolymer) is covered by another, and set out the methodology: site selection, soil characterisation to Indian Standards, a xanthan gum dosage programme, bio-engineering, micropile and drainage design, limit-equilibrium and finite-element stability analysis of four scenarios, and a reduced-scale rainfall model. Expected outcomes are stated qualitatively because no test data exist yet. Materials, a prototype work plan, a maintenance routine and future research needs are also listed.***

Keywords: ***landslide mitigation, hillside housing, xanthan gum, vetiver grass, bamboo, micropile, French drain, siphon drainage, slope stability***

I. INTRODUCTION

A. Background

A landslide is the downslope movement of rock, soil or debris under gravity. Some slides creep for years; others fail in seconds and travel fast enough to leave no time for warning. As populations grow and flat land runs short, settlements keep climbing onto steeper ground, and in hilly regions landslides have become one of the most frequent natural hazards for homes, roads and farmland.

Whether a slope stands or fails comes down to a balance between the forces that drive the soil downhill and the strength that holds it back. Anything that adds to the first or eats into the second moves the slope closer to failure, and prolonged heavy rain is the most common trigger. Water that infiltrates the ground raises pore-water pressure, which lowers the effective stress between grains and weakens the soil. At the same time, runoff strips particles from the surface, and the rills and gullies it cuts weaken the slope further. India is among the most affected countries, with the Himalaya, the north-east and the Western Ghats as the most susceptible belts.

B. Problem Statement

Protective measures are usually installed singly: a retaining wall for lateral support, a trench for groundwater, plants for surface erosion, deep foundations for bearing. Each helps, but a slope that fails for several reasons at once is unlikely to be rescued by any one of them. For low-cost housing there are further difficulties. Cement-based stabilisation and heavy structures are expensive, carbon-intensive and hard to carry out on steep, remote sites; the construction work itself can disturb a slope enough to start movement; and the role of water is often neglected.

What is needed is a solution that is affordable, can be built with light equipment, sits comfortably with the environment, and treats soil, surface, foundation and groundwater together instead of one at a time. This work therefore asks whether low-impact, locally available measures can be combined in a coordinated way, and how much each of them contributes. We approach the question through a laboratory study and a physical model of an integrated housing system.

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C. Motivation

Three observations motivated this work. First, biopolymers such as xanthan gum are being studied as bio-based alternatives to cement and lime; they are natural, are needed in small quantities and can be mixed into soil by simple means. Second, plants such as vetiver and bamboo give a living, inexpensive form of slope protection that also brings environmental and community benefits. Third, small-diameter drilled foundations (micropiles) and simple drainage arrangements are practical on steep, restricted sites where large machines cannot work. None of these measures is new on its own. What we want to find out is how they behave as one housing system, and to measure, in a controlled setting, how much each contributes and how far they cover for one another.

D. Objectives

The study has six objectives:

1) To characterise the selected soil and define the slope conditions to be modelled.
2) To find the optimum xanthan gum treatment by testing treated and untreated soil in the laboratory.
3) To evaluate how bamboo and vetiver affect soil loss under controlled rainfall.
4) To build a micropile-supported housing model and record its settlement under controlled loads.
5) To install a French drain and siphon pipe arrangement and measure the volume and rate of water discharged.
6) To compare the model configurations and identify which measures improve the measured properties.

E. Significance of the Work

If the planned tests show that the combined measures outperform the individual ones, the work will offer an evidence-based starting point for low-cost, sustainable housing in landslide-prone areas. If some components turn out to add little under the test conditions, that is also useful, because it shows which ones deserve further study and which need changes. We will report what is measured, whichever way it falls.

The expected contributions are:

1) a design concept that addresses the cause (water), the resistance (soil and root strength) and the consequence (foundation support) together;
2) promotion of eco-friendly materials, namely biopolymer, bamboo and vetiver, in place of cement-heavy solutions;
3) a focus on low-income and rural households, who are the most exposed and the least able to pay for engineered protection; and
4) a base for experimental and numerical work in the next phase, and for guidelines that local bodies could adopt.

F. Landslide Situation in Kerala and the Western Ghats

The Western Ghats receive heavy south-west monsoon rain, often in short bursts of extreme intensity. Their slopes carry deep residual soils produced by intense tropical weathering of crystalline rock, and many have been steepened by roads, plantations, quarrying and building. After a long wet spell, a sudden burst of intense rain can bring such soil close to saturation quickly, and the slope may fail with little warning. Land-use change adds to the hazard when it removes deep-rooted vegetation, blocks natural drainage lines or concentrates runoff. Kerala's recent record includes failures in 2018, 2019 (Puthumala and Kavalappara), 2020 (Pettimudi) and the 2024 disaster at Mundakkai and Chooralmala in Wayanad, which destroyed homes, roads and livelihoods.

Houses tend to sit on the gentle benches of a slope and at the foot of hills, which are exactly the places where slides start or arrive. Public agencies have prepared landslide susceptibility maps and issued guidance for building in hazard zones, yet a large number of existing and new houses remain in areas of moderate to high susceptibility, and relocating all of them is not realistic. Housing that can be built in place and still lowers the risk is therefore needed, and that is the gap this work aims at.

II. BACKGROUND STUDY

A. Landslide Types, Causes and Mechanism

Landslides are usually classified by the type of movement (fall, topple, slide, spread, flow) and by the material involved (rock, debris, earth), following the scheme of Varnes and Cruden [1]. In the Western Ghats the commonest forms are shallow translational slides and debris flows in residual soil and colluvium. They typically occur during or after heavy rain, when infiltration lifts the water table and builds positive pore pressure at the contact between the soil and the weathered rock beneath.

Stability is commonly expressed as a factor of safety (FoS), the ratio of the shear strength available along a potential failure surface to the shear stress acting on it. Shear strength follows the Mohr–Coulomb criterion

$$\tau = c' + (\sigma - u) \tan \varphi' \qquad (1)$$

where c′ is the effective cohesion, σ the total normal stress, u the pore-water pressure and φ′ the effective friction angle. The equation shows directly that a rise in u cuts the effective normal stress and therefore the frictional resistance. For an infinite slope with seepage parallel to the surface, the factor of safety is

$$FoS = [c' + (\gamma z \cos^2\beta - u) \tan \varphi'] / (\gamma z \sin \beta \cos \beta) \quad (2)$$

in which γ is the unit weight of the soil, z the depth of the slip surface and β the slope angle. Because u enters the numerator with a negative sign, FoS falls as pore pressure climbs, which is why drainage matters as much as strengthening the soil itself. Table I lists the main contributing factors and the measure used against each in this project.

TABLE I
LANDSLIDE FACTORS, EFFECTS AND MITIGATION MEASURES

Factor	Effect on the slope	Measure used here
Rainfall infiltration	Raises pore pressure, lowers effective stress	French drain, siphon pipe
Surface erosion and rilling	Strips soil cover, creates gullies	Xanthan gum, vetiver, bamboo
Low shear strength of soil	Reduced cohesion and friction	Xanthan gum treatment
Shallow foundations	Move together with the failing soil	Micropile foundation
Loss of vegetation	Loss of root reinforcement and interception	Bamboo and vetiver planting

B. Soil Stabilisation Using Xanthan Gum

1) *Nature of Xanthan Gum:* Xanthan gum is an anionic, extracellular polysaccharide made by fermenting sugars with the bacterium *Xanthomonas campestris*. Food and cosmetic industries use it widely as a thickener. It is non-toxic and biodegradable, and in water it forms a viscous hydrogel that thins under shear.
2) *Mechanism of Improvement:* Mixed into soil, xanthan gum forms hydrogel bridges between particles and coats their surfaces. Hydrogen bonding and electrostatic attraction between the negatively charged polymer chains and clay surfaces, assisted by cations, raise inter-particle cohesion. As the soil dries, the gel hardens into a thin film that binds grains together, which raises unconfined compressive strength and resistance to erosion. The gel also fills pore space and lowers the hydraulic conductivity of the treated soil.
3) *Reported Performance and Limits:* Laboratory work reports that small dosages, generally within a few per cent by dry weight of soil, can markedly raise the strength of sandy and silty soils and reduce erosion [2]. The gain depends on soil type, moisture, gum content, curing time and mixing method, and it levels off at higher dosages. The well-known weakness is water sensitivity: strength gained during dry curing can fall when the soil stays saturated for long, and the gum may biodegrade over time [3]. This is one reason why the proposed system does not rely on xanthan gum alone and pairs it with drainage and vegetation.

C. Bio-Engineering with Vetiver and Bamboo

1) *Vetiver Grass:* Vetiver (*Chrysopogon zizanioides*) is a perennial tufted grass with a dense, fibrous root system that can reach several metres down. The roots have high tensile strength, and when the grass is planted in close rows along the contour it forms a living hedge that slows runoff, traps sediment and holds the soil. It tolerates drought, flooding and a wide range of soils, and the cultivars normally used are sterile and therefore non-invasive. The vetiver system has been applied for slope protection in many countries.
2) *Bamboo:* Bamboo is a fast-growing grass with a spreading network of fibrous rhizomes and roots in the upper soil. The roots bind the soil mass and the culms intercept rainfall, so clumps planted at the toe and mid-slope can act as a living barrier against shallow movement. Bamboo is also a sustainable building material with a good strength-to-weight ratio, so the same planting can later supply the frame, fencing and formwork of the housing system.
3) *Combined Use:* Vetiver supplies dense, fine, deep roots that reinforce roughly the top one to three metres of soil and control surface erosion. Bamboo adds coarser, wider-spreading roots and a sturdier living barrier. Together they place roots at different depths and scales, and so give more uniform reinforcement than either would alone.

D. Micropile Foundations

Micropiles are small-diameter drilled and grouted piles, typically 100–300 mm across, usually reinforced with a steel bar or casing. Light drilling rigs can install them, so they suit steep and hard-to-reach sites and disturb the slope very little. They carry load in compression and tension through the grout-to-ground bond, and they can resist lateral loads when used in groups or at an inclination. Current practice is documented in the FHWA manuals [4], [5]. For a house on a slope, micropiles should be socketed below the potential sliding surface into stable weathered rock or dense soil, so that the structure is carried independently of the moving layer. Lateral load from soil movement, group effects and the connection to the plinth beam or pile cap are the important design checks.

E. French Drain

A French drain is a trench filled with free-draining gravel, normally wrapped in a geotextile filter, with a perforated pipe at its base. It intercepts shallow subsurface water and carries it to a safe outlet. Placed on the uphill side of a building and along the slope, it limits the water reaching the foundation zone and lowers the local water table. Filter design must be done carefully, otherwise fines will clog the drain.

F. Siphon Pipe Drainage

A siphon drain is a flexible tube whose intake sits in the groundwater and whose outlet lies at a lower elevation. Once primed, water flows out under the head difference without any pump. Compared with horizontal drains it needs no long drilling and no external power, and it has been used on slopes to lower the groundwater level and pore pressure. Its performance depends on keeping the line fully primed, stopping air from accumulating and providing an outlet below the intake. Periodic inspection is therefore essential, and in this system the siphon acts as an additional safeguard alongside the French drain.

III. LITERATURE REVIEW

A. Biopolymers for Soil Improvement

Kumar *et al.* [6] reviewed biopolymers as sustainable soil-improvement materials, concentrating on xanthan, agar and guar gum. In their account, xanthan gum improves water retention and reduces permeability; agar gum raises strength and shows promise for liquefaction remediation; and guar gum increases strength, lowers permeability and can support slope stability. The common mechanism is the formation of hydrogels and links between soil particles. Suggested applications include erosion control, slope stabilisation, soil remediation and tailings stabilisation, with low toxicity and possible greenhouse-gas savings as attractions. The authors stress that results change with soil type, concentration, curing time, moisture and environment, and that long-term durability, field performance, soil compatibility and economics still need work.

Chang *et al.* [2] found that xanthan gum worked best in well-graded soils with fine particles, that its effect depended strongly on hydration level, and that the strengthening levelled off at higher concentrations. Bagheri *et al.* [3] examined xanthan gum as an alternative to cement using Atterberg limits, unconfined compression, and consolidated-undrained and unconsolidated-undrained triaxial tests, together with wetting–drying cycles and water exposure. Strength rose with gum content and suitable curing, and a 2 % dosage gave roughly two and a half times the compressive strength of untreated soil. Treated soil also kept more of its strength through wet–dry cycles, and electron microscopy showed the gum coating and bonding particles and filling pores. Under saturated conditions, however, the gum absorbed water and strength fell, which makes moisture control a central design issue.

B. Vegetation-Based Reinforcement

Kumar and Kumari [7] reviewed vetiver for slope stabilisation and erosion control and describe it as a natural, low-cost and eco-friendly option. Its deep roots bind particles and add shear strength, which improves resistance to shallow failures, while the hedges slow surface flow and reduce soil loss. Some of the studies they surveyed recorded erosion reductions above 90 % relative to bare slopes under particular conditions, and some applications reached slopes of about 75°. Performance depends on soil type, slope angle, rainfall intensity and root development, and the authors call for more quantitative, long-term field studies and for comparison with conventional methods.

Work on vetiver and bamboo fibres as soil additives in Arunachal Pradesh [8], and a worldwide overview of bamboo diversity in landslide bioengineering [9], add support for using these plants and show that bamboo in particular is being examined as a landslide measure.

C. Micropiles in Slopes

Otoma and Ayothiraman [10] review the use of micropiles in slope and landslide protection. Micropiles move load to stronger ground mainly through friction along the grouted bond length and sometimes by end bearing. They can be installed vertically or at an inclination, and guidance documents classify them by grouting method and by design role, either as load-bearing elements or as reinforcement elements within a soil mass. Typical uses are underpinning, new foundations on restricted sites, seismic retrofit and slope stabilisation.

Ziccarelli *et al.* [11] studied deep counterfort drains rather than micropiles, but their finding is relevant to foundation design. A structural element socketed into stable ground below the slip surface adds resistance through a "shear key" effect, and for silty and clayey base soils the contribution was reported to be of the same order as the gain from permanently lowered pore pressure. This supports the logic of founding the house below the potential failure surface.

D. French and Trench Drains

A typical French drain has a trench filled with coarse aggregate, a perforated pipe laid at a gradient towards the outlet, and a filter or geotextile that keeps fines out of the aggregate. Trench dimensions, pipe size, depth and gradient depend on soil properties, groundwater conditions, expected flow and topography.

The counterfort drains in [11] differ from ordinary French drains, but the work is useful for understanding how drainage structures interact with the soil around them. Chen and Chui [12] studied sustainable drainage systems in a landslide-prone catchment and concluded that drainage and infiltration measures must be sited carefully on slopes, since changes in groundwater conditions can affect stability.

For hillside housing this argues for site-specific planning. French drains are best considered on the uphill side of buildings and where seepage is found to accumulate. Their benefit rests on correct installation, a dependable outlet and regular maintenance against clogging and erosion, and they should be combined with soil stabilisation, vegetation, surface-water management and a suitable foundation.

E. Siphon Drainage

A siphon system consists of drain pipes in the ground, a connecting tube and a discharge outlet, and it works by keeping a continuous water column between the collection zone and a lower outlet. With enough elevation difference and suitable hydraulic conditions, a primed siphon moves water without a pump. Performance depends on soil permeability, pipe diameter, installation depth, available head and the prevention of air entry and blockage.

Sun *et al.* [13] combined anchoring and siphon drainage in a single inclined borehole. In their Hongpu Village case the factor of safety rose by 0.085 over a common anchor bar with the same anchoring length, and the combined method also performed better than siphon drainage or a full-length bar over the same borehole length. Wang *et al.* [14] used siphon drainage to lower groundwater and pore pressure for soft-soil consolidation, found that permeability and hole spacing influence efficiency (1 m spacing worked better than 2 m), and supported the method with a field test.

Earlier, Sun *et al.* [15] reported that a tube of about 4 mm bore forms plug flow that prevents air from accumulating and lets the siphon restart by itself, and described a slope installation running smoothly since 2013 with groundwater drawdown of up to 8.5 m. Together these studies show the promise of combining groundwater control with structural reinforcement, but they also confirm that a siphon needs suitable hydraulic conditions, a safe discharge point and regular checks against blockage or loss of siphon action.

F. Stilt and Modular Housing

Housing form has also been studied for hazard-exposed sites. Rashid *et al.* [16] proposed a prefabricated modular version of the traditional stilt house in Munshiganj, Bangladesh, where communities face flooding and river erosion. Standardised panels of 4 ft × 8 ft, built from locally available timber and metal sheet, were estimated to cut panel weight by about 50 % and construction cost by 18–24 %, and to be easier to transport, assemble and reuse.

Asmal *et al.* [17] examined adaptive stilt housing in Cambayya, Makassar, Indonesia, using field observation, spatial analysis, surveys and interviews. They describe timber-frame houses on piles whose surroundings are adapted to daily life and livelihoods, note problems such as flooding, sanitation and crowding, and argue that stilt housing should be planned as part of a settlement system with community involvement. Neither study concerns landslides, but both support the idea of a lightweight, raised, locally built house that suits the micropile foundation proposed here.

G. Research Gap

The literature supports each element separately. What the studies reviewed here do not offer is a coordinated test of xanthan gum, vetiver and bamboo, micropiles, French drains and siphon drainage as one housing system on a rainfall-prone residual-soil slope, with the contribution of each isolated. That is the gap this project addresses.

IV. PROPOSED INTEGRATED SYSTEM

The proposal treats the slope problem at four levels at once, as sketched in Fig. 1: the soil itself, the slope surface, the building foundation and the groundwater that triggers failure. Table II sets out the function of each component.

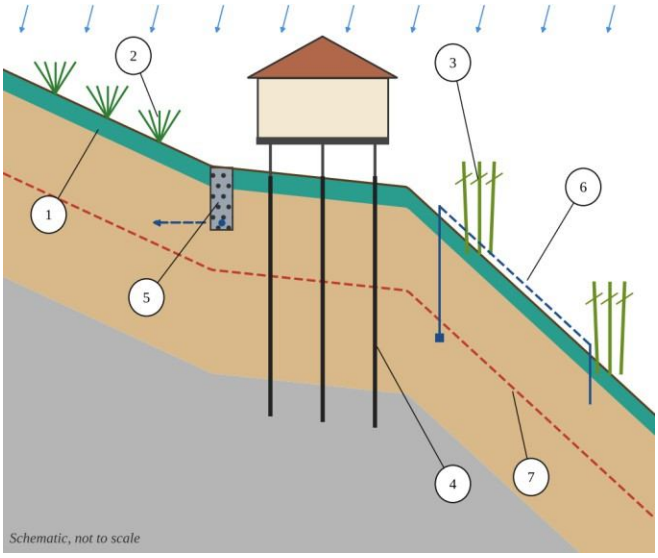

Fig. 1 Schematic of the proposed system: (1) xanthan gum-treated surface layer, (2) vetiver contour hedgerows, (3) bamboo clumps at mid-slope and toe, (4) micropiles socketed below the potential slip surface, (5) French drain on the uphill side of the house, (6) siphon pipe, (7) potential slip surface (dashed).

TABLE II
FUNCTIONS OF THE SYSTEM COMPONENTS

Function	Component	How it contributes
Soil improvement	Xanthan gum treatment	Binds soil particles; may raise strength and erosion resistance
Surface protection	Vetiver grass	Slows runoff, traps sediment, binds surface soil with roots
Surface and shallow reinforcement	Bamboo	Adds root and rhizome reinforcement and cover in selected areas
Structural support	Micropile foundation	Carries building load to sound ground below weak surface soil
Water collection	French drain	Intercepts and collects subsurface water
Function	Component	How it contributes
Water removal	Siphon pipe	Conveys collected water to a lower discharge point

The measures are meant to cover one another's weaknesses. The water sensitivity of the biopolymer is offset by drainage, which keeps the treated layer from staying saturated. The shallow reach of roots is offset by micropiles, which extend below the slip surface. Vegetation in turn shields the treated surface from direct raindrop impact, while the French drain handles shallow seepage and the siphon pipes act as an extra safeguard in the saturated zone near the base of the potential slip zone.

The house itself is a lightweight stilt-type structure, for instance a bamboo frame with light infill walls and a sloping roof whose gutters lead roof water into the drain. The building therefore adds little load to the slope and does not feed water into it. Bamboo is planted away from the foundation so that its roots do not interfere with the piles and pile cap.

V. METHODOLOGY

A. Site Selection and Data Collection

A representative landslide-prone slope, or a typical soil type from the Western Ghats region of Kerala, will be chosen using landslide susceptibility maps, rainfall records and records of past events. We will collect the topography and slope angle, rainfall intensity, geology, existing house types and the soil profile. Disturbed and undisturbed samples will be taken from different depths, mainly the upper one to three metres, for laboratory testing.

The study will proceed in the sequence shown in Fig. 2.

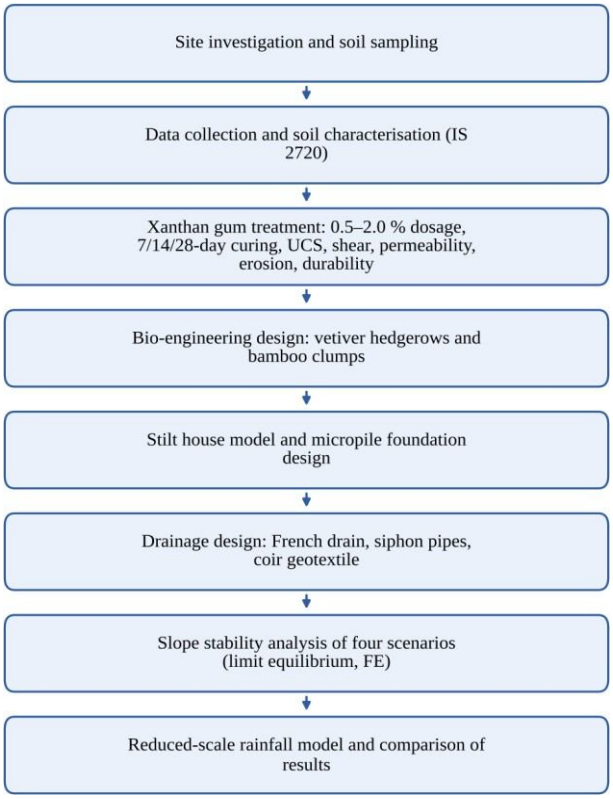

Fig. 2 Work flow of the proposed study

B. Soil Characterisation

The baseline properties of the collected soil will be determined according to the relevant Indian Standard codes [18]:

- natural moisture content, specific gravity and particle size distribution (sieve and hydrometer analysis);
- Atterberg limits (liquid limit, plastic limit, plasticity index) and soil classification;
- standard Proctor compaction for maximum dry density and optimum moisture content;
- direct shear or triaxial test for cohesion and angle of internal friction; and
- permeability test (constant or falling head).

Tests will follow the relevant parts of IS 2720 for grain size, Atterberg limits, compaction, unconfined compression, direct shear and permeability. Any modification needed for treated specimens will be recorded, and the standards actually used will be listed in the final report.

C. Xanthan Gum Treatment

Xanthan gum will be mixed with the soil at several dosages, for instance 0.5, 1.0, 1.5 and 2.0 % by dry weight, at the optimum moisture content, alongside an untreated control. Specimens will be compacted and air-cured for 7, 14 and 28 days. Because the gum spreads more evenly when mixed dry, it will be blended with the dried soil first and water added afterwards. Treated and untreated soil will then be tested as listed in Table III, and durability will be checked through wet–dry cycles and prolonged soaking.

The optimum dosage will be chosen by comparing strength gain, durability under saturation, permeability reduction and cost, since a higher dosage costs more and may cut permeability excessively.

TABLE III
PROPOSED LABORATORY TEST PROGRAMME

Test	Purpose	Specimens
Grain size, Atterberg limits	Soil classification	Untreated soil
Standard Proctor compaction	Optimum moisture and dry density	Untreated and treated
Unconfined compressive strength	Strength gain with dosage and curing	Treated, several dosages and curing periods
Direct shear	Cohesion and friction angle	Treated and untreated
Permeability	Change in hydraulic conductivity	Treated and untreated
Erosion (drip or flume test)	Resistance to rainfall and runoff	Treated and untreated
Wet–dry and soaking cycles	Durability under water	Selected optimum dosage

D. Bio-Engineering Design

Vetiver will be planted in contour hedgerows with about 10–15 cm spacing within rows, and the vertical interval between rows will be chosen from the slope angle, typically 1–2 m. Bamboo clumps will go at the toe and mid-slope, away from the foundation. Locally available bamboo species and vetiver varieties will be preferred. In the stability analysis, root reinforcement will be treated as an additional apparent cohesion, c_r, added to c' in Eqs. (1) and (2), using values from the literature and, where possible, from root-strength tests.

E. Micropile Foundation Design

The foundation will be designed in the following steps:

1) Estimate the dead and live loads of a lightweight bamboo-frame or light masonry house, and the wind or seismic loads, using the relevant IS codes;
2) identify the potential sliding surface from slope stability analysis and fix the minimum micropile embedment below it;
3) select the pile diameter, reinforcement and grout, and calculate axial capacity from the grout-to-ground bond strength and the structural capacity of the pile section;
4) check lateral capacity and the additional lateral pressure from moving soil, using group arrangements or inclined piles where necessary; and
5) design the pile cap or plinth beam connection and corrosion protection.

F. Drainage Design

1) *French Drain:* The drain will be designed with adequate trench depth, width and gradient, a perforated pipe bedded in clean, graded gravel, and a non-woven geotextile wrap that meets the filter criteria for the base soil (Fig. 3a). Flow capacity will be checked against the design rainfall intensity and the expected seepage, and the outlet will be connected to a stable natural stream or a lined channel so that discharge does not cause erosion downslope. A coir geotextile is also included in the work flow as a natural, biodegradable cover or filter material; its exact use will be fixed during design.

2) *Siphon Pipe:* Siphon pipes will be placed with their intake in the saturated zone near the base of the potential slip zone and the outlet at a lower elevation outside the slope (Fig. 3b). Pipe diameter, spacing and number will be selected from the expected seepage rate and the target drawdown. Details such as an intake filter, air-release arrangement, priming and an inspection chamber will be included, and a maintenance schedule will be proposed. Field experience suggests that very narrow tubes, about 4 mm in bore, can clear air by themselves [15], so the 10–25 mm range listed in Section VII is an initial choice that will be reviewed against this during design.

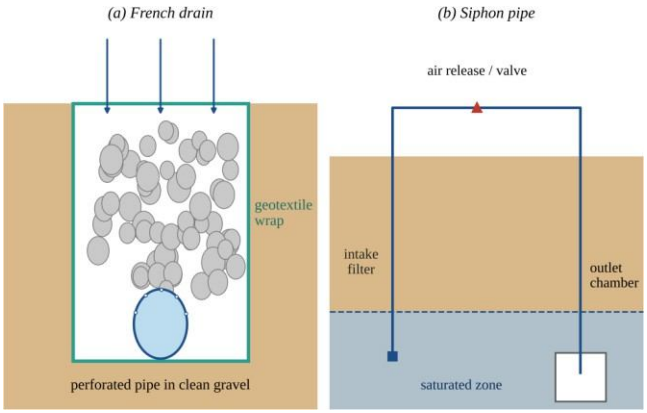

Fig. 3 Construction details: (a) French drain, (b) siphon pipe

G. Slope Stability Analysis

Stability will be analysed with limit-equilibrium methods such as Bishop's simplified method [19] and, if possible, finite-element or finite-difference software such as GeoStudio (SLOPE/W and SEEP/W) or PLAXIS. Four scenarios will be compared for the same slope and rainfall: (1) the untreated slope, (2) xanthan gum treatment, (3) xanthan gum with vegetation, and (4) the full integrated system with drainage and micropiles. Factor of safety, pore-pressure distribution and displacement will be compared for dry and fully saturated conditions.

H. Model Study

A reduced-scale slope model in a flume or tank will be prepared with treated and untreated soil. Rainfall will be simulated with a sprinkler system, and pore-water pressure, surface erosion and displacement will be monitored. The model will also provide the measurements called for in the objectives: soil loss with and without vegetation, settlement of the micropile-supported model under controlled loads, and the volume and rate of water discharged by the drain and siphon arrangement. The result will be a qualitative and quantitative comparison of the conventional and proposed arrangements.

VI. EXPECTED OUTCOMES

No test data exist yet, so the outcomes in Table IV are expectations drawn from the literature, to be confirmed or refuted by testing.

TABLE IV EXPECTED OUTCOMES

Component	Expected outcome (possible)
Xanthan gum	May improve selected soil strength properties and erosion resistance
Bamboo	May reduce erosion under suitable conditions
Vetiver grass	May reduce runoff and soil loss
Micropiles	May provide foundation support with limited settlement
French drain	May collect and remove subsurface water
Siphon pipe	May convey collected water to a lower outlet

A. *Expected Soil Behaviour*

Xanthan gum-treated soil is expected to show higher unconfined compressive strength and cohesion, and lower permeability, than untreated soil. The improvement should rise with gum content up to an optimum, beyond which the benefit levels off or the mixture becomes too viscous to work. Treated soil should also resist surface erosion better. A loss of strength after repeated wetting and long soaking is anticipated and will be quantified. Numerical values cannot be predicted in advance for the study soil and will be established by testing in the next phase.

B. *Expected Effect of Vegetation*

Vetiver and bamboo are expected to reduce surface erosion and runoff velocity and to raise the shear strength of the root zone. Their contribution to the factor of safety should be significant for shallow failures and small for deep ones. Vegetation also adds benefits that stability numbers do not capture, such as habitat, carbon uptake and, in the case of bamboo, a harvestable material.

C. *Expected Effect of Foundation and Drainage*

Micropiles are expected to keep the house supported on stable ground even if the surface soil moves, and to add some restraint to the slope. The drainage system is expected to lower the groundwater level and pore-water pressure during intense rain. In the stability analysis this lowering is expected to give the largest single gain in factor of safety among all the measures, since pore pressure is the principal trigger. The combined system is expected to give a higher factor of safety than any single measure alone. These are working hypotheses, not findings.

VII. PROTOTYPE MATERIALS AND WORK PLAN

This section lists what is planned for the next phase. All quantities, dimensions and dosages are indicative starting values taken from the literature and standard practice, and will be finalised after the soil tests and design calculations. The materials are given in Table V.

TABLE V
MATERIALS PLANNED FOR THE PROTOTYPE

Item	Material	Use
Xanthan gum	Commercial or food-grade powder, about 0.5–2 % of dry soil weight	Treat surface and near-surface soil
Soil	Site soil from 0–3 m depth, classified by IS tests	Specimens, slope model, treated layer
Vetiver	Slips or tillers of a local non-invasive variety, about 10–15 cm plant spacing	Contour hedgerows
Bamboo	Mature local bamboo (3–5 years), treated against insects and moisture; seedlings or rhizomes	Planting at toe and mid-slope; house frame
Micropile	Steel bar or hollow bar, cement grout, centraliser and spacer	Piles, 100–150 mm hole diameter (to be designed)
Pile cap or plinth	Reinforced concrete or bamboo-reinforced beam with steel connection	Joins piles to superstructure
French drain	Perforated PVC or HDPE pipe, clean graded gravel (20–40 mm), non-woven geotextile	Subsurface drainage on uphill side
Siphon pipe	Flexible PVC or polyethylene tube, 10–25 mm initially, intake filter, valve, air release	Lowering groundwater and pore pressure
Instruments	Piezometer, soil moisture sensor, inclinometer or tilt sensor, rain gauge	Monitoring of model and pilot house

A. Soil Stabilisation Work Plan

1) Collect soil samples and determine index properties, Proctor compaction parameters and baseline strength.
2) Dry-mix the xanthan gum thoroughly with the dried soil so that the powder is spread evenly and does not form lumps; then add water to reach optimum moisture content and mix again into a uniform paste.
3) Compact the soil in layers to the target density, in moulds for laboratory specimens and in thin layers (for example 150–200 mm) on site.
4) Cure the specimens or treated layer by air drying for fixed periods (7, 14 and 28 days) and test for strength, permeability, erosion and wet–dry durability.
5) Select the optimum dosage and treatment depth, apply it on the slope surface and around the foundation zone, and cover the treated surface with vegetation as protection against direct rain impact.

B. House and Foundation Work Plan

1) Survey the plot, fix the house footprint and mark the drain alignment and outlet.
2) Investigate the soil profile (borehole or dynamic cone penetration test) to locate the stable layer and the potential failure surface.
3) Install the micropiles below the failure surface: drill the holes, place the reinforcement and grout from bottom to top; allow the grout to cure and test trial piles.
4) Construct the pile cap or plinth beam and connect it to the piles.
5) Erect the lightweight superstructure, for example a bamboo frame with light infill walls and a sloping roof with gutters that carry roof water to the drain.
6) Excavate the French drain trench on the uphill side, line it with geotextile, place the perforated pipe and gravel, and connect the outlet to a safe discharge point.
7) Install the siphon pipes with their intakes in the saturated zone, prime them and check the discharge.
8) Plant vetiver along the contour and bamboo at the toe and mid-slope, away from the foundation, and water the plants through the first season until they are established.
9) Install the monitoring instruments and record readings through the monsoon.

C. Maintenance Plan

1) Before and after each monsoon, inspect the drain outlet, clean out silt and check the siphon pipes for air locks and clogging.
2) Replant gaps in the vetiver rows and trim the vegetation as required.
3) Inspect the treated soil surface for cracks and erosion and repair damaged patches.
4) Check the house for cracks and tilting, and review the instrument readings.

VIII. FUTURE WORK

The following work is proposed for the later phases, grouped under laboratory, numerical, field and implementation studies. Together they would move the system from a concept to a validated and adoptable design.

A. Laboratory Investigations

- Complete the test programme of Table III on soils from the selected site, covering strength, permeability, erosion resistance and durability of xanthan gum-treated soil.
- Optimise the dosage for the main soil types of the region (sandy, silty, lateritic and clayey) and examine the effect of moisture content, curing time and temperature.
- Study long-term performance under repeated wet–dry cycles, prolonged saturation and microbial degradation, since the strength of biopolymer-treated soil can fall with time.
- Investigate blends of xanthan gum with other low-carbon additives such as guar gum, lime, fly ash or fibres, and compare them with cement stabilisation for strength, permeability and cost.
- Measure root tensile strength and root area ratio of bamboo and vetiver grown in local soil, and the shear strength of rooted soil by in-situ or large direct shear tests.

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B. Numerical Modelling and Analysis

- Carry out coupled seepage and slope stability analysis for different slope angles, soil depths and design rainfall events, including antecedent rainfall.
- Run a parametric study of xanthan gum dosage, vetiver spacing, French drain depth, siphon spacing and micropile length against factor of safety.
- Model the interaction between the sliding soil and the micropile group to estimate lateral load and bending moment on the piles.
- Apply reliability and probabilistic analysis to account for variability in soil properties and rainfall, and to estimate the probability of failure with and without the system.

C. Physical Model and Field Studies

- Build a reduced-scale slope model in a tank or flume and test it under simulated rainfall; a centrifuge model test may be considered where facilities exist.
- Conduct axial and lateral load tests on trial micropiles at the site to verify design capacities and the grout-to-ground bond.
- Construct a pilot house instrumented with piezometers, inclinometers, soil moisture sensors, settlement points and rain gauges, and monitor it for at least one full monsoon season.
- Study the field behaviour of siphon pipes (discharge, priming stability, air accumulation, clogging) and design a simple, low-cost maintenance routine.

D. Monitoring and Early Warning

- Integrate low-cost sensors (rain gauge, soil moisture and tilt sensors) with a simple alert system, so that the household is warned when rainfall or pore pressure crosses a threshold.
- Correlate field monitoring data with regional rainfall thresholds for landslide initiation, to refine the design and the alert levels.

E. Structural and Architectural Aspects

- Develop a standard lightweight house design in bamboo or light masonry that suits the micropile foundation and the local climate and culture.
- Study the durability and treatment of bamboo against moisture and insects, and check the structure for wind and seismic loads under the relevant IS codes.
- Prepare typical layout drawings for different slope angles and plot sizes.

F. Economic, Environmental and Social Assessment

- Prepare a detailed cost estimate and a cost–benefit comparison with retaining walls, soil nailing and conventional foundations.
- Carry out a life-cycle and carbon-footprint assessment, including the environmental impact of producing xanthan gum.
- Study the benefits of vegetation for biodiversity, soil carbon and local livelihoods, for example bamboo and vetiver products.

G. Standardisation and Community Adoption

- Prepare a construction manual and maintenance guideline in the local language for masons, local bodies and households.
- Run training and awareness programmes for the community, involving local self-government institutions and disaster management authorities.
- Explore inclusion of the system in government housing and rehabilitation schemes for landslide-prone areas, and work towards design guidelines or codal provisions.

IX. SCOPE AND LIMITATIONS

This paper reports the concept, literature basis, methodology and plan of the first project phase and contains no experimental results. Statements about performance come from published studies and should be read as expectations. Several concerns remain open: the water sensitivity and possible biodegradation of xanthan gum; the time vegetation needs to establish and its limited influence on deep failures; the priming and upkeep that siphon drains demand; and the fact that micropile capacity and slip-surface depth can only be fixed from site investigation. All quantities given here are indicative, and results from one slope may not carry over to other soils.

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X. CONCLUSIONS

This paper has proposed an integrated landslide-resilient housing system that combines xanthan gum soil stabilisation, vetiver and bamboo bio-engineering, micropile foundations, and French drain and siphon pipe drainage. The literature indicates that each element answers a distinct part of the landslide problem: soil strength, surface erosion and shallow sliding, foundation support, and above all the pore-water pressure that triggers rainfall-induced failure. The central idea is that these measures work best when designed together and when they make up for each other's weaknesses. The water sensitivity of the biopolymer is compensated by drainage, and the shallow reach of roots by deeper micropiles. The system is low in cost, compatible with local materials and labour, and buildable on steep sites with light equipment. A methodology has been set out for laboratory evaluation, design and stability analysis, and the expected outcomes have been stated qualitatively. The next phase will replace those expectations with measurements.

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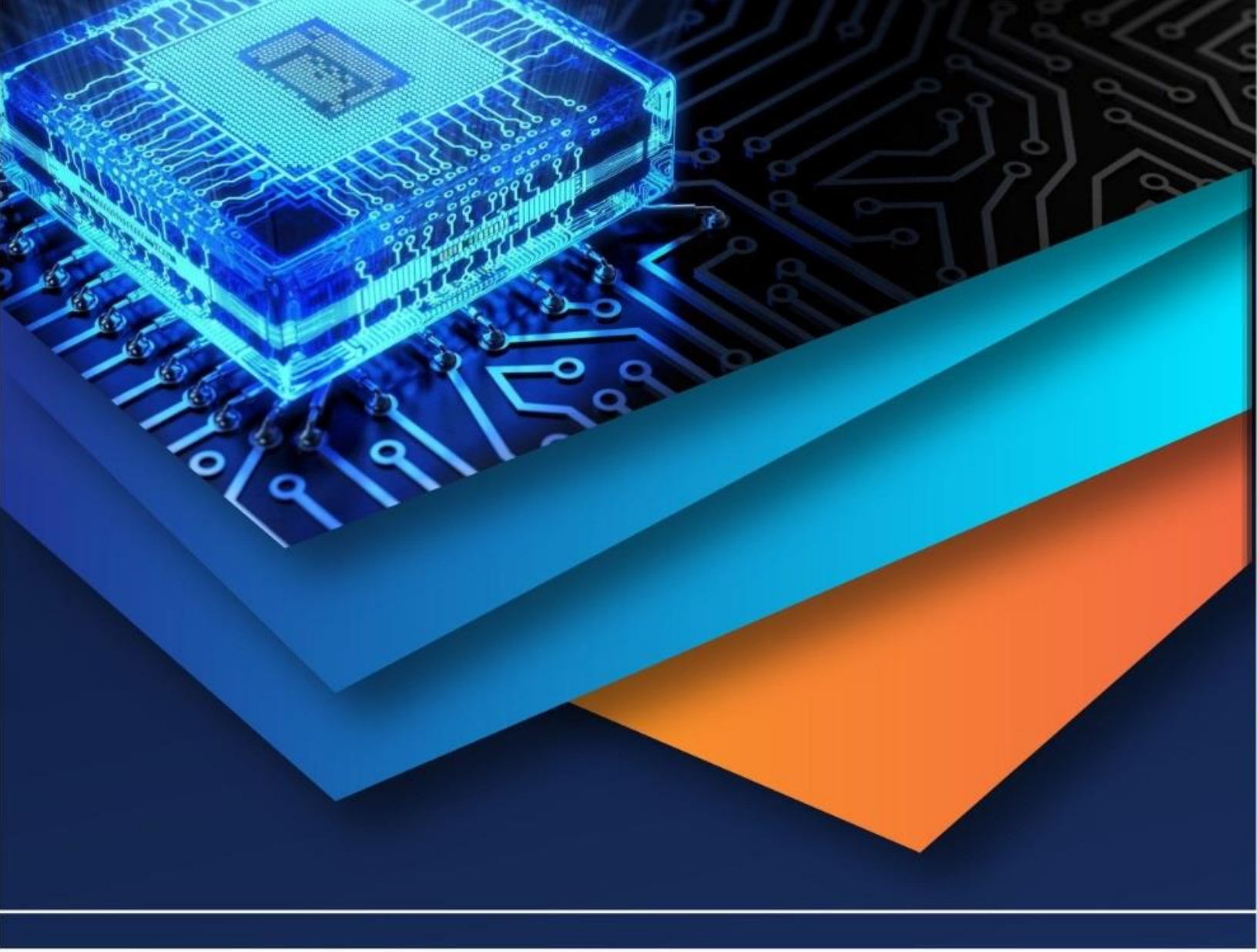

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