1. Introduction

The Western Himalayan mountain range has some of the highest altitudes on earth with extreme climate and steep terrains covered with glacier and ice. Environmental scientists have long tracked the melting of glaciers and rising of temperatures in the region. These trends correspond to increased precipitation particularly in Zanskar, Ladakh, Spiti and Kinnaur regions along the Indo-Tibet border in the Indian Himalayas. Dendrochronological studies also indicate that historically the level of precipitation was 150 mm per year in the early 1900s; over the course of time of a hundred years precipitation rate has increased threefold to 450 mm per year, as recorded in 2000 [1]. Meanwhile studies on melting and receding Himalayan glaciers conducted by World Glacier Monitoring Service (WGMS) under UN Environmental Programs [2] hint towards an increase in the global and regional temperature. The studies also suggest that the glaciers in these areas, at current rates of global warming, could disappear within the coming decades. Apparently over the past few years rising temperature and increased precipitation is slowly turning this cold and dry Himalayan desert into a warmer and wetter place with shorter winters and moderate summers. The cultural landscape of this region especially at higher terrains, previously devoid of trees and vegetation is slowly converting into small farmlands and orchards. Recent climate change has triggered fast and large-scale impacts on cultural heritage of the Western Himalayas. Increased rainfall and rise in over all temperature has potentially dangerous effect on ancient structures and threatened the existence of historic architecture in the region. Changes in the climate not only affect the historic structures and the built environment but impact on socio-economic status that in turns influences ever changing and developing cultural landscape. Traditional building materials and techniques that are unable to cope up with changing environment are replaced with technologies and materials from foreign lands. The Himalayan region is no exception. Experimentation and adaptation to new building materials and technologies without understanding their compatibility with the existing buildings and environment has resulted in rapid deterioration and disappearance of a cultural landscape developed and sustained for several centuries in this region. A strategy to conserve the historic structures in such dynamic and changing environment requires a scientific and multi dimensional approach that not only addresses the issue of materials and structural preservation through compatible intervention but at the same time puts forward a plan for sustainability through a designed maintenance and monitoring plan.

2. Cultural Landscape of the Western Himalayas

The Lahaul, Spiti and Kinnaur valleys of Western Himalayas of Himachal Pradesh preserve a substantial amount of cultural fabric from the ancient period of 10th Century AD to 15th Century AD in the history of Tibetan Buddhism. The cultural landscape in this region is mostly speckled with Buddhist monasteries, temples and houses some of which date back to 10th century AD. Historic buildings, particularly temples, have always been simple, rectangular geometric spaces with carefully designed structural members. This approach unveils an outcome of years of trials and wisdom against extreme climatic conditions and natural disasters like earthquakes and landslides. Due to the arid climate timber has always been scare and was imported from lower regions of the western Himalayas just for the roof, columns, doors and windows. The walls of these historic structures are primarily made of Adobe, a large sun-dried mud brick laid in mud mortar with the foundation in rubble stone masonry, generally rests on a stable solid ground. The thickness of the walls varies from 75cm to about 150cm in some of the early period structures. Due to the cold climatic conditions for most of the year, the openings in the walls of the temples are minimised and contribute to less than 5% of the total wall surface and are generally located at the center of the wall. The only source of light and ventilation is generally through the low height, narrow entrance doorway.
The roofs of the temples are flat, due to lack of rainfall in the region and are made of mud laid in various layers and compacted. Generally the buildings have from 17cm to about 20 cm of compacted mud rest on 50mm thick rectangular wooden panels or a mesh of willow twigs, with a layer of local shrubs or birch bark sandwiched between the two for waterproofing. These are in turn supported over wooden rafters and beams, which are further supported directly on load bearing mud walls and wooden columns. Interiors of some of the historic temples are decorated with elaborated murals and polychrome clay sculptures supported on the walls. These historically well-engineered 1000-year-old earthen buildings housing some rare Tibetan artwork and wall paintings today lie susceptible to innumerable natural threats and human interventions.

Figure 1: Dhangker village, Spiti Valley, India

3. Impact of Climate Change

Geographical isolation as a natural barrier in the Himalayas helped in the survival of historic buildings for centuries until the 1970s when the region was allowed visitors for the first time in 1974. The last thirty years have witnessed an irreversible erosion of cultural, social and architectural fabric of the heritage components. Regular rainfall and frequent seismic activity have further challenged the existence of these earthen structures and resulted in their rapid deterioration. The higher rate of rainfall in the Western Himalayas over the past few years has increased water intrusion into the walls of historic structures, causing erosion and washing away of finer particles from the internal and external plaster. The wide temperature fluctuations throughout the year, as well as heavy snowfall in winter and the accumulation and melting of snow, have not only caused leakage but also several structural problems, such as the sagging of wooden members due to excessive snow load. Roofs, supported with structural wooden beams and rafters, rest directly on the load-bearing mud walls. Point loads developed by structural members resting on the walls without interstitial wall plates have created enormous stress on the walls, especially with vertical loads, such as snow-related dead load, or during oscillations caused by an earthquake. This stress has resulted in major and minor structural cracks below the ceiling level at the junctions between the roof and the walls. These cracks have now become the inlet points for water into the interiors. Moisture intrusion, temperature fluctuation, and lack of ventilation have made the interiors of the buildings humid, resulting in accelerated deterioration of the internal plaster and wooden structural members. Damp walls also impact the structural integrity of the polychrome clay sculptures by threatening the stability of their wooden supports in the walls. The addition of layers of clay intended to waterproof the earthen roof have contributed to the roof load even further. This has not only caused sagging of structural members but also deformation of load bearing walls especially in the upper courses just below the ceiling level.

Below ground and semi-subterranean structures [3] are the worst affected due to increased moisture level in the surrounding ground which seeps into the structure and its foundation in absence of a proper drainage system. Water intrusion into the foundations and seismic vibrations has also caused settling of load-bearing walls. It is known that the deteriorating agents do not act alone; action of one renders the surface or the structure susceptible to the subsequent action of another. Environmental humidity is another decay agent, which causes water-induced stress in the outer most porous surface of the walls and helps in the development of plants and microorganisms.
Wind has been a main factor in the erosion of external renders, which with the impact of rain results in the loss of surface material. The surface exposed to several wet-dry cycles is easily abraded by coarse sand and dust particles carried by these high velocity winds in the region. Traditional adobe buildings, which are susceptible to the changing climate, have lost their creditability among the locals who now adapt moisture resistant cement concrete blocks or cement stabilized compressed mud blocks for new construction, additions and repairs to the existing buildings. The traditional compacted mud roofs are either replaced with cement concrete slabs or with corrugated galvanized sheet metal roofing system. These actions are slowly changing the whole cultural landscape into a concrete and sheet metal jungle and resulting in a large-scale depletion of nearly a 1000 years old historic Man – Nature – Material relationship [4]. Cement, corrugated sheet metal, steel rebars and compacted cement stabilized block is manufactured and transported to the regions 100s or 1000s of kilometers from the lower regions of India contributing further to the deterioration of not only the region’s and the world’s environment but also the local economy and culture. Building materials are not in themselves good or bad. They are appropriate or inappropriate depending on the geographical, climatic and supply factors which also make them practical and sustainable.

Changing climate certainly calls for re-evaluation of the entire situation from a scientific, environmental, social, cultural and economic perspective. A 1000-year-old cultural landscape that preserves in its terrains rare artwork, art forms and architecture requires a compatible yet sustainable modification to the traditional building materials and technologies, which not only responds to the changing environment but also at the same time alleviates dependence on imported materials. Reduced dependency on alien materials would not only improve the local economy but would ensure appropriate development and growth of cultural landscape.

4. Mitigation:

The deterioration of historic building components as explained above necessitates remedial actions, including protection of exterior envelope against water damage and modification of traditional roofs against increased moisture, while addressing the drainage issue not only for subterranean structures but also for above grade earthen buildings. The current Situation also necessitates a methodology of identifying and investigating various monitoring tools in order to determine the most effective and appropriate tools for assessing and then mitigating the particular threat. Authors would like to share their experiences through a series of examples and studies conducted in the region for conservation of heritage buildings.

1) Case study of a subterranean structure

Figure 2: Horizontal crack in the load-bearing wall of the semi-subterranean structure.
The temple of Gya-Pag-Pai, a 12th century semi-subterranean structure located in a small village of Nako, in the northern Indian state of Himachal Pradesh at about 3600 meters above sea level in the Himalayan mountains, was damaged in the earthquake of 1975 and has since been under enormous structural stress. Documentation of the structure revealed that there is tremendous movement in the upper portion of the load bearing walls. The lateral outward horizontal movement in walls has resulted in large-scale bulges and cracks in the masonry. Increased moisture due to recent changes in the climate has further caused enormous seepage into the interiors and has also disturbed the structural integrity of the temples. Moisture measurement [5] inside the masonry using a conductivity meter revealed that there is large-scale ingress of water and moisture from the surrounding ground. In the absence of any proper drainage facility from the roof of the Gya-Pag-Pai, the rainwater and water from the melting snow seeps into the building walls and foundation causing damage to the water-soluble un-reinforced masonry. In addition to this, the site of the temple complex is sloping and consequently the excess water draining from the nearby properties on the higher level towards the rear of the temple contributes excessive moisture to the ground adjacent to the load-bearing wall. As a result the soil outside the building swells after gaining moisture, which exerts horizontal pressure on the load bearing walls.

![Figure 3: Perforated clay pipe laid at the bottom of the drain sloped away from the site.](image)

The rear wall of the temple is unable to resist the horizontal shear stress along the floor level outside, resulting in a major horizontal structural crack. The excessive moisture accumulated outside the wall, gradually seeps inside causing serious damage to the masonry, plaster and surface finishes inside. Problems of salts and other agents of chemical, environmental and biological decay following the water seepage cause severe damage to the structure. Constant drying and wetting of the painted area especially at the lower courses causes deterioration and eventually looses its binding strength. The interior plaster is decomposes into a powdery mass and has started falling away, revealing the masonry below. There has also been a drastic change in the humidity and level of moisture content in the walls since the insertion of impermeable cement flooring in the past, which has not only affected the strength of the plaster but has also affected the strength of the mud blocks. The moist adobe walls with horizontal structural cracks and deteriorated base are not only vulnerable to any seismic vibrations but are also a major threat to human life and artwork stored inside the building in the event of a collapse. It is necessary to divert the excessive moisture and surrounding ground water away from the building to reduce stress on the load bearing walls.

a) Remedial action:

Historically and in modern days sub surface drainage systems like French drains have been effective in removing excessive ground water flowing from the surrounding areas towards the building foundations. In case of Gya-Pag-Pai temple in Nako, a similar drain 2.5 meters wide placed exactly 1.5 meters away from the buildings was dug along the load bearing walls of the two semi-subterranean temples (Gya-Pag-Pai and neighboring Gongma Lha-khang temple). The depth of the drain was kept about 2.4 meters that was decided according to the internal floor level. The bottom surface of the drain was kept at least 60cm below the internal floor level of the temples so that all the water is drained out without any possible danger of seepage into the surrounding area.
The perforated terracotta pipe laid at the bottom of the drain is protected with steel bars laid across and above the pipe. The drain was then covered with stones of descending size up to the ground level for effective evaporation. The drainage had outlet points for effective cleaning and the slope of the drain was designed as per levels of the surrounding site to effectively drain water away from the building complex. This state of the art inception of the drainage system was tested and monitored for a year for its effectiveness by checking the moisture levels in the ground outside the building and also inside the masonry. Sub surface drain substantially decreased the amount of moisture in the masonry and prevented ground water draining from the higher level towards the foundations of the temple. Repairs to the horizontal cracks can proceed as the moisture subsides.

Figure 4: Eight feet deep drain dug at a distance of 2 meter from the walls of semi subterranean structures.

b) Monitoring:

This drainage system is further intended to be connected to on-site monitoring wells, which is a potential method to monitor groundwater levels and salinity of the groundwater. Monitoring wells are generally 200 to 240 cm deep and require a pipe with holes and gauze or a mesh wrapped around it, which allows water to enter but keeps sand from the drains entering the pipe. Monitoring wells can provide information on how the surrounding ground moisture level varies over different seasons and the effectiveness of the drainage system. The groundwater can be regularly tested and examined for contaminants such as salt and one can monitor the concentration of these contaminants over time without damaging actual historic masonry for samples. The sub surface drainage system (‘site drains’) is one example for mitigating stress from increased ground water that requires a detailed documentation of the site topography, underground water movement and soil properties at various levels around the building. The building drainage system (including the roof downspouts and leaders) can be integrated into the site drains in a historic settlement or around an archeological site that lacks a proper drainage system.

2) Adaptation:

High performance exterior envelope and roofs are key contributory factors for the longevity of the buildings. The buildings that were historically designed for an arid climate require adaptation to the exterior envelope to cope up with the increased moisture conditions. Lightweight and efficiently drainable roofs are key to the structural integrity of these buildings while on the other hand a durable render is essential in the protection of exterior masonry.
Changing climate calls for modification of traditional building materials to improve their resistant to moisture so that they can continue to be part of the cultural landscape and can be easily adapted as the region plans for environmental change.

a) **Technological modifications in traditional roofing system:**

![Diagram of Traditional Roof & trail Roof](image)

Figure 5: Illustration of Traditional Roof & trail Roof

A study [5] on the improvement of the traditional roof began with trial work on an ancillary structure, which involved inserting a layer of waterproofing materials compatible with the system and easily available locally. A drainage system was then designed for the roofs without significantly altering the architectural typology that defines the cultural landscape of the region. The original roof had been quite flexible but heavy and not watertight. The concept of the replacement roof was to respect the historic architectural typology of flat roof and modify the system by inserting a more durable layer of stabilized earth and at the same time reducing the weight of the roof hence reducing the stress on the bearing walls.

The existing roof is constructed of 20 to 25cm of mud laid over a tight mesh of willow twigs. These twigs are in turn supported over wooden purlins or beams, which are further supported on load-bearing mud walls (without wall plates) and wooden columns. Historically, birch bark was spread over the twigs, followed by a 5 to 7 cm thick layer of compacted mud. A final layer of waterproofing clay covers the roof to prevent water penetration. The weight of the historic roofs is approximately 300 kg/m² and the total thickness of the roof is approximately 45 cm including wood structural members and 20 to 25cm of mud.
The experimental trial roof kept the original wooden beam, rafters, and twigs. The historic compacted mud fill, which was 20 to 25cm thick, was modified into three layers. The first layer was 7.5 cm of compacted earth with a grain size varying from 0.5mm to 1.5mm. The second layer of lime-stabilized mud was one part local hydrated hydraulic lime known as kankar lime, two parts clay, and four parts sharp sand 50mm thick. It was graded towards the perimeter where drains were added. This layer was protected with hessian cloth to prevent rapid drying and allowed to cure for two days. The third layer was 12mm of compacted fine dry clay (Fig. 5). This uppermost layer acts as a sacrificial layer, swelling during contact with water and contracting during drying. The top layer can be renewed every few years, depending on the degree of erosion observed. The total height of the roof was reduced from 25cm to 20cm, thereby reducing its weight. The roof trials were observed and monitored for their performance against water and wind erosion for five years. This light weight roof performed relatively well against rainfall. The top most layer of the roof showed signs of erosion which need to be renewed for the next five years and can be added to the maintenance plan.

b) External Render

Render, being the first line of defense of these structures, is a key element for their structural longevity. Well-plastered walls not only impart durability to the masonry but also contribute to its better performance in seismic events. The local tradition is to replaster the walls when required, using only the local earth and clay admixture. Clearly, the render erodes and cracks due to inherently high shrinkage due to fluctuating precipitation levels. To stabilize the locally available soil against the changing climatic conditions and provide a water resistant render, a scientific study [6] and technical examination of samples of the various render mixes formulated from the local soil and clay with different stabilizers was carried out in the village of Nako in the northern Indian state of Himachal Pradesh. Materials were chosen based on their compatibility with historic material; cost, availability, familiarity to the context (i.e., from locally available materials) and ability to maintain the character of the building. The final mix needed to provide water-resistant qualities and also impart strength by consolidating the otherwise fragile surface of the historic buildings.

Figure 6: Fifteen plaster samples with combination of local soils, clay and locally available organic and inorganic stabilizers.
Fifteen samples (P1 through P15) were created by varying the proportions of clay, sand, lime, burnt ash, straw, and tap water. The wall surface selected for application was dry and was exposed to environmental conditions representative of the area. The first step for surface preparation for the application of the render entailed scraping with a wire brush to create a key on the surface, so that the new render could adhere to the wall. Next the wall surface was wetted carefully with water spray at a very low pressure before render application. This process was done to avoid absorption of water into the wall from the new render mix. The various render mixes were then prepared in a mixing tray with a trowel and applied to the wall surface as a sacrificial coat. They were allowed to dry for two weeks and observed for surface characteristics and any formulation of cracks.

To test the behavior and performance of various render samples against water erosion, water was sprayed directly at the center of each sample at a pressure of 50 Kpa and at a distance of 60cm. Each sample was exposed to equal water pressure for about 180 seconds. It was observed that the spray jet used in this test has flow rates approximately 2 times higher than the combined effect of rain and wind documented in this region to factor in prolonged exposure to the rain. The depth of the erosion was carefully recorded manually with a measuring scale. It was observed that the finer particles (comprising the soil) washed out of the plaster mixes creating initial pits on the surface and finally resulting in absolute failure. The plaster mixes P8, P9 and P10 with lime as a binder and a stabiliser could resist water pressure for a longer time.

The intention of the exercise was to generate a sustainable solution against the changing climatic conditions that can be used for the protection of exterior envelope of the earthen buildings with a stable render. The materials selected, which were used for stabilisation, were preferred to be locally available so that they are easily available for future repair and maintenance. The selected mixes (P8, P9, P10) after the tests are not only stable against moisture but at the same time porous enough to facilitate evaporation of moisture.

The strategies thus derived after interpretation of the above results for the surface consolidation of these historic earth structures against the natural forces and changing climate are not only practical and economical, but at the same time reinforce thousand years old local traditions.

Conclusion

Instead of undermining the durability of these structures in the present context, it is important to trace their evolution in history and understand the deterioration processes in order to further evaluate the structure, materials and the techniques that are specific to the Himalayan context in the light of changing times and needs. There is also a need to understand and implement conservation ethics. Understanding of the existing and historic terrain including surface and subsurface characteristics is an important factor. Knowing the soil types allows one to draw upon the scientific classification system for soil chemistry, stratigraphy and chemical and mechanical properties. Such information is helpful for modification of these properties to achieve the desired performance. The last few years have witnessed the introduction of stronger and stiffer materials with more compressive strength, which have lead to a decrease in the durability of historical structures. The criteria for evaluation of different factors in the materials depend on their position in the whole structure. The exterior envelopes of historic earthen structures were not originally designed to withstand frequent rainfall and the historic seismic ties in the walls have been compromised due to age. The roofs are too heavy for historic walls and the walls have undergone serious deformations due to previous seismic activity. Retrofitting of roofs would alter and interfere with the historic fabric. Such upgrading of the performance characteristics of historic buildings without making significant alterations in the architectural typology is a matter of great challenge for designers and craftsmen alike. These interventions were made to the historic roofing by insertion of waterproofing layer and perimeter drainage. Large-scale applications of conservation science like this must involve local craftsmen. Dedicated craftsmen ensure sustainability and quality control of procedures and materials of the proposed interventions.
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