J. Myanmar Acad. Arts Sci. 2019 **Vol. XVII. No.5**

PRELIMINARY STUDIES ON SUBSIDENCE IN BAGAN - NYAUNG OO AREA, MANDALAY REGION

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Abstract

Bagan - Nyaung Oo area is the most important architectural complex in Myanmar and is situated between 94°45’ 00” E to 95°00’ 00” E and 21°00’ 00” to 21°15’ 00” N. The research aim is to assess whether any subsidence is currently occurring in Bagan- Nyaung Oo area and to identify whether groundwater extraction is the main case. Subsidence is a typical geohazard for low elevated coastal areas and river basin especially when densely populated. It was only recently that the potential for hazard in Bagan – Nyaung Oo area was acknowledged, but the rates and extent of such hazard remain unknown. Bagan – Nyaunng Oo has a large urban extent and is expanding rapidly. Inhabitants and ecosystems in delta and river basin areas are becoming increasingly vulnerable to the effects of subsidence, triggered both by natural causes and anthropogenic causes. The study area covers mostly the alluvial plain beside the Ayeyarwady River and partly the debris and small fan materials derived from Tuywin Taung and Tantkyi Taung hills which are exposed with rocks of Miocene to Oligocene. Bed rocks are mainly represented by rocks of Irrawaddy Formation (Late Miocene to Pliocene), Okhmintaung Formation (Upper Oligocene) and Padaung Formation and Shwezettaw Formation (Lower Oligocene). Mainly the alluvial soils of Quaternary-Recent are deposited on the plain and along the river banks by fluvial action. The areas susceptible to landslides, rock falls, mass movements, and debris flows hazards are demarcated in the Tuywin Taung and Tant kyi Taung that have been encountered with a number of small tension cracks, active and old landslides. Side cutting in both sides of Ayeyarwady River is caused by river bank scouring and rain water resulting into steep slopes. In the rainy season, low lands adjacent to the Ayeyarwady River and the main streams in the area are affected by flood. Bagan – Nyaung Oo area is situated on the bank of Ayeyarwady River. So water-based transformation and rich agricultural soils create an environment that is suitable for rapid economic growth and urbanization along river basin area. The level of human influence throughout this rapid urbanization and excessive groundwater extraction requires detailed examination in order to prevent man-made disasters and irreparable damage being caused to the environment. Subsidence is a key contributing factor to flood risk and extreme weather events and soit needs to be better evaluated, especially in

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area with large exposed populations. Human-induced land subsidence is mainly caused by excessive groundwater extraction as a result of rapid urbanization or extraction of other resources. The results of land subsidence are an increased vulnerability to flooding, infrastructural failures, aquifer salinization and permanent geological deformation.

Keywords–*Subsidence, Inhabitants, ecosystems, anthropogenic causes, groundwater extraction, irreparable damage, flood risk, infrastructural failures, and aquifer salinization*

Introduction

Inhabitants and ecosystems in delta, low elevated coastal area and river basin areas are becoming increasingly vulnerable to the effects of subsidence, triggered both by natural causes and anthropogenic causes. Ground surface in delta regions, low elevated coastal area, and river basin areas are susceptible to subsidence as a result of both natural and human-reduced causes. Bagan-Nyaung Oo area is the most picturesque architectural complex in Myanmar and is a global pilgrimage center. The area contains ancient Buddhist shrines that have been restored and repaired to retain the original architecture. The study area has a large urban extent and is expanding rapidly and resulting this geo-hazard. Human-induced land subsidence is mainly caused by excessive groundwater extraction as a result of rapid urbanization. In Bagan-Nyaung Oo area, the problem that can rise as a result of land subsidence which are an interested vulnerability to flooding and storm surges, infrastructural failures, aquifer salinization and permanent geological deformation. Subsidence in the study area is a key contributing factor to flood risk from sea-level rise and extreme weather events and so it is needed to evaluate the hazard of subsidence.

Location

Bagan-Nyaung Oo area is situated between 94° 45’ 00”E to 95° 00’ 00” E and 21° 00’ 00” N to 21° 15’ 00” N. It is located on both sides of the Ayeyarwaddy River and approximately 145 km southwest of Mandalay and 187 km from Yangon. Bagan stands on the east bank of the Ayeyarwaddy (Figure 1).

Bagan-Nyaung Oo area is the most important architectural complex in Myanmar-Bagan, in which the Buddhist religion took deep root, strengthening and broadening the outlook of the whole society. The World Heritage Site of Bagan is the Golden Land of wonders. Over 3,000 extant monuments are scattered across a vast arid plain that proclaim the piety and power of Myanmar's first empire. As a manifestation of a dynamic and original form of architecture, Bagan stands the other great Buddhist center of South-East Asia, such as Angkor in Cambodia or Borobudur in Java.

Bagan is a pilgrimage center and contains ancient Buddhist shrines that have been restored, redecorated and are in current use. The study area is dominated by the ancient temples and pagodas and the area also occupies both of urban and rural environments.

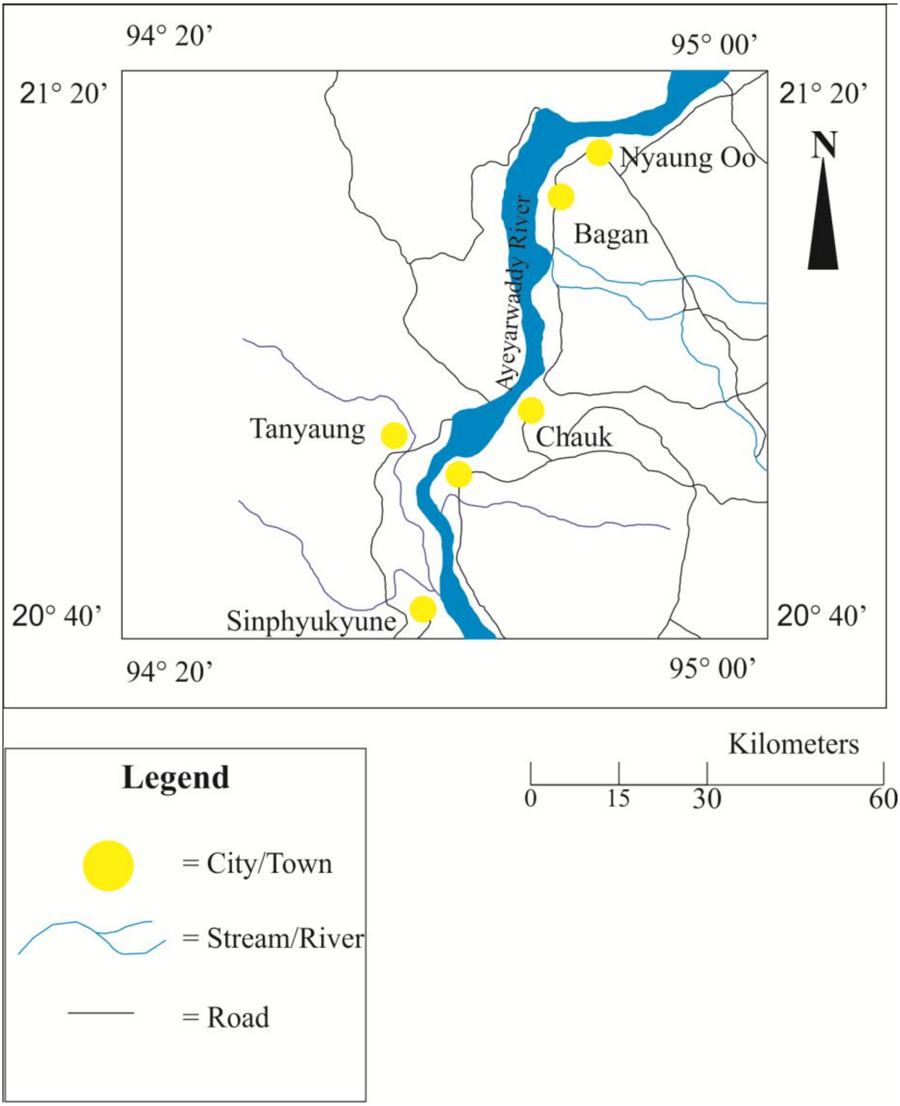

Figure 1: Location Map of the Research Area

Topography and Drainage

Generally, the study area is mainly within the low level plain situated beside the Ayeyarwaddy River (Figure 2).The attitude of the study area ranges from 5.2 m to 408m above sea level. Bagan-Nyaung Oo area lies on either side of Ayeyarwaddy River, as a vast plain on the eastern bank. There are mountain ranges namely, Taywin Taung in the southeast and Tantkyee Taung in the west (Figure 3).

The drainage pattern in the study area is dominant by dendritic drainage pattern (Figure 4). Most of the drainage are very poorly dense that means the dry streams in the dry season. Ayeyarwaddy River is the main drainage channel of the research area and it is running into the nearly N-S direction. Ayeyarwaddy River morphology is controlled by underlying structures and active tectonism.

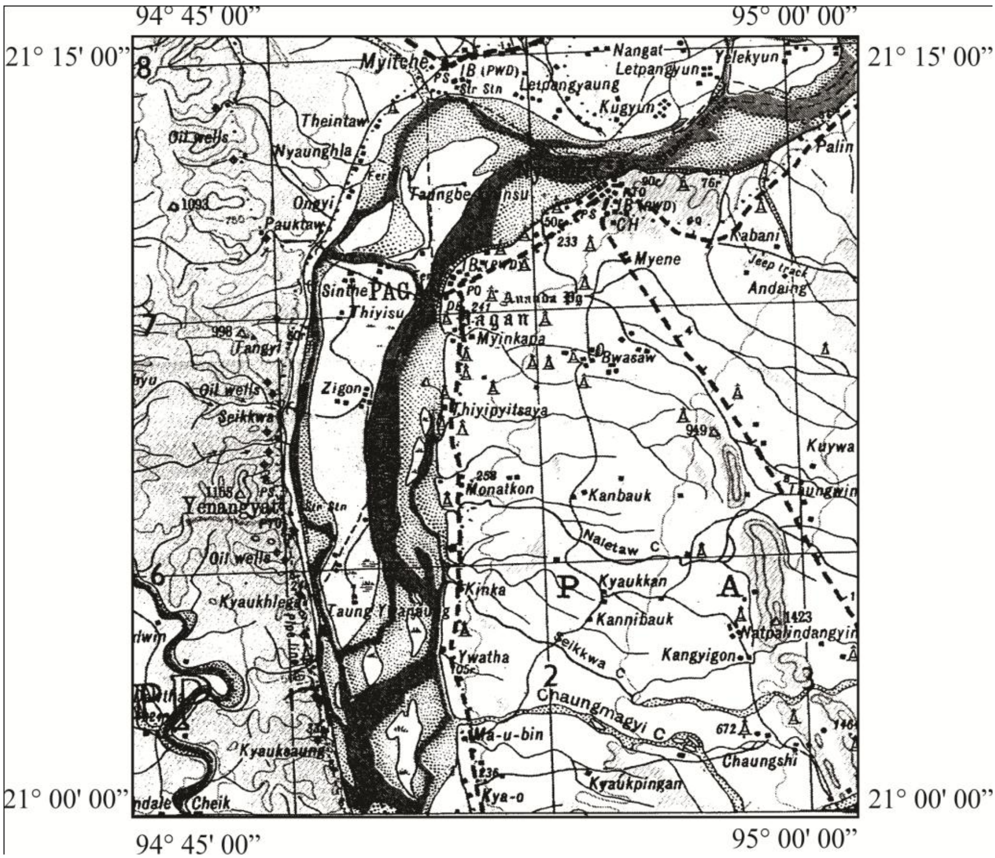

Figure 2: Topographic Map of the Research Area

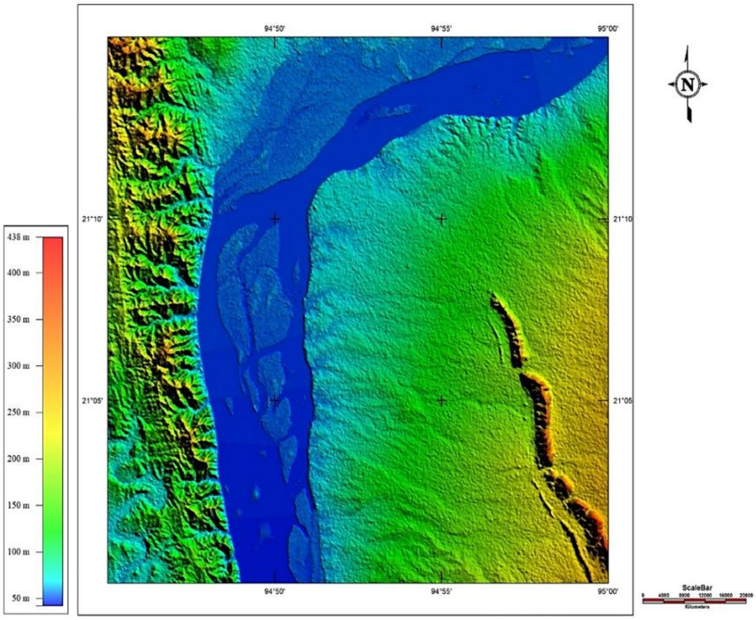

Figure 3: Physiographic Map of the Research Area

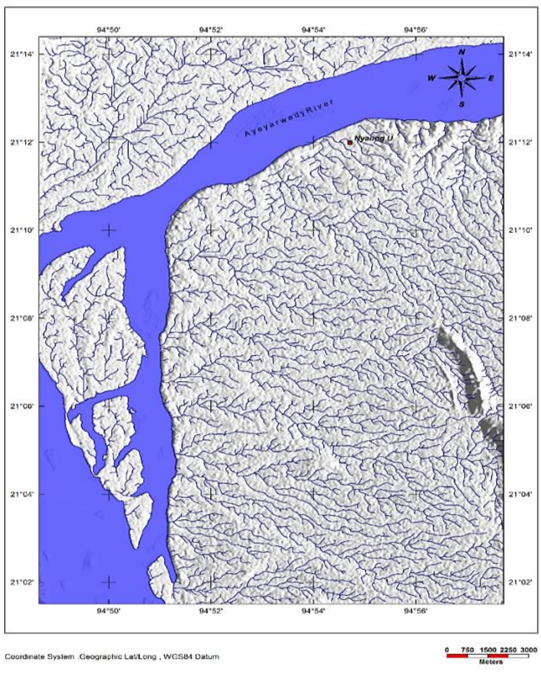

Figure 4: Drainage Map of the Research Area

Climate

The climate of the research area is tropical but the seasons can vary drastically. In summer (from March to May), the temperature rises to 43°C during the day and falls to 24°C in the night, with no rainfall. In the winter (from November to February), the temperature is about 30°C in the day and night temperature is about 30°C. Monsoon starts in June and ends in October (Figure 5).

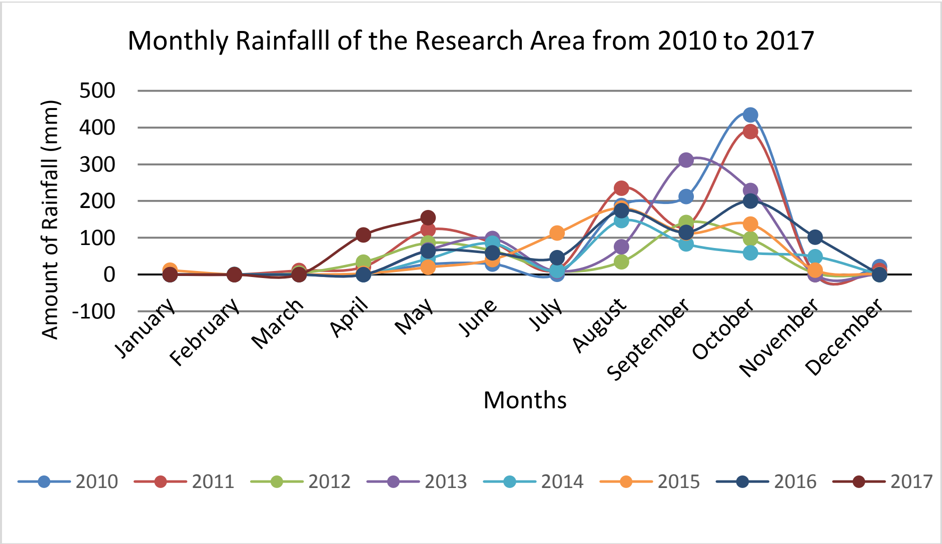

Figure 5: Monthly Rainfall of the Research Area from 2010 to 2017

Methods and Materials

The study aims to demonstrate the application of remotely sensed digital image processing and visual interpretation for engineering geology approach to environmental studies in a specific area. To carry out the ground survey for land interpretation is necessary to check and link the information received from satellite images. The methodology of the study can be divided into interpretation of image, spatial analysis and field survey. Materials used in the study are maps, information, software facilities and other.

(1) Satellite Images

The following satellite images were collected:

Landsat 7/ TM year of acquisition. (2010, 2015)/ path and row 133/045/7 bands/ CCT, BSQ, 8 bits.

Landsat 8 OLI/TIRS Level 1 Data Product, Date: 2/5/2018, row/path = 134/45, mainly OLI bands.

(2) Spatial Data

Topographic map, the scale of one-inch map sheet no. 84K/16 is used as base map for geographic database of the research area. UTM (quarter-inch) and topographic map (quarter-inch) scale are used to identify the significant topographic criteria.

(3) Non-Spatial Data

Statistics data (monthly rainfall, monthly mean water level, and earthquake data from Department of Meteorology and Hydrology (DMH).

(4) Software

Microsoft Excel 2013 for plotting the graph

Global Mapper v.15.2

ArcGIS 10.1

CorelDRAW X8

ENVI 4.2.

MapInfo 2011

(5) Technical Methods

Basically, technical methodology consists of three parts, the first one is visual analysis, the second is digital image analysis and the third is integration of field data and remote sensing analysis.

Satellite Image Analysis

Satellite data of Landsat 7 Thematic Mapper TM were selected from the research. These data are recorded on seven bands with Landsat 7 satellite, the study area fells within path/row 133/045 with 30 meters ground resolution (Figure 6). Visual image interpretation and digital image processing were applied for classifying images in a base of land cover/land use and to enhance image quality. In this research, ground control points were selected by following permanent features evenly distributed throughout the area and identified easily both in image and topographic maps. The Universal Transverse Mercator (UTM) projection method is employed in the research. The scale of Topographic maps used this research area was quarter-inch.

Image enhancement and band combination in the manipulation of image density can see more easily certain features of the image. In this research, the false colour composite (R: G: B=4:5:3) was made for land use/land cover interpretation. TM images were analyzed to identify the major structural patterns and lithology, and LULC by using ENVI 4.2.

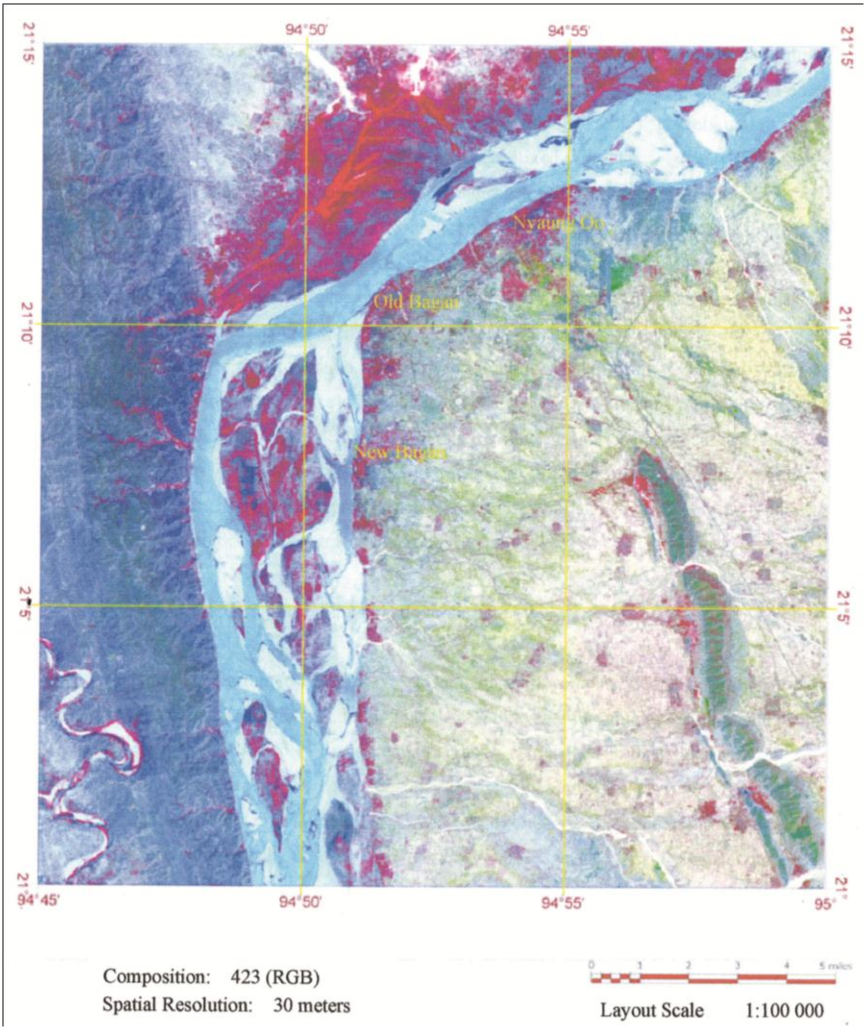

Figure 6: Satellite Image of the Research Area (Image Rectification)

Geological and Geomorphologic Setting

Bagan-Nyaung Oo plain is part of a system of sedimentary basin developed during Miocene-Pleistocene in the Central Myanmar Basin. The basin is filled by a thick succession of Miocene-Pliocene marine sediments (mainly clay and silty clay) and Pleistocene fluvial sediments (mainly gritty sandstone, coarse sandstone and gravel bed) (Figure 7).

The study area covers mostly alluvial plain, the debris and small fan materials derived from Tuywin Taung and Tankyee Taung hills which are composed of rocks of Miocene to Oligocene.

In the research area, the exposed rocks units are Irrawaddy Formation (Late Miocene to Pliocene), Okhmintaung Formation (Late Oligocene), Padaung Formation and Shwezettaw Formation (Early Oligocene). The Shwezettaw Formation is well-exposed at the Tuywin Taung Range. The Pyawbwe Formation well-exposed at the Tankyee Taung Range.

The vast plain in the area consists of flood sediments derived by the Irrawaddy River. The alluvial soils (Quaternary-Recent) are deposited on the plain and along the Irrawaddy river bands. There are five types of soils such as: (1) active alluvial fan, (2) river bed deposits, (3) gravel deposits, (4) colluvial soil and (5) residual soil.

Active alluvial fan is derived from landslides and brought down by tributaries to the main stream. River bed deposit occurs along the riversides and on the flood plain itself. Gravel deposit is locally developed on the both sides of the rivers and streams. Gravel deposit consists of sub-angular to pebbly and gravelly rounded quartzite, gneiss and phyllite with fine sand, silt and clay matrix. Colluvial soil occurred at the base of slopes and consists of clay, silt and sand with angular gravel to cobble size fragments of shale, phyllite and quartzite/ meta-sandstone). These colluvial deposits are derived from old landslides. Residual soil is developed in place on flat to gentle hill slopes. Residual soil mainly consists of clay, silt, and gravel size rock fragments.

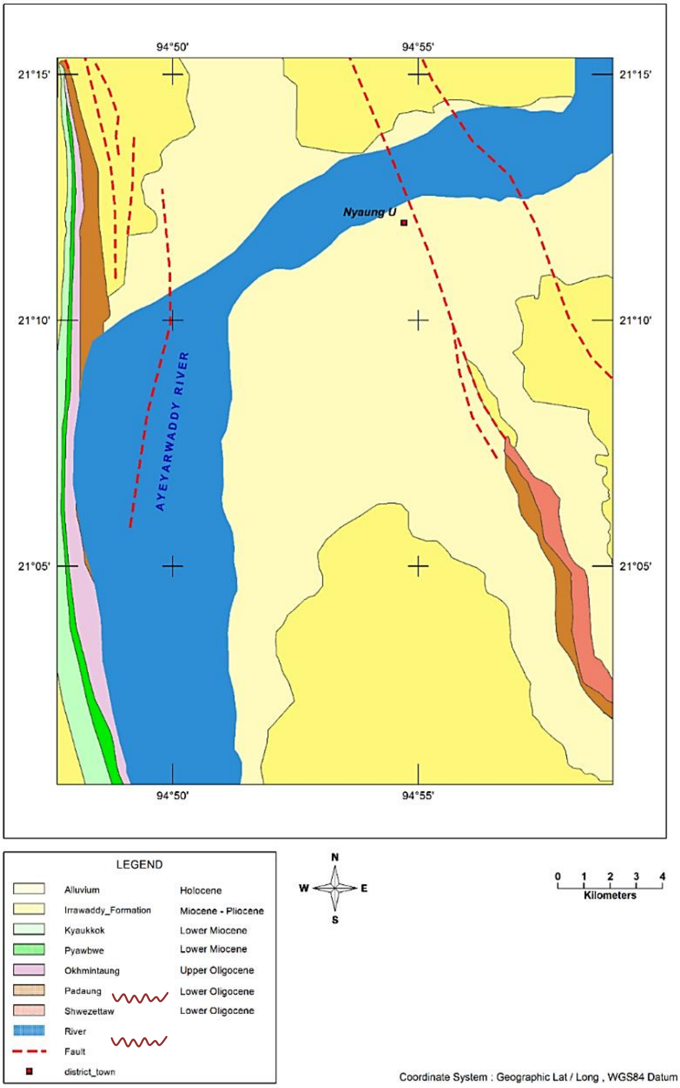

Figure 7: Geological Map of the Research Area (Tun Naing Zaw, Min Thura Mon and Swun Wunna Htet, 2017)

Groundwater Extraction and Subsidence

Despite the presence of urban and industrial areas, the plain is characterized by the presence of a diverse range of industries, with large sectors characterized primarily by agriculture. Indeed, the Bagan-Nyaung Oo plain is one of the largest agricultural basins in Bagan-Nyaung Oo area, due to the extensive use of intensive cultivation practices.

Each one of the hundreds of small farms and estates is self-sufficient in term of water supply, and despite the public water supply network, several independent and usually uncontrolled water wells have been drilled.

Groundwater has been considered a secure and unlimited resource and has been withdrawn for the main economic activities, particularly providing water supply for industrial, agricultural, household and hotels purposes. Water demand has continuously increased, due to both the development of several new economic activities and the sight rise of the population of the plain, particularly in the main hotel zones, and in the main industrialized centers. Increased groundwater pumping, without sufficient surface recharge, has forced the groundwater in the basin to drip with related acceleration of sediment compaction.

The gradual lowering of the water table has led to a reduction of pore water pressures in the saturated soil. Water withdrawal, without replacement of water by air, causes increased consolidation. The ultimate effect is the non-reversible lowering of the land surface. Thus, total volume of unconsolidated fine-grained deposits and weekly cemented sediments of the exploited aquifer is reduced, with a consequent reduction of aquifer storage capacity.

Land subsidence is more and more often related to land and water use practices. The natural compaction of unconsolidated and normal-consolidated fine-grained deposits is exacerbated by human activities, such as excessive ground water pumping from aquifer with related water table decline, rapid and progressive urbanization, and huge load imposition.

With many urbanized and industrialized areas in Bagan-Nyaung Oo and its conurbation have been developed over fine-grained deposits; alluvial materials deposited in tectonically subsiding basin represents the most productive type of aquifers.

Subsidence can have a strong impact on landscape in terms of both loss of land elevation and changes of topographic gradient where land drop is not uniformly distributed.

Flood and Subsidences

Side cutting in both sides of Ayeyarwaddy River is caused by riverbank scouring and rain water resulting into steep slopes. Slope failures causing landslides are common along eastern bank of the river in central portion of the area. There is a number of river bank failures within 5 to 10 meters.

A buffer zone of 30m is desirable not to have any settlements and construction works to allow natural stabilization.

River bank cutting between Nyaung Oo and New Bagan is another threat to cutting failure that needs to be taken care of soil failure. Low land area gets flooded and covered with sediment deposited during the rainy season by flood.

In the rainy season, lowlands adjacent to the river and the river and the main streams in the area are likely to be affected by flood as they are prone to flood hazards. Hence, these areas are not suitable for human settlements but can be utilized for agricultural field. A risk of flash flood can always be a threat in these areas in future in the rainy season.

Ayeyarwaddy River is general bed load channel type. River flowing between the banks on the beds composed of sediments is transported by the river are sensitive to changes of sediments load, water discharge and variation of valley floor slope. In the research area, western bank of Ayeyarwaddy River, three steps of river terraces are observed in bagan-Nyaung Oo area (Chhibber, 1934) and alluvial terraces and colluvial deposits are widely distributed in the research area.

In 2010, the rate of western river bank erosion and deposition are obviously increased, therefore the west bank of Ayeyarwaddy River is more vulnerable to river bank erosion and flooding (Figure 8a and 8b). The same phenomenon happened in 2015 (Figure 9a and 9b).

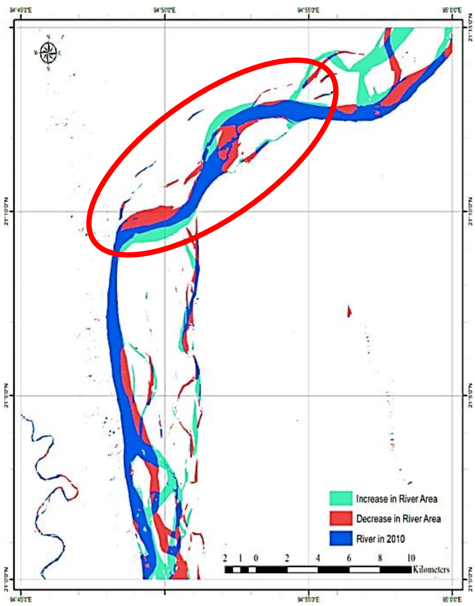

Figure (8a)

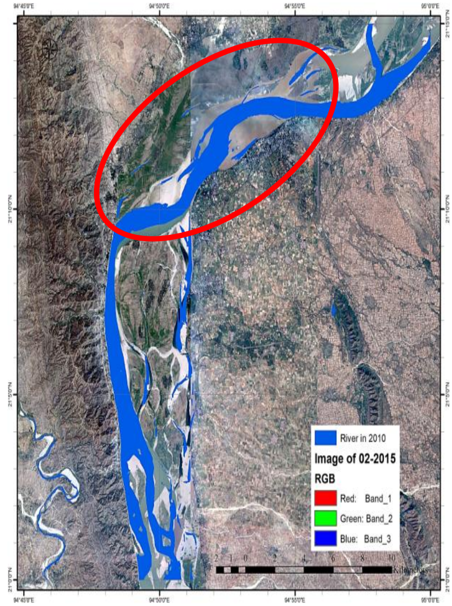

Figure (8b)

Figure 8 (a and b): 2010 Ayeyarwaddy River Line with Increase and Decrease in Water Body

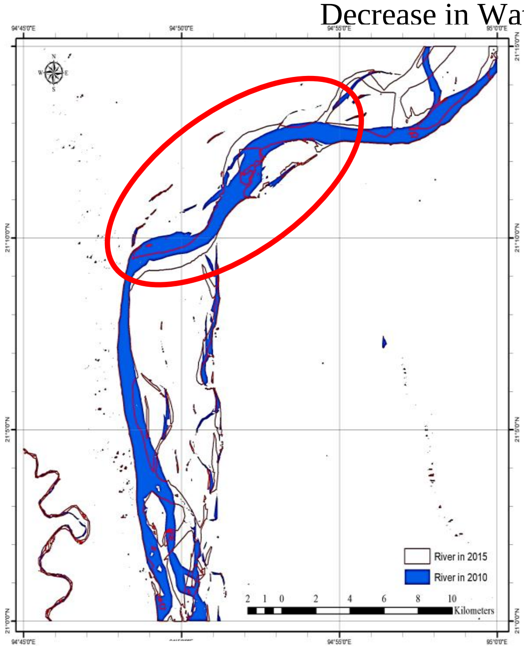

Figure (9a)

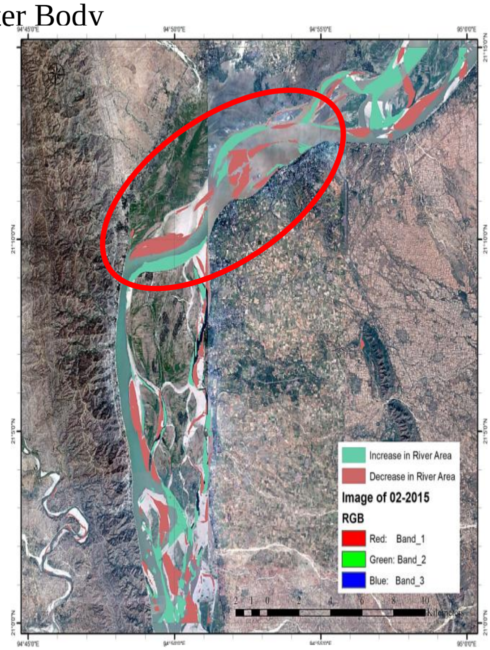

Figure (9b)

Figure 9 (a and b): 2015 Ayeyarwaddy River Line with Increase and Decrease in Water Body

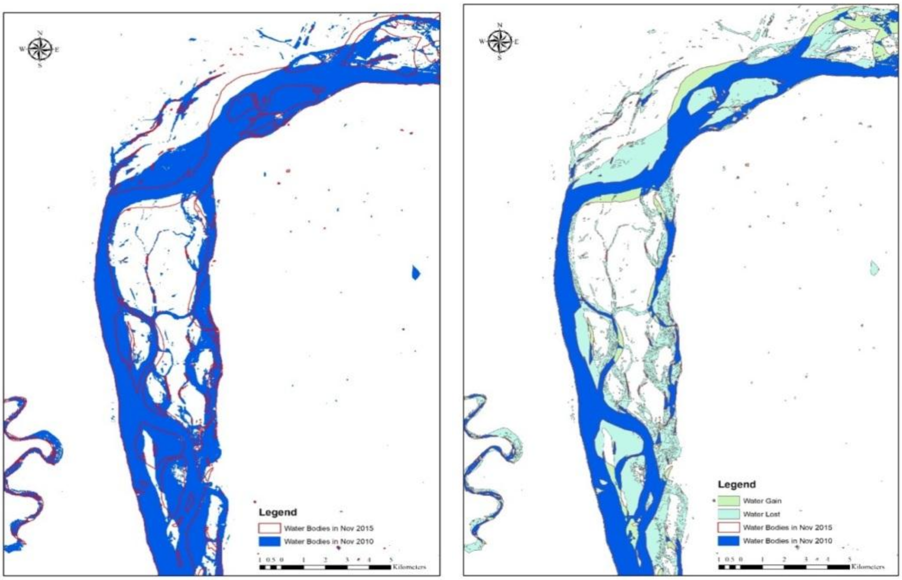

Figure 10: Comparison of Water Bodies and Water Gain/Lost in 2010 and 2015 (Drawing Based on Satellite Images)

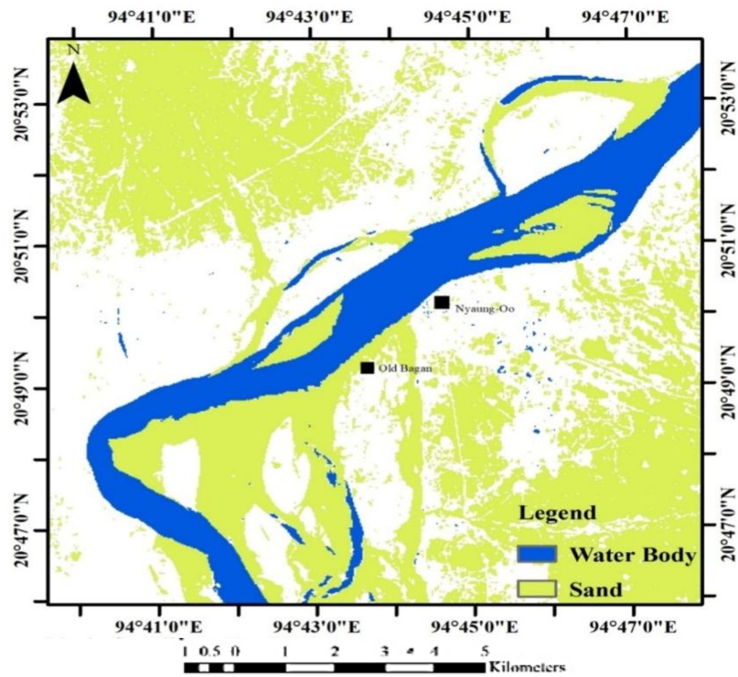

Figure 11: Delineated body of river water and sand of the research area (from Landsat 8 image) (Map by Tun Naing Zaw, Swun Wunna Htet and Min Thura Mon, 2018)

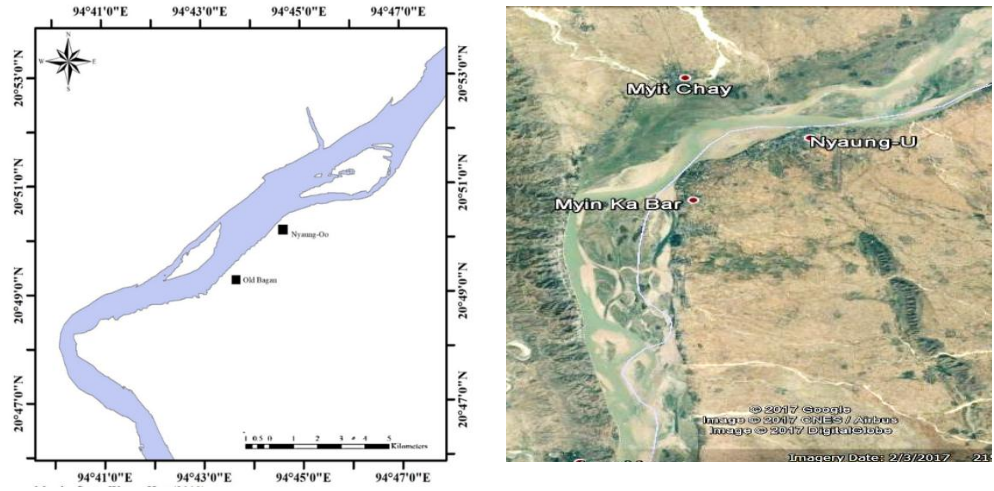

Figure (12) Comparison of water body of Ayeyarwaddy River in 2017 (right) and 2018 (left)

Differential Erosion and Relief of River Banks along the Ayeyarwaddy River

Rate of the Ayeyarwaddy River in the base level for adjacent hill slope of river banks because of flooding which can cause creep and wash landslides near the river banks. River erosion and deposition contribute to arise the base level of Ayeyarwaddy River.

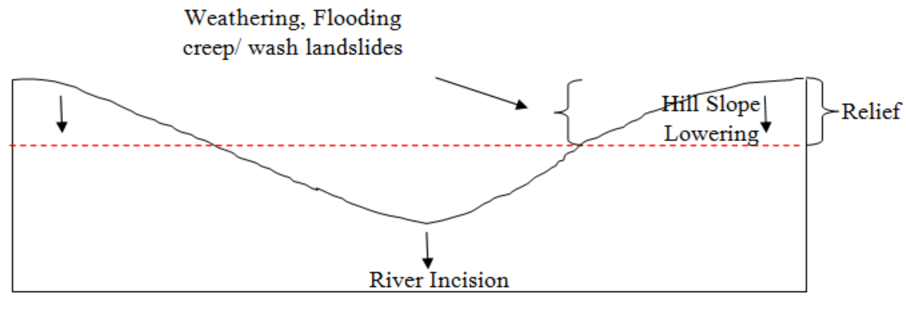

Figure 13: Sediment Fluxes in Ayeyarwaddy River

The sediment load of Ayeyarwaddy River can be partitioned into the bed load, suspended load and dissolved load. Whereas the highest bed load fluxes typically occur during high water discharge, the highest solute concentration typically occur during low flows. Suspended-load fluxes typically occur during flood. Input of sediment from adjacent river banks can vary in predictable ways in different climatic regimes. River bank landslides and subsidence occur under water saturated condition of riversides.

River landslides and subsidences drive the sediment flux, sediment discharges tend to be spiky and can be weakly tied to water discharge. If most sediment input to river is landslide-generated, the stochastic nature of landslide can cause a mismatch between water and sediment discharges.

In Bagan- Nyaung Oo area, migrating sinuous river bends are visible. The bends are extending and translating downstream. This process is taking place at a stable and predictable rate, but is highly dependent on both up- and downstream conditions.

Within the last 15 years the river transformed from a straight channel to a sinuous channel. Only the middle bend of the river is currently capable of lateral migration. In the south the river is confined by resistant river banks. The incoming channel has changed its angle and has bifurcated into two channels from different directions. The discharge ratio of the two incoming channels determines the dominant flow direction and planform in the rest of this section, and with that determines the degree of sinuosity and related erosion of less resistant floodplains. The river will behave like a classic sinuous river when the incoming flow from the eastern direction is strongest, and behave like a straight channel when the incoming angle from the north-east is dominant. The physical boundaries of the river are evidently the resistant riverbanks, making the effects of the boundaries on free migration easy to predict.

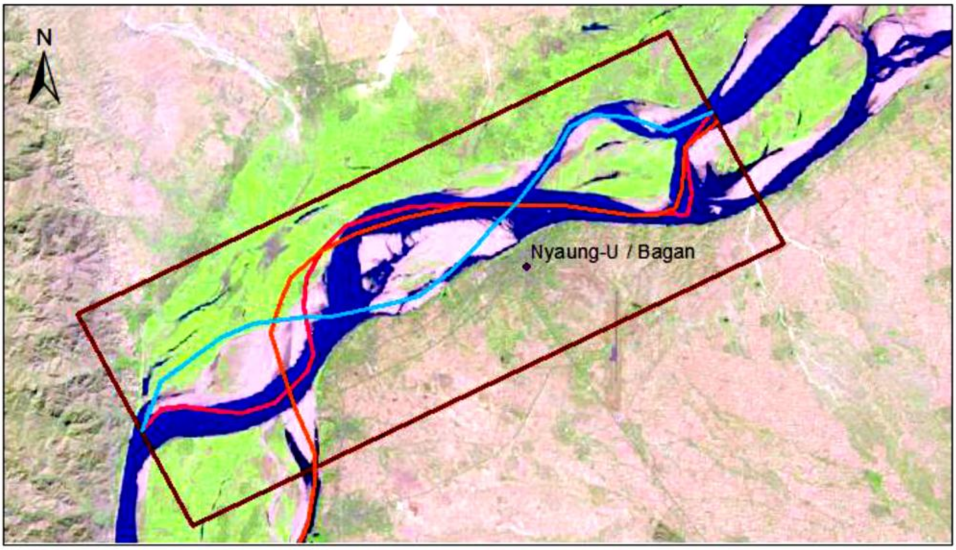

Figure 14: Ayeyarwaddy River's recent sinuosity between Bagan-Nyaung Oo and Mandalay Blue line represent 2015 river line. Red line represent 2018 river line.

For instance, in July 24th, 2017, at 3:40 pm, flood waters swallow Thiri Yadana Pyilone Chantha Pagoda sinking into the raging waters of the Ayeyarwady River in Magway Region, with shocked bystanders looking on as its golden spire collapsed beneath the waves (Figure 15).

"This pagoda was built in 2009, when it was far away from the river," Year by year, the river has eroded the land and now the pagoda has fallen into the river."

Flooding was common in the area during the monsoon that runs from May to October, but this year's floods caused alarming erosion. Some riverside villages have been washed away entirely.

Continuous periods of flooding are likely to 'wash away' the soil and contribute to landslip which can either be a gradual creeping of soil in a downward direction over a period of time, or a sudden movement, often associated with flash floods.

Figure 15: Subsidence due to Flash Flooding (Wash Landslide along the Ayeyarwaddy River Bank)

Engineering Properties of Soil and Flooding

In the research area, existing land use patterns are agricultural land, sparse forests and scrub, settlements, industrial, recreation centers, infrastructures and small land fill/ waste disposal sites. The research area has heterogeneous soil distribution character with different engineering properties.

Low to medium-bearing capacity (1.8 to 4 TS F) areas are concentrated in the area where active alluvial fan and river bed deposits have high permeability and low density.

Most plain area is a firm soil with a stable bearing capacity and so appropriate from small to medium scale construction purposes.

Gravel deposit in Nyaung-Oo area, being derived from landslide-induced active alluvial fans and river bed deposits by erosional forces, is locally developed on the both sides of the rivers and streams. It consists of sub-angular to pebbly and gravelly rounded quartzite, gneiss and phyllite with fine sand, silt and clay matrix.

Colluvial soil occurred at the base of slopes and consists of clay, silt and sand with angular gravel to cobble size fragments of shale, phyllite and quartzite/ meta-sandstone). These colluvial deposits are derived from old landslides.

In Bagan area, residual soil is developed in place on flat to gentle hill slopes. It mainly consists of clay, silt, and gravel size rock fragments. Mostly, the residual soil in New Bagan is derived from Irrawaddy Formation.

Four boreholes data measured by JICA Project and Ministry of Construction are used in engineering analysis for calculation of bearing capacities of each boreholes and test pits (Figure 16, 17 and 18).

We would like to conclude that the bearing capacity of gravel bed in Nyaung-Oo is sufficient for shallow foundation; however, without the compaction of gravel soil under the footing of the specific foundation, it is likely that the differential settlement will occur causing the foundation unstable due to the poorly sorted gravels. For Bagan area, since the residual soil comes from Irrawaddy Formation which has a bearing capacity of 2.9 – 4 TSF at the depth of 2m according to geotechnical analysis, shallow foundation with square footing for two to three-storey houses and hotels are suitable for construction. In spite of the availability, the Ministry of Construction restricts only to build structures of 30ft high with two levels.

Depth	Bearing Capacity
2.1 Ft	1.7 TSf
3.2 Ft	2.5 TSf
4.3 Ft	2.3 TSf
5.3 Ft	2.4 TSf
6.5 Ft	2.7 TSf
7.5 Ft	2.8 TSf
8.6 Ft	2.9 TSf

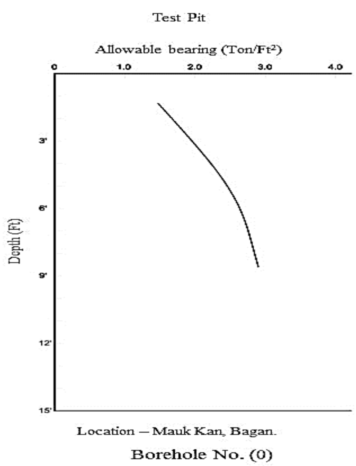

Figure 16: Test Pit Result of Borehole No.(0), Mauk Kan, Bagan

Depth	Bearing Capacity
2.1 Ft	2.9 TSf
3.2 Ft	3.3 TSf
4.3 Ft	3.7 TSf
5.4 Ft	3.8 TSf
6.5 Ft	4 TSf

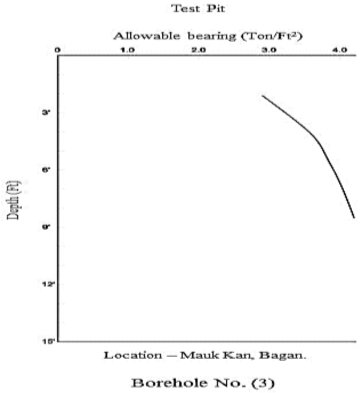

Figure 17: Test Pit Result of Borehole No. (3), Mauk Kan, Bagan

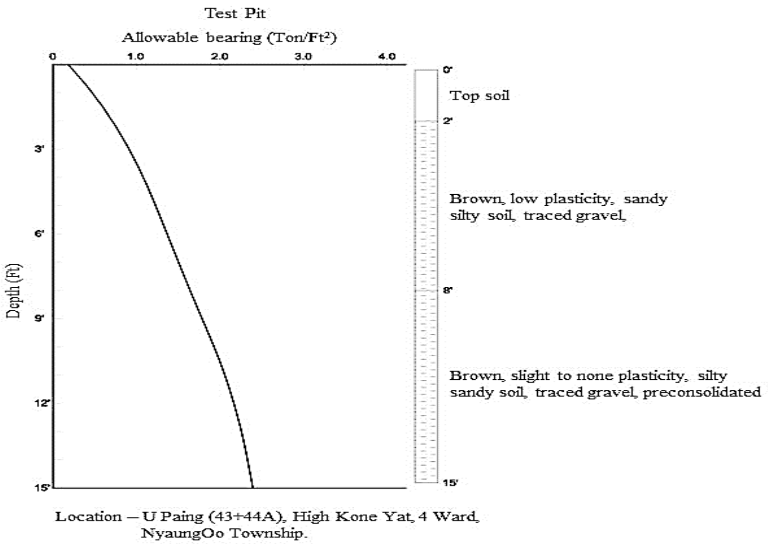

Figure 18: Test Pit Result of Nyaung Oo Township

Figure 19: Subsidence in Temple No. 1752 at Bagan Area

The temple No. 1752, believed to have built in 13th century, buckles after weeks of heavy rain. Only 20% of the original structure remains due to rainwater –induced subisidences. The temple was previously damaged by an earthquake in 1975, renovated to the tune of 2.5 million kyats, and now suffered from structural degradation by unusual rainfall in Bagan area. (Occurred at 12th August 2015)

Pagodas in Bagan area are affected by subsidence which can be caused by the movement of the ground with changing weather conditions Figure (19). The time of year (the height of summer) when warmer temperatures and drying ground often occur leads to subsidence.

The amount by which the ground can shrink and/or swell is determined by the water content in the near-surface. Fine-grained clay-rich soils can absorb large quantities of water after rainfall, becoming sticky and heavy. Conversely, they can also become very hard when dry, resulting in shrinking and cracking of the ground. This hardening and softening is known as ‘shrink-swell’ behaviour.

Shrink–swell occurs as a result of changes in the moisture content of clay-rich soils. This is reflected in a change in volume of the ground through shrinking or swelling. Swelling pressure can cause heaving, or lifting, of structures whilst shrinkage can cause differential settlement. This shrink–swell behaviour is the most damaging geohazard.

The rock formation (Irrawaddy Formation) the most susceptible to shrink-swell behaviour are found mainly in Bagan –Nyaung Oo area. Other superficial deposits such as alluvium, peat and laminated clays can also be susceptible to soil subsidence and heave.

Subsidence has the potential to cause engineering problems such as damage to foundations, buildings and infrastructures. Properties built on clay soils or with shallow foundations are more at risk of subsidence. This is because clay-based soils shrink and swell according to their moisture content. If previously dry clay is overloaded with too much moisture, it expands causing ground heave. This is the upward movement of the ground beneath part or all of a building. Leaking or damaged drains are a key contributor; they are usually unseen, will build up moisture levels over times and repeatedly soften and swell the soil

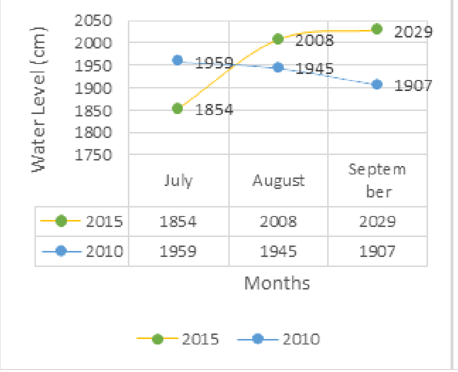

Figure 20: Monthly Mean Water Level of Research Area in 2010 and 2015

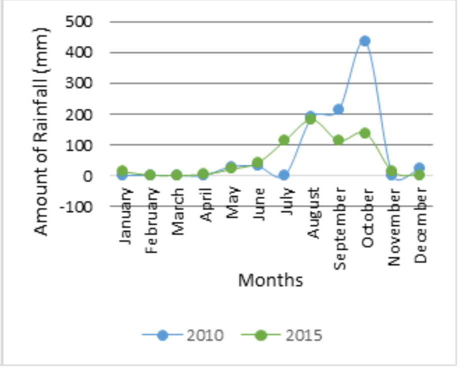

Figure: 21: Monthly Rainfall of Research Area in 2010 and 2015

Land Use

In the research area, existing land use patterns are agricultural land, sparse forests and scrub, settlements, industrial, recreation centers, infrastructures and small land fill/ waste disposal sites.

(1) Agricultural and Scrub Lands

Most of the flat, lowlands in the plain along the river bank and hilly sides are covered by sparse forests and scrubs. Open forests, swamp forest, orchard, palm trees, scrub, bush and grass are categorized in the research area. Low angle sloping lands (hill sides) are good for dry cultivation (maize, millet, wheat and cereals).

(2) Urban Settlement and Industrial Areas

Urban settlements are existing area, planned area, proposed area, and expanded area. Proper drainage system in Nyaung Oo and Bagan is adequate in now. Crucial area of man-made pollution is located in the east of Nyaung Oo.In the banks of the Ayeyarwaddy River, squatters' settlements are creating.

(3) Recreation Centers and Open Spaces

Lawkananda reserve forest near new Bagan is the only existing public and natural park in the area. The research area has religious and cultural values where most of deities are located form north to south. Bagan golf field and Recreation Park is located west of Nyaung Oo beside of the main highway road.

(4) Landfill and Waste Disposal Sites

Nyaung Oo municipality is lack sanitary landfill site to manage safe disposal of its solid wastes produced from the urban settlement and industries. Municipality is temporarily dumping its daily wastes into the river bank.

Engineering Approach to Land Use for Construction

The research area has heterogeneous soil distribution character with different engineering properties.

Low to medium-bearing capacity (1.8 to 4 TS F) areas are concentrated in the area where active alluvial fan and river bed deposits have high permeability and loose density.

Most plain area is a firm soil with a stable bearing capacity and so appropriate form small to medium scale construction purposes.

Gravel deposit in Nyaung-Oo area, being derived from landslide-induced active alluvial fans and river bed deposits by erosional forces, is locally developed on the both sides of the rivers and streams. It consists of sub-angular to pebbly and gravelly rounded quartzite, gneiss and phyllite with fine sand, silt and clay matrix.

Colluvial soil occurred at the base of slopes and consists of clay, silt and sand with angular gravel to cobble size fragments of shale, phyllite and quartzite/ meta-sandstone). These colluvial deposits are derived from old landslides.

In Bagan area, residual soil is developed in place on flat to gentle hill slopes. It mainly consists of clay, silt, and gravel size rock fragments. Mostly, the residual soil in New Bagan is derived from Irrawaddy Formation.

Four boreholes data measured by JICA Project and Ministry of Construction are used in engineering analysis for calculation of bearing capacities of each boreholes and test pits.

We would like to conclude that the bearing capacity of gravel bed in Nyaung-Oo is sufficient for shallow foundation, however, without the compaction of gravel soil under the footing of the specific foundation, it is likely that the differential settlement will occur causing the foundation unstable due to the poorly sorted gravels.

Figure 22: Land Use Map of the Research Area

For Bagan area, since the residual soil comes from Irrawaddy Formation which has a bearing capacity of 2.9 – 4 TSF at the depth of 2m according to geotechnical analysis, shallow foundation with square footing for two to three-storey houses and hotels are suitable for construction. In spite of the availability, the Ministry of Construction restricts only to build structures of 30ft high with twolevels.

Conclusion

1. The study showed that remote sensing techniques are useful tools for assessing and analyzing the geological purposes.. The study focuses on understanding of the river's dynamic morphological behavior within the project area. Water levels between the cold season and the hot season (monsoon period) vary up to 10 meters.
2. Bagan stands on the east bank of the Ayeyarwaddy River whichforms an important navigational artery for trading and recreational use. The river is very dynamic in its platform changes, which are largely dependent on the discharge regime. This variation in water levels and the dynamic morphology of the river create navigational problems.
3. Landslides are found inriver flanks between Bagan and Nyaung Oo.
4. Floods are the most common and the most destructive geologic hazard. We need to control by non-structural approach through sound flood plain management and engineering efforts such as artificial levees, flood-control dam and channelization. Heavy rains cause major problems in flood and subsidence.
5. Heavy rains in Bagan-Nyaung Oo area lead to the collapse and sinking of pagodas in 2014. Subsidence is a lowering or collapse of the ground. It can be triggered by man-made disturbance, a change in drainage patterns, heavy rain or by water abstraction
6. TM images are analyzed to identify the major structural patterns and lithology and LULC.
7. Squatters' settlements of the banks of the Ayeyarwaddy River are creating an alarming threat of encroachment of the river bank and flood plain.

8. Effects of disasters will be different, past and present depending on density of population and sophisticated structures.
9. We suggest that more accelerated research on river bank protection and assessment. Thus, remedial measures, including pruning or removing trees, investigating and repairing damaged/ leaking drains, restoring brickwork and underpinning (strengthening and deepening the foundations) are required.
10. We suggest that more preparedness for mitigation of natural hazards in all-time necessary.

Recommendations

1. **Restriction of groundwater extraction**

   This measure is very important for counteracting human-induced subsidence. In vulnerable areas extraction of groundwater should be reduced or completely phased out.

2. **Natural and artificial recharge of aquifers**

   When addressed consistently and effectively, the reduction of groundwater mining can eliminate one of the primary causes of land subsidence.

3. **Development of alternative water supply (instead of groundwater)**

   To meet the increasing (urban) water demand, an alternative water supply for industry and domestic users is required.

4. **Integrated (urban) flood water management Improved groundwater management and subsidence**

   Water resources management should be linked to flood mitigation. Ultimately, land subsidence is closely linked to integrated land and water management, including surface as well as subsurface resources and constraints.

5. **Improving governance and decision-making**

   This involves (public) awareness, encouraging (public) participation, cooperation and coordination between stakeholders at different scales and levels,

6. **Decision support models and tools**

   To support good decision-making, models and tools are needed.

   It is especially important to analyse the relationship between groundwater levels and subsidence, develop modeling and forecasting capabilities by implementing an integrated groundwater–subsidence monitoring and analytical model. Moreover, it is essential that local agencies have the expertise and tools to conduct studies, and that they are engaged in ongoing capacity building, training, and knowledge exchange.

7. **Appropriate monitoring and database system**

   Ongoing studies show that the weak spot in efforts to reduce subsidence and related flood risks is accessed to reliable ground truth data.

8. **Integration of geotechnical aspects in planning and design of buildings and infrastructure.**

   In the planning and design of (heavy) buildings and road infrastructure, geotechnical research and modelling of the subsoil should be taken into account in order to avoid subsidence problems including differential settlements, in the short or long term.

9. **Asset management, financing and public-private-partnerships (PPP)**

   To minimize damage caused by subsidence, the main financial risks associated with investments and maintenance of assets (buildings, infrastructure) should be assessed.

10. **Exchange of knowledge and best practices**

    Through international conferences, workshops, expert meetings, and courses, knowledge and best practices can be exchanged to extend the common knowledge base efficiently and effectively. This step can be further supported by development of collaborative research projects preferably in the framework of international (research) networks and initiatives such as the UNESCO, and the Delta Alliance.

Acknowledgements

The authors are deeply grateful to Professor and Head, Dr. Day Wa Aung, Department of Geology, University of Yangon, for allowing us to do this research.

Heartfelt thanks are extended to Professor Dr. U Thein (Retired Rector), for his suggestion and advice given to us during the preparation and compilation of our research.

We would like to express our sincere thanks to U Win Maw, Retired Chief Executive Officer, MOGE, for his encouraged discussions, suggestions and permission.

With our deepest gratitude, we acknowledge U Than Htay, Deputy Director General (Retd.), DGSE, Ministry of Mines, for his kindness to immensely improve not only English but also the geologic sense of this paper.

We acknowledge JICA Projects in Nyaung-Oo Area and Administration Department with gratitude for their vital technical data support.

We also thanks the Department of Meteorology and Hydrology for their relevant data and information.

Finally, the authors would like to deeply thank U Than Htut Khine, (1984 Geology), Deputy Director, Directorate of Hotels and Tourism (Bagan Branch), for his generous hospitability and informations concerning land use/ land cover.

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