SEMI-TIERED HOUSING FOR LATERITE EARTH SLOPING LANDS—A SUSTAINABLE SOLUTION WITH ALTERNATIVE MATERIALS AND METHODS

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ABSTRACT

Increased demand for affordable housing and the limited availability of flat terrain for its construction are two major problems facing the provision of houses of acceptable quality in many countries around the world. There is limited research integrating the utilization of a stepped approach to sloping terrain with appropriate housing models to minimize slope instability potential. This paper introduces a new semi-tiered housing model where the footprint of the house is located on tiers prepared with short vertical cuts of 1.5–2m. Such vertical cuts are found to be stable with laterite soil which is a commonly available type of soil in the tropics. The excess soil generated from cut material was transformed into cement stabilized rammed earth, which is a cost effective material with low embodied energy. This is an ideal candidate for the construction of retaining walls and foundations, and such applications are demonstrated with adequate details. Further, many other types of sustainable building materials are highlighted with a case study of this housing model in a scheme of 13 housing units in Sri Lanka. The attention to detail required in construction and the applicability of alternative building materials and methods to improve the sustainability of such houses have been discussed in detail. These semi-tiered houses have the potential to address many of the current construction challenges.

KEYWORDS

stepped housing, stabilized earth, micro concrete roofing tiles, sustainable construction

1. INTRODUCTION

With economic development and increase in population, houses with a reasonable quality but affordable in cost will be needed in many countries [1]. This has resulted in a housing deficiency where the number of units of adequate quality falls short of the requirement and hence some houses would be considered as substandard. Therefore, there is a significant need for houses of reasonable quality in many developing countries. To add to this deficiency in the number of

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houses, there could be the larger issues related to the land tenure, lack of availability of land, lack of infrastructure facilities, etc. Some examples can be highlighted from Malaysia [2], India [3], Nigeria [4] and Sri Lanka [5].

One important factor that has been highlighted in many of these studies is affordability which means the ability of occupants, specially the low and middle income earning category to afford the housing satisfying basic needs with adequate quality, while not affecting the ability to spend for other needs. This means, the cost effectiveness of the solutions given would also be a major factor to be considered.

Another issue that has to be considered when housing is needed in such large numbers is the extensive use of conventional building materials and methods that could consume a significant amount of natural resources and run the risk of having a relatively high carbon footprint [6] [7]. Thus, the adoption of alternative construction materials along with efficient construction techniques could be the key to meet affordable housing needs with minimum impact on the environment.

The availability of buildable lands has also become scarce in the urban and suburban areas in many countries which in turn has led to inflated land prices. Since building on flat land is not always feasible, the possibility of converting the sloping lands into buildable ground has been explored in some research studies. Although sloping marginal lands are significantly low in land cost, such lands are often not inhabited due to the potential for slope stability related issues. It has been found that the slope failure potential can be minimized by the use of stepped construction in moderately sloped land [8]. Hence, good drainage and use of stepped construction could lead to a favourable and stable ground for house construction.

Therefore, in this study, attention has focused on reducing the slope stability related issues by developing a tiered single storey house. Since the tiers created for the houses could still have stability related problems, a series of measures have been developed to improve performance. Since the cutting of the sloping land to create tiers could generate a large quantity of good quality soil, special strategies have been adopted to maximize the reuse of such soil in a very effective manner to reduce the cost of the houses and thus improve their affordability.

Furthermore, this research discusses the application of tiered single storey house construction technique in residual soils with the use of sustainable building materials of significantly lower embodied energy while keeping the total cost to a minimum. After developing the concepts needed for tiered housing, the application of such methods has been checked with a case study of a housing project carried out in a sloping marginal land with laterite soils in Sri Lanka. This construction gave a first-hand experience in adopting the design concepts to create affordable housing with lower embodied energy and carbon footprint. It is also shown that paying sufficient attention to the details of construction is of significant importance to ensure that such housing could become a long lasting solution in the quest for providing houses of reasonable quality for the low and middle income societal members in many developing countries with undulating ground profiles.

2. METHODOLOGY

In order to achieve the main objective of developing an affordable house suitable for undulating terrains susceptible to slope stability related issues, the following methodology has been adopted:

1. A concept of tiered single storey houses has been developed to suit the sloping lands where stability can be improved with stepped construction.

2. An assessment was made with typical properties of laterite soil to assess the stability of ground with vertical cuts.
3. An effective reuse of excavated laterite soil was assessed by transforming the soil into stabilized rammed earth.
4. Cement stabilized rammed earth has been adopted as a foundation and earth retaining material to improve cost effectiveness of the tiered houses while lowering the embodied energy and the carbon foot print.
5. Alternative building materials have been incorporated for the super structure of the house to utilize a greater degree of sustainability.
6. These concepts and methods have been fully tested in a real-life application by using them in an actual construction case to assess the advantages and challenges.

3. STABLE SLOPING GROUND WITH STEPPED CONSTRUCTION

Sloping lands are not widely used for construction of houses due to the various slope stability related issues that could damage the houses during heavy rains where the slopes tend to fail due to their sliding potential. However, if the sloping land has residual soil that contains both clayey particles along with sand and gravel, it offers a good possibility of improving the stability with tiered housing that will suit the stepped profiles created for the building footprint.

3.1 Laterite soil

According to Tardy [9], laterite earth covers nearly one third of Earth's continental land area, particularly concentrating in the land area between the tropics of Cancer and Capricorn. Laterite soil is formed due to the weathering of rock in tropical climates. Hence, this soil has a certain percentage of clay and silt in addition to sand and gravel. The presence of clay and silt gives cohesion to the soil which remains in the range of 20–100 kN/m^2 or more. Due to the presence of finer particles, the friction angle remains in the range of 25°–35° in most cases. Table 1 indicates some typical effective shear strength parameters for laterite soil, as found in several studies.

As can be seen in Table 1, for typical laterite soils, the cohesion is generally in the range of 30–50 kN/m^2 or more. An unusually low value of 20 kN/m^2 has been found at the Pussellawa landside location [12] in Sri Lanka. However, the high friction angle of 33° indicates that the soil is more of sandy in nature.

TABLE 1. Typical effective shear strength parameters of laterite soil.

Country	Effective cohesion (kPa)	Effective internal angle of friction (°)
Nigeria (DALL Quarry in Ilorin metropolis) [10]	60–100	31–35
Hawaii [11]	48–345	27–57
Sri Lanka (Pussellwa land slide location) [12]	20	33
Singapore [13]	30–45	25–27

3.2 Stability of a vertical cut

The lateral earth pressure exerted in active state is given by equation 1:

$$\sigma'_h = K_a \sigma'_v - 2c' \sqrt{K_a} \tag{1}$$

With $K_a = (1 - \sin \phi')/(1 + \sin \phi')$ where σ'_v, c', ϕ', K_a means effective vertical stress, effective cohesion intercept, effective angle of internal friction and coefficient of active earth pressure, respectively [14] [15].

If the cohesion is taken into account, the height of a vertical cut that would be stable can be found using equation 1 and the calculation is explained with an example. For this, the friction angle has been taken as 26°. This gives a $K_a = 0.39$. The value of σ'_v is calculated using a typical density of 18 kN/m^3 [11] [13]. When $\sigma'_h = 0$, equation 1 gives $K_a\sigma'_v = 2c' \sqrt{K_a}$, where $\sigma'_v = 18\,h$. This will allow finding suitable values for h depending on the value of c'. The heights are tabulated in Table 2. It also gives the heights when a surcharge of about 10 kN/m^2 has been allowed to take account of the loads from the house.

When the resultant horizontal pressure is considered against the wall, it would result in double the value presented in Table 2 [15]. However, such values are not considered since those could be considered as theoretical maximums and actual maximum heights will be slightly less. Hence, the heights tabulated in Table 2 can be considered as conservative.

However, if the soil becomes saturated, it is necessary to take account of the saturated density of soil (γ_s = 20 kN/m^3) and also the hydrostatic pressure from which equation 1 can be modified. This gives equation 2. In this case, the density of soil has to be taken as the submerged density ($\gamma_s - \gamma_w$), or 20.0 – 9.81 kN/m^3 where γ_w is the density of water and σ_h is the lateral earth pressure:

$$\sigma_h = h_w \gamma_w + K_a \sigma'_v - 2c' \sqrt{K_a} \tag{2}$$

Equation 2 permits obtaining the allowable heights for the vertical cuts when the soil is saturated. Even with the saturated soils, it is possible to consider the surcharge of 10 kN/m^2.

The values given in Table 2 indicate the importance of keeping the soil in either dry or a partially saturated state so that additional hydrostatic pressure will not develop. With unsaturated soil, any height up to 3 m would be safe with laterite soil. Even when the soil is almost saturated, still a height of about 1.5 to 2.0 m could be stable depending on the soil properties when the clay content is reasonably high.

TABLE 2. The height of stable vertical cuts for different values of cohesion.

Cohesion kN/m^2	Friction Angle ϕ (°)	Height with dry or partially saturated soil (m)	Height with dry or partially saturated and also with surcharge (m)	Height with saturated soil (m)	Height with saturated soil and surcharge (m)
20	30	3.86	3.00	1.81	1.52
25	28	4.44	3.89	2.26	1.98
30	26	5.33	4.78	2.71	2.43

However, it should be noted that such vertical cuts can become unstable due to the subsequent weathering of soil that could lead to a change in composition and also allow the formation of tension cracks. Sufficient attention must be paid to this in stepped housing to ensure a long lasting and safe solution.

In addition to the favourable situation created by cohesion, if the soil is unsaturated, it can further develop additional stability. When laterite soil is slightly moist (unsaturated), the presence of negative pore water pressure (matric suction) significantly increases the shear strength of soil through an apparent cohesion and hence the heights indicated above will be safer. However, if the soil becomes saturated, this advantage will not be available.

In order to explain the metric suction, the equations of shear strength envelopes for saturated and unsaturated soils are expressed in Eqs. 3 and 4, respectively [16] [17].

$$\tau = c' + (\sigma_n - u_w)\tan\phi' \tag{3}$$

$$\tau = c' + (\sigma_n - u_w)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{4}$$

In the above equations, σ_n is the vertical stress, c', ϕ' are effective shear strength parameters of soils, u_w and u_a represent the pore water pressure and pore air pressure, respectively, and the metric suction is given by $(u_a - u_w)$. In this, ϕ^b is the rate of increase of shear strength with respect to the increase of matric suction. The term $(u_a - u_w)$ tan ϕ^b is referred to as the apparent cohesion. It can be observed from Eq. 4 that the presence of matric suction would significantly increase the shear strength of laterite soils through apparent cohesion though it will vanish if the soil becomes saturated.

4. DETAILS OF THE PROPOSED TIERED SINGLE STOREY HOUSE

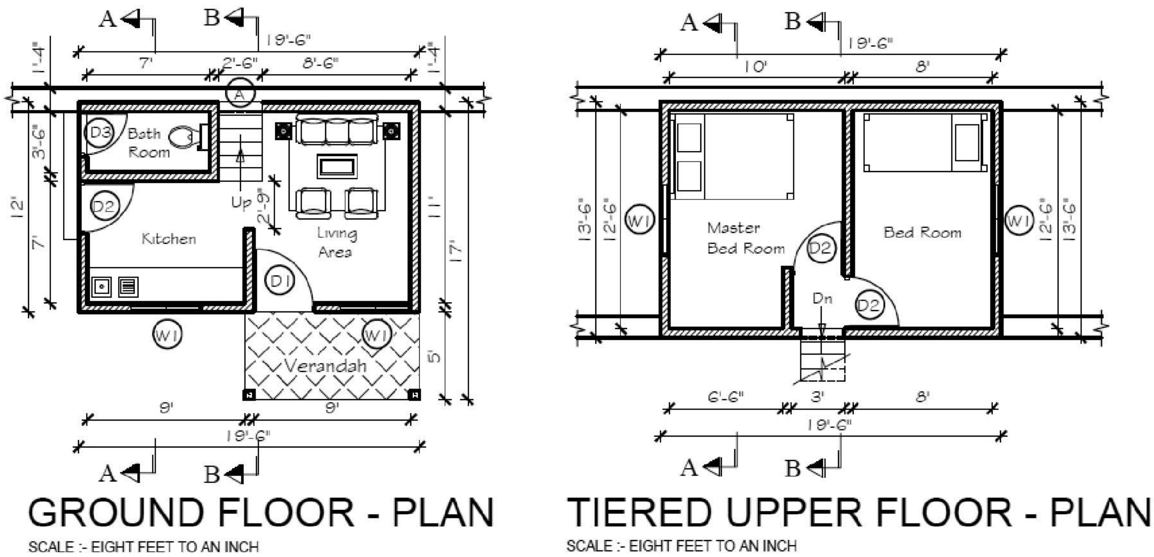
The tiered house planned is a basic one with only 50 m^2 of floor area since it is necessary to ensure that it would be affordable to those with low to middle income. Nonetheless, the same concept could be extended to a larger house with several tiers as well. The plan is given in Figure 1. The side and front elevations are shown in Figure 2 and the sectional views are in Figure 3.

5. CONSTRUCTABILITY AND ADOPTABILITY OF THE PROPOSED HOUSE

The tiered single storey house developed has been adopted in a housing project funded as a corporate social responsibility (CSR) project of a leading cement manufacturer in Sri Lanka. Each house was about 50 m^2 and provided with a verandah, living area, kitchen, a wash room and two bed rooms. There were thirteen (13) houses constructed in total. Some of these are shown in Figure 4. The housing project considered in the case study was on a sloping land. The tiered housing concept has generated excess soil, which can allow reuse of such soils for the application of Cement Stabilised Rammed Earth as a very effective construction material for many items of the houses thus resulting in a cost-effective solution.

The main building elements were constructed with alternative building materials such as cement stabilized rammed earth (CSRE), micro concrete roofing (MCR) tiles, and compressed stabilized earth blocks (CSEB) with cost effective finishes. With the selection of alternative

FIGURE 1. Floor plan of the tiered house.



SCHEDULE OF DOORS AND WINDOWS			
TYPE	SIZE	SILL	DESCRIPTION
D1	3'-6"X8'-0"	—	SINGLE SASH H.W. TIMBER DOOR
D2	3'-0"X7'-0"	—	SINGLE SASH H.W. TIMBER DOOR
D3	2'-6"X7'-0"	—	SINGLE SASH H.W. TIMBER DOOR
W1	4'-0"X5'-0"	3'-0"	TIMBER & GLAZED WINDOW

FIGURE 2. Front and side elevation of the tiered house.

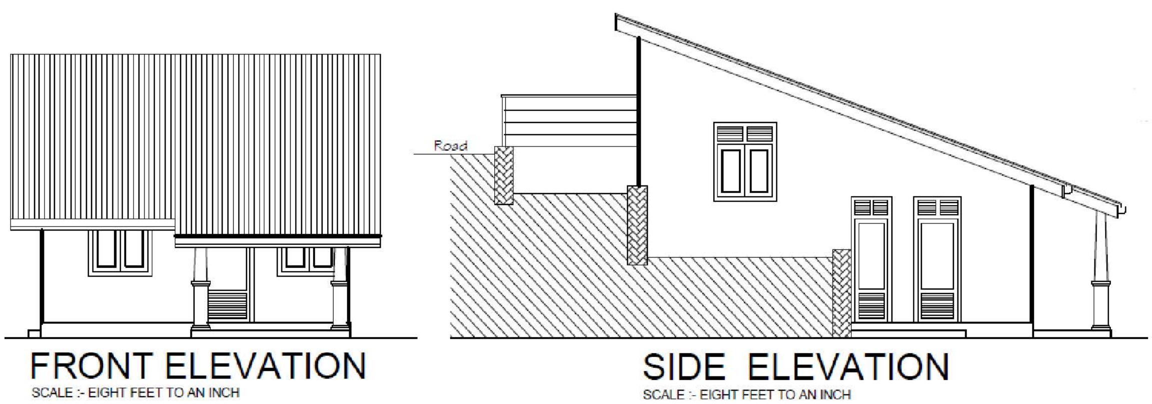
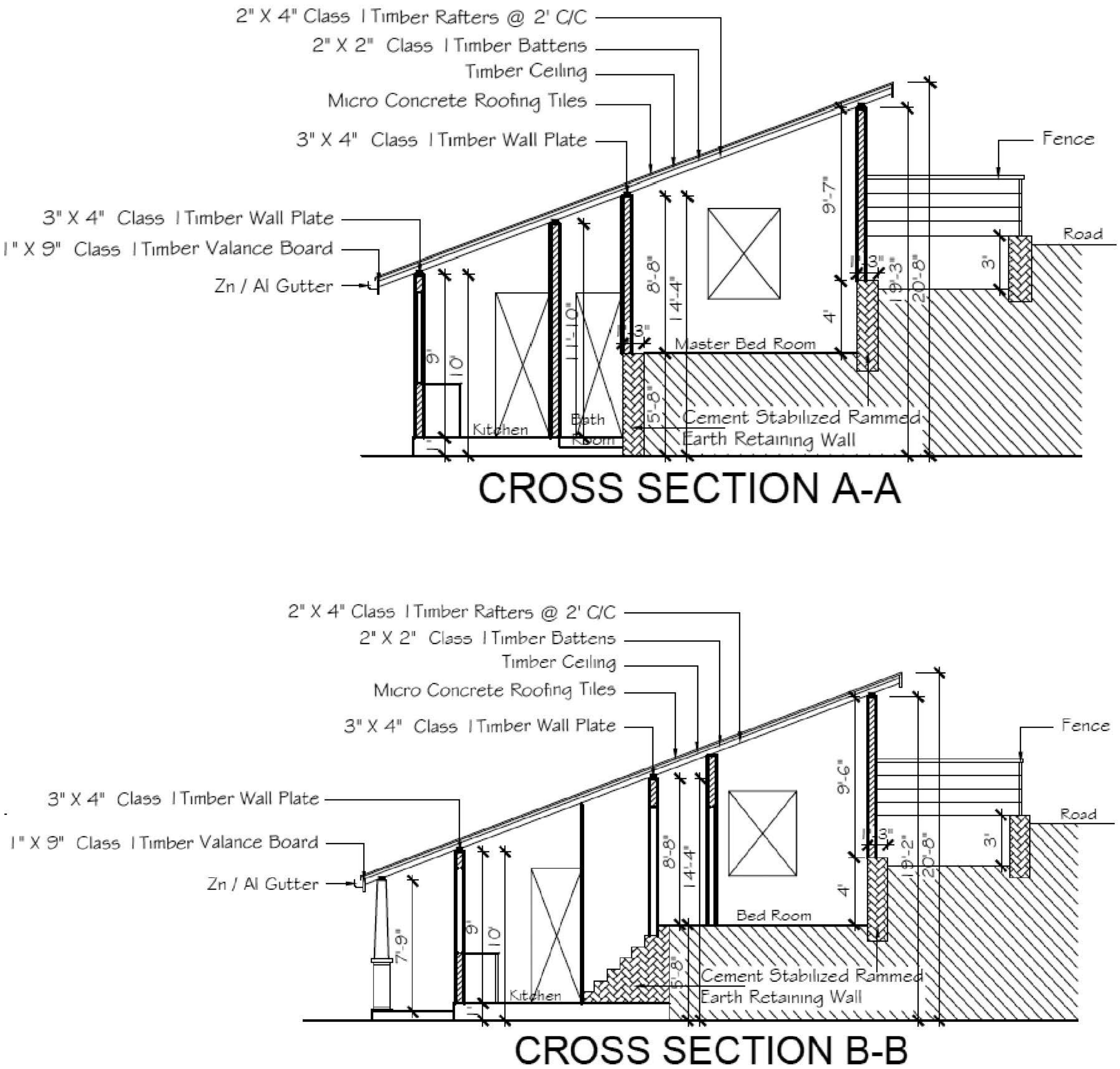


FIGURE 3. Sectional elevations of a tiered house.



building materials and innovative building techniques, the cost of construction has been brought down to $160 per sq. m. (in 2015 considering 1 USD=140 Sri Lankan Rupees). The following sections outline the alternative building materials and the techniques used in the project.

6. STABILIZED RAMMED EARTH FOR RETAINING WALLS

The cross sections shown in Figure 3 indicate that the existing slope has to be cut in steps to form the flat land needed at each tier. This has generated a lot of excess soil and part of this soil was used to create a flat land in front of the house to act as the access road. Each house had at least two vertical cuts or sometimes more. Once a vertical cut is formed, it is necessary to protect it. This can be achieved by having retaining walls. It was possible to use cement stabilized rammed

FIGURE 4. A completed house containing many alternative materials and methods.

earth (CSRE) for these retaining walls since a lot of excess soil was available at site. There are many advantages that can be offered by CSRE.

For laterite soil, it is possible to improve the properties to a desirable level by adding about 6–8% of cement. Various research studies have indicated that laterite soil with clay and silt content less than 35% can be stabilized with 6–8% cement to give a material with a characteristic compressive strength in the range of 1.6–3.0 N/mm^2 [18] [19]. Its flexural strength is also in an acceptable range of 0.4 N/mm^2 when spanning vertically and about 0.9 N/mm^2 when spanning horizontally [20]. The erosion resistance, wet compressive strength and shrinkage resistance of well compacted CSRE was also found to be high [21].

Another key advantage of CSRE is its lower embodied energy despite the use of cement as a stabilizing agent [22]. When the soil is available at the site, the embodied energy can be further reduced since no energy is needed for transportation. Considering these favourable aspects of CSRE, it was decided to construct the retaining walls with the soil available at the site. The actual height of a vertical cut can be up to 1.5 to 2.0 m depending on the slope available. In this height range, laterite soil will be stable on its own as shown in Section 3. Therefore, any vertical retaining wall that is out of a material which can withstand long term weathering will be able to retain the soil mass and also prevent its erosion. Hence a wall between 400 to 450 mm thicknesses can be selected for the construction of the retaining wall. This retaining wall will act as the foundation for the vertical walls constructed for partitioning and also to support the roof as shown in Figure 3. It is also possible to have additional retaining walls in the front and the rear of the house depending on the original slope.

When the retaining walls were constructed, they were extended about 1.0 m beyond the outer boundaries of each house as shown in Figure 5. In this figure, thick recycled polythene

FIGURE 5. A CSRE retaining wall extended beyond the house to retain the soil

sheet was used in between the vertical cut and the CSRE retaining wall. One of the main purposes of this polythene layer is to prevent any wet patches appearing on the face of the retaining wall exposed to the interior of the lower tier accommodating the living area as shown in Figure 1. It may also serve to retain the moisture in the soil mass behind the retaining wall so that additional stability is available due to matric suction described in Section 3.

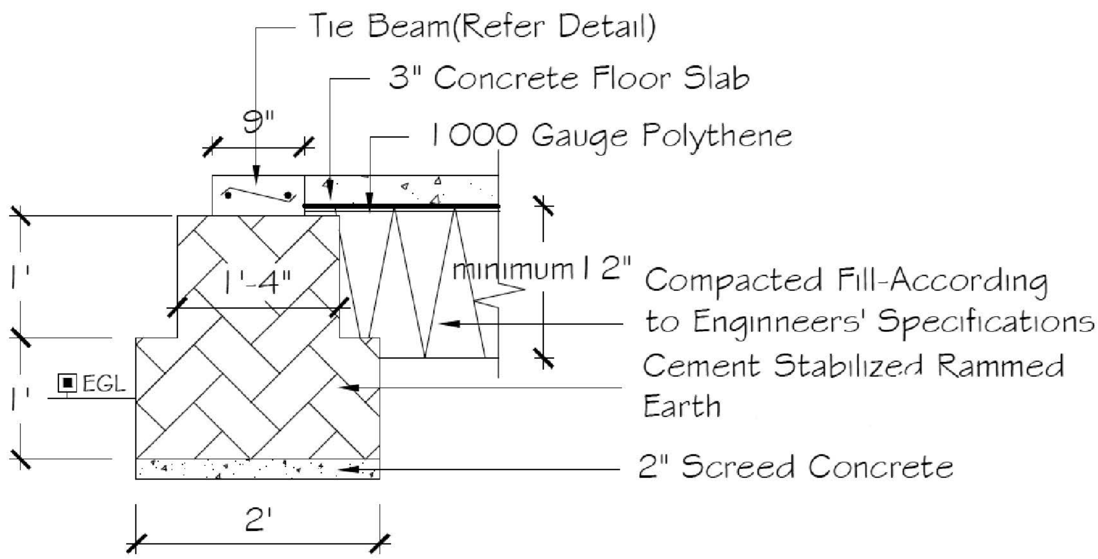
Another precaution that can be taken at the CSRE retaining wall is improving the drainage. This is valid for the upper retaining walls shown in Figure 3 and also to the portion extended beyond the house. The improvement to the drainage can be achieved by having a thin layer (50 mm) of CSRE laid on the ground to a slope so that the rain water will drain easily. This is the type of special attention that is needed for finer details to minimize the risk of slope instability.

The retaining wall shown in Figure 5 did not indicate any sign of deterioration after one year of construction. Thus, CSRE can be considered as an effective structural material with low carbon footprint for retaining earth rather than random rubble masonry (gravity) or concrete (gravity or cantilever retaining walls).

7. STABILIZED RAMMED EARTH FOR FOUNDATION

The desirable properties of cement stabilized rammed earth explained in Section 6 allowed its use as a foundation material. The cement content was maintained at 8% when used as a foundation material to further enhance the strength and the erosion resistance. A typical cross section is shown in Figure 6. A reinforced concrete tie beam of 200 mm width and 100 mm depth has been used to tie all the foundations together. The reinforcement provided was 2 numbers of 10 mm diameter high yield steel bars.

FIGURE 6. A typical foundation detail.



8. COMPRESSED STABILIZED EARTH BLOCKS FOR WALLS

Various research studies have been conducted on cement stabilized earth blocks for their strength and durability and subsequently used in many projects [23] [20] [24]. A comparative study on the strength and embodied energy of several walling materials is given in Table 3 [24].

The walls of the houses of the case study were mainly constructed using CSEB of 300mm (length) × 150mm (width) × 100mm (height) in size, manufactured using laterite soil stabilized with 6% cement. A larger block of 240mm × 240mm × 125mm in size can be used in the walls of heights in excess of 3.5 m. In order to comply with the slenderness requirements and to improve the robustness as stated in BS 5628: Part 1: 1992, lintels were provided with

TABLE 3. Comparison of strength and embodied energy of different walling materials.

Material	Wall compressive strength (Nmm^{-2})	Wall flexural strength (N/mm^{-2})		Embodied energy (MJm^{-3})
		// bed	⊥ bed	
Local burnt clay brick (225mm thick, mortar designation III)	2.5 [25]	0.3 [25]	0.9 [25]	3491 [26]
Hollow cement sand block (200mm thick hollow mortar designation III)	2.8 [25]	0.15 [25]	0.25 [25]	895 [26]
Cement stabilized rammed earth(CSRE) (240 mm, Sandy laterite 8% cement)	2.94 [21]	0.46 [21]	0.92 [21]	500 [22]
Cement stabilized earth blocks (CSEB) (225mm thick)	2.6 [27]	0.24 [20]	1.28 [20]	960 [26]

FIGURE 7. Compressed Stabilized Earth Block wall after applying the finishing coat of mud paint.

concrete tie beams at the level of 2.1 m [25]. Since the blocks were machine made with a good surface finish, a finishing coat was applied with a mud paint. This paint was produced with the proportions 1 part of cement, 1 part of lime and 6 parts of soil (sieved through 2mm mesh), which can give a durable surface coating with an acceptable erosion resistance and less water absorption [28] [29]. Doing away with the plaster has saved a significant amount of cement, sand, and lime, which in turn has optimized resources; this has reduced the embodied energy of the house as well. Figure 7 shows the completed walls with CSEB coated with mud paint.

9. THE CEMENT RENDERED FLOOR

The cement rendered floor consists of a base of 65mm thickness that was made out of cement stabilized rammed earth on which a cement sand mortar of 20 mm thickness was laid. In order to improve the bond, 20 mm coarse aggregate was spread as a thin layer and then compacted into a soil mix after compacting the soil to a thickness of 65 mm. Cement rendering was laid on this prepared surface, thus avoiding the need for a floor concrete. If a ceramic tile finish is needed, it also can be laid on the surface prepared with cement rendering.

10. ROOF WITH MICRO CONCRETE TILES

The roof construction of the project consists of micro concrete roofing (MCR) tiles and a cost effective timber framework.

10.1 MCR tiles

In this housing scheme, Micro Concrete Tiles (MCR) have been used instead of burnt clay tiles. The MCR tile used is strong and also has a weight comparable with burnt clay tiles as indicated

TABLE 3. Comparison of the properties of roof covering materials.

	Weight with framework (kg/m²) [30]	Total cost with framework (USD/m²)	Transverse strength (kN) [30] [31]	Embodied energy [26] (MJ/m²)
MCR	57.0	19.1	4.5	134
Calicut tiles	55.0	22.5	1.4	412

in Table 3 [30]. The strength properties have been obtained from the relevant standards. It is stronger and has a lower embodied energy per square meter.

MCR is manufactured using a mix of concrete to the recommended proportion of 1 part cement, 12 parts chips (6 mm) or quarry dust and 2 parts sand [32]. These tiles can provide a wider coverage than a clay tile. Each tile covers an area of 0.25 m^2, thus needing only 4 tiles to cover 1 m^2. The thickness of the tile is in the range of 8–10 mm which will continue to gain strength and has the potential to last well over 50 years. It has a good interlocking arrangement and hence offers a significant resistance to strong winds. MCR tiles can be used with a natural finish or can be painted with a water-based paint for better fungus resistance. Once painted, it provides an attractive finish as shown in Figure 8.

11. ROOF STRUCTURE

The roof structure was out of timber since it is a renewable source. The timber variety is called Alstonia (*Alstonia macrophylla*), and it has a maturity period of about 10–15 years and can provide a durable and strong timber when mature [33], [34]. In order to give an attractive finish, the timber members were sized to the required dimensions and then provided with a water-based varnish after changing its pale colour to a more attractive mahogany colour by using a water based dye. With a short cropping cycle, Alstonia can be used to create a carbon sink since the

FIGURE 8. Roof with MCR tiles.

FIGURE 9. Exposed roof structure with the ceiling.

timber can be effectively used as a structural material. With the exposed timber structure, the ceiling of the house was provided with plywood sheets protected by a thick recycled polythene layer against any moisture damage on the upper surface. The roof structure with the ceiling is shown in Figure 9.

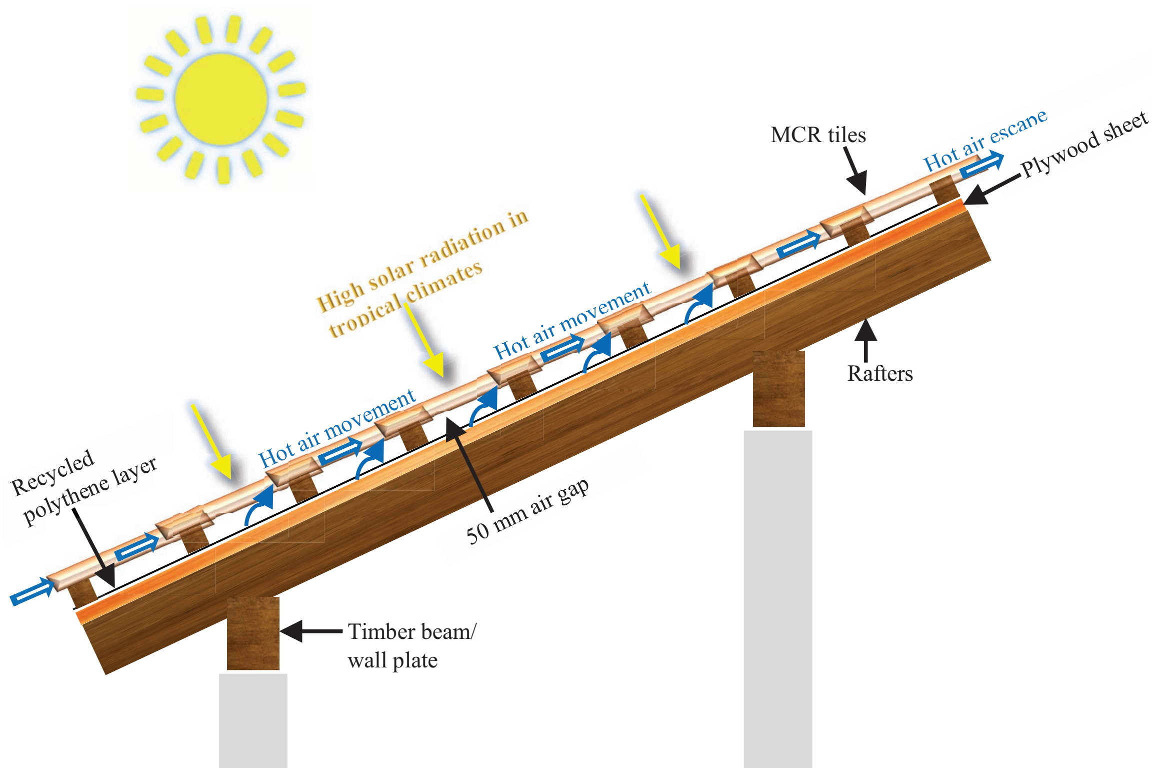
11.1 Roof arrangement

One of the key requirements for preventing slope instability is improving the drainage which will prevent the soil becoming saturated. Therefore, the roof has been arranged as sloping in one direction (Figure 8). Hence, all the rain water will drain towards the access road in front, thus keeping the soil retained behind the vertical cut relatively dry. As described earlier, extra strength is available in laterite soil when it is not saturated.

With this roof arrangement, there is an added benefit in tropical climatic conditions. With the shape of the MCR tiles, the roof structure shown in Figure 10 can allow the hot air to rise during the daytime thus allowing a certain degree of heat loss due to the formation of convective streams. The need for a high roof angle with the tiered housing also facilitated a reasonable head room as shown in Figure 3 and this also facilitated better ventilation. Thus, these tiered houses are able to provide a reasonable level of thermal comfort due to reduced heat gains and the reduced transmission through the timber ceiling.

Therefore, the roof sloping in one direction coupled with semi-tiered floors with bedrooms in the upper level provide an ideal solution to ensure very good drainage for the soil mass in the surrounding area. This can ensure that the soil mass will remain relatively dry but slightly moist. This is an ideal condition needed to ensure a soil mass that develops a very high level of cohesion so that it will not exert any outward pressure for a vertical cut height of 1.5m as used

FIGURE 10. Roof structure and its arrangement to enhance passive cooling.



in this particular housing scheme. Therefore, this particular arrangement can minimize slope failure potential when building on sloping lands.

The road in front of the houses has been constructed using the excess soil made available when the tiers are formed. This fill can also assist in stabilizing the slope since toe loading is an ideal way of reducing any possibility of instability of slopes. The septic tank of each house has been located in the front to assure relatively dry conditions for the soil in the footprint of the house.

Since this semi-tiered house is fully developed, and most of the durability related issues have been addressed, it could now be adopted as a housing concept in sloping lands of tropical climatic conditions where the availability of flat lands is becoming scarce.

12. DISCUSSION

With this single storey tiered house, it is possible to gain many advantages and also offer the potential for further improvements which can be described as follows:

1. The formation of tiers for the footprint of the house is a much better and stable way of controlling the slope instability potential than creating one large flat area with deep cuts. A larger footprint with a deep cut can increase the slope instability potential and also makes controlling drainage more cumbersome. In this context, the tiered cuts of limited height, such as 1.5m to 2.0 m maximum, can be an ideal solution when the access road is created by using the cut soil in front of the house at a lower elevation.

Such toe loading can further stabilize the sloping land. The road also can be paved with cement stabilized earth so that it will not absorb much water on rainy days since compacted dense cement stabilized earth will be less pervious than a natural soil. Cement stabilization of the road can prevent erosion, and it is possible to form the side drains using cement stabilized earth with about 8% cement. This will allow draining of rain water safely away from the hilly terrain, using water paths where pipe culverts will be needed across the road to prevent erosion. Thus, it can be stated with confidence that tiered houses can become an ideal candidate for sloping lands which are prone to instability in tropical hills.

2. The tiered house presented in this case has only two tiers with bedrooms located at the upper level. These two bedrooms have a high level of privacy, good ventilation, better thermal comfort, while having a high level of natural lighting. This is an ideal condition that can be expected in tropical climates since thermal gains during day time is a major problem. If a larger house is needed, it is possible to have another tier or else it is possible to make the house longer parallel to the road. Therefore, these tiered houses need not be as small as 50–60 m^2, but can be easily converted to about 100m^2, which could have about 3 bedrooms, 2 washrooms and, living, dining etc., while maintaining the salient features of semi-tiered houses.
3. When sustainable housing is created in hilly terrains due to a lack of flat lands, it is possible to create shading by planting the species that have been used as roof timber on either side of the roads, thus facilitating creation of a carbon sink and also roof timber for future houses.
4. The use of cement stabilized earth as the retaining wall material has allowed the use of earth that is readily available as cut material generated rather than bringing in any additional material. This is of particular use since the embodied energy of the construction materials can be kept as low as possible and thus assuring a lower carbon footprint.

13. CONCLUSIONS

A tiered single storey house has been developed to suit a stepped profile in a hilly terrain that has the risk of slope instability in times of heavy rainfall. It is shown that when laterite soil is available, such a stepped profile formed with vertical cuts of less than 1.5m height could be safe even under saturated conditions. However, the stability can be improved significantly if the soil can be maintained as dry or partially saturated. In the proposed solution, these conditions have been achieved while using the excess soil resulting from the excavation as cement stabilized rammed earth to form the retaining walls, foundations, the floor preparation and also improving drainage. Once these techniques are coupled with other alternative materials and techniques, such as compressed stabilized earth blocks, micro concrete roofing tiles, harvested timber, etc., it is possible to achieve a house with a greater degree of affordability and sustainability while ensuring an acceptable level of quality.

It is argued that with the special roof arrangement, it is possible to keep the drainage of the land at a reasonable level to prevent any instability to the slopes created by saturation of the soil mass. This roof sloping in one direction also has the potential to provide a reasonable degree of thermal comfort while providing an adequate level of natural light and ventilation. Hence, this tiered single storey house concept can be adopted for sloping lands to minimize the risk of slope instability while ensuring a house of a reasonably low cost and thus providing an affordable housing solution.

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