Developmental research of sustainable technologies to minimise problematic road embankment settlements

N Ratha\(^1,2\), T N H T Ismail\(^2,3\), D C Wijeyesekera\(^2\), I Bakar\(^2\), A J L M Siang\(^2\), M K Abu Talib\(^2\) & A Zainorabidin\(^2\)

\(^2\)Faculty of Civil & Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia
\(^3\)Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia.

E-mail: nurvin05@ymail.com

Abstract. Challenging, problematic and non-uniform ground conditions are a nightmare to geotechnical engineers tasked with the design and construction of buildings and transport infrastructure. These often suffer undesirable structural settlements. Designing within the current understanding of geotechnics; settlement in peat and organic soils need to be recognised to include the known “primary and secondary consolidation characteristics” and the lesser known “tertiary consolidation phase”. These eventually contribute cumulatively to the consequential uneven and hazardous “bumpy road” surfaces. Undulating flexible road pavements result primarily from the transference of the heavy self-weight of the embankment fill to yielding and non-uniform subgrade. The adoption of conventional design/repair methods such as pile, vertical drain, soil replacement and soil stabilisation are expensive and inappropriate in very soft ground conditions. These then lead to unjustifiably high and repetitive maintenance costs. There being no one quick fix solution for all; pragmatic research must necessarily identify the best/progressively improved practical and sustainable solution. A viable solution is to develop criteria and explore the concept of a “masonry arch bridge structure/lintel-column structure” and adopting sustainable materials through pragmatic searching for appropriate recyclable waste materials. This will lead to the basis for a sustainable, innovative, strong, stiff, permeable composite mat structure that can be used on soft and/or yielding ground conditions. Conceptual lightweight fill technology including the popularly used expanded polystyrene (EPS) and the innovative composite mats recently being developed by the research team are outlined.

1. Introduction

Current world news on natural geo environmental disasters of (somewhat predictable) hurricanes and (unpredictable in location and time) earthquakes attempt to question the credibility of engineering science when subjected to limiting conditions. On a similar note, but with a considerable time lapse, road users question their discomfort even in some newly constructed highways. On the basis of the extent of areal coverage and of all the engineering structures, highways/pavements leave the most
dominant imprint on the natural landscape. Accordingly, rigid/flexible pavements contribute to the urban environments as a vital socio-economic pathway to a better quality of life. The pace of all infrastructure development in Malaysia and in other countries have led to the limited availability of “suitable” sites or the demands of highway routing necessitate the adoption of challenging sites bearing problematic ground conditions. Rigid pavements are increasingly desirable in highway construction due to the lesser maintenance needed when compared to flexible pavements. Nevertheless material sciences have researched into sustainable waste materials to reduce the compressive strength of the concrete in the rigid pavements while being able to increase the tensile or flexural strength of the normal concrete mix. Such composite materials combinations are bottom ash and waste foundry sand, steel slag and waste glass, and third combination being bottom ash and fly ash.

Under the 11th Malaysian Plan (2016-2020) [1], the government plans to spend a whopping amount of RM1.4 billion to build and upgrade 700 km of rural roads nationwide. A sum of RM200 million is provided for the upgrading of roads in Federal Land Development Authority (FELDA) settlements. FELDA lands, primarily being an agricultural hub are located in areas of clay and peat soil (in other words, soft soil). The development plan accordingly cites that this is where construction and road upgrading works would be carried out extensively. Thus, this government plan gives directed impetus to the significance of exploring new and innovative concepts with a sustainable approach in developing long term solutions in tackling problematic soft soils.

Historically, appropriate technologies were adopted as far back as in 2500 BC in Babylon. Figure 1 illustrates the construction technology, where hewn tree trunks (logs) were laid on the yielding soft ground to form a permeable, stiff but disconnected mat structure.

![Figure 1. Road in Ur, circa 2500 BC (Adopted from [2])](image)

2. Extent of soft soil in Peninsular Malaysia (Possible construction sites)

Figure 2 is a map of Peninsular Malaysia showing the general distribution of Quaternary Deposits including peat and soft soils, and implying the extent of the areas over which construction of infrastructure on soft soil can occur. Hence the prime outcome of this research will benefit many Malaysians. Problematic grounds other than the Quaternary peat or soft soil deposits but resulting from inland geo environmental conditions are not shown. The figure highlights the current road networks, especially the North-South Highway which traverses the western part of Peninsular Malaysia and is
constructed extensively soft soil areas such as Alor Setar, Kedah, Georgetown, Penang and western regions is Johor. In an article of the Sunday Daily Mail, dated 18th June 2014, it mentions that Plus Malaysia Berhad (PLUS) spends some RM600 million or 20% of the company's annual toll collection for highway maintenance and upgrading works [3].

![Figure 2. General Distribution of Quaternary Deposits including Peat and Soft Soils in Peninsular Malaysia [4]](image)

All soil types are subjected to settlement due to compressive loads with consequent reduction of volume filled in the ground. The evaluation of settlement evolution should be carried out during the design process with the aim to limit the amount of residual settlement occurring at the end of construction [5]. The amount of total or differential settlement that a structure can undergo without resulting in unsightly building cracking, structural damage, or loss of intended use is dependent on the type of structure, structural system type, and planned use. The structural engineer provides the total and differential settlement tolerances for the structure. But these values should not be “zero,” because every structure that imparts a load on the ground must cause some settlement, even if it is very small [6].

2.1 Case studies of soft soil turning uneven and creating hazardous infrastructures

Research conducted by personnel from the Public Work Department (JKR) in Malaysia [7], shows statistics of geotechnical forensic investigation on problematic projects carried out as summarized in table 1 since 2010 to 2015. There are 182 cases out of 252 forensic highway distress cases (approximately 72%) are related to the issue of ground settlement, the remaining 28% are caused by other factors such as vibration, erosion, foundation failures and so forth.
Table 1. Geotechnical forensic cases carried out by JKR [7]

| Contributing Factors                          | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
|----------------------------------------------|------|------|------|------|------|------|-------|
| Vibration                                    | 2    | 1    | 3    | 6    |      |      |       |
| Soil erosion                                 | 3    | 2    | 4    | 9    |      |      |       |
| Foundation failures                          | 2    | 1    | 6    | 3    | 12   |      |       |
| Retaining structure failures                 | 1    | 4    | 2    | 7    |      |      |       |
| Slope stability                              | 6    | 3    | 12   | 4    | 25   |      |       |
| Ground settlement                            | 1    | 8    | 10   | 63   | 70   | 30   | 152   |
| Water infiltration                           | 4    | 4    | 1    | 9    |      |      |       |
| Collapsible soil                             | 1    | 1    | 2    |      |      |      |       |
| Total                                        | 1    | 10   | 10   | 85   | 95   | 42   | 252   |

2.1.1 Settlement of bridge embankment in Parit Yaani.

A local and current case closely monitored by the authors in Jalan Sengkuang, Sri Bengkal, Parit Yaani is a site where the approach fill embankment to a bridge, built by JKR in 2010 has often undergone pavement distress due to settlements under the embankment loading. Here the sub grade soil largely consist of marine clay. After the completion of the bridge’s construction and during its liability period, the edge/slant which is supported by the reinforced concrete bridge had undergone movement due to settlement in the horizontal direction and the resulting hazardous road surface deformations have had to be continuously repaired, every 7-8 months at a considerable road repair cost as shown in figure 3. To solve the settlement problem, JKR has repaired the embankments by adding fill materials on the settled area to make it even again, however this solution has not been effective as the replaced soil fill induces further settlement of the subgrade and the embankment becomes uneven again.

Figure 3. Chronology of pavement distress observed at Parit Yaani Bridge embankment (Oct 2015 – Jan 2016 – Oct 2016 – Jan 2017)

3. Innovative approaches in Highway Construction Materials

In civil engineering, the lightweight construction technology is adopted to describe particular methods for increasing economic and structural efficiency in reducing the weight of building structural constructions together with costs and construction lead time with the use of special construction materials. Highway ‘failure’ occurs due to settlement of subgrade affected by dead load, and not necessarily live load, which is momentary and has less effect on subgrade settlement, the awareness to
use lightweight fill technologies as a means to develop more sustainable highways is crucial, [8]. Suitable for soft organic soil or peat soils that tend to settle unevenly due to its geological history or in man-made situations such as back filled inactive mining sites. There is no limit on the thickness of the lightweight fill to be adopted but developments in sustainable material sciences have widened the choice of such materials. Table 2, [8] shows some recent researches of alternative lightweight fills and their properties. RAP shown in the table is an example of sustainability in the form of recycling being adopted to form a flexible pavement. This is still heavy (compared to soil) and does not fully arrest the bumpy settlements that are caused when dead and live loadings are imposed on soft subgrades of variable thickness. As a consequence the roads demand frequent expensive maintenance.

Geofoam blocks in the form of lightweight expanded polystyrene (EPS) blocks have been popularly adopted in highway construction as a pioneering stiff and discontinuous mat structure (conforming to the brickwork concept described later in section 4 – and in contrast to the stiff linear structures used with logs in the road in Ur [2]. EPS is a manufactured material, and is affected by buoyancy, rodent attack and poor fire rating. Waste tyres have been bundled together to form irregular but not light mats are being used in Canada to make access roads over marshy soft ground conditions. Sustainable, stiff and light mat structures are being developed at UTHM and more information on these will be published as laboratory and field data becomes available. Ismail [9] reports on the performance of such a product made of recycled plastic tubes.

Table 2. Recent Published Research on Alternative Lightweight Fill Material [8]

| Alternative Composite Material & Production Method | Functional use, Technical Properties & Approximate Costs |
|-----------------------------------------------------|----------------------------------------------------------|
| a) Foamed recycled glass — Low weight foamed recycled glass aggregates of up to 40 mm in size | Non-structural fills in embankments, Retaining wall backfill and pipe bedding; Gap graded material Max. Dry density = 2.84 kN/m³ LA Abrasion = 94% |
| b) Recycled Asphalt Pavement (RAP) – Fly ash (FA) Geopolymer A 30% FA mixture and a 50:50 ratio of NaOH and Na2SiO3 is used at a curing temperature of 40 C. | Stabilized pavement base course material; Compressive strength = 5.3 MPa Fly Ash 1 tonne – Price insignificant. Transportation cost and safety certificate required due to hazardous nature. |
| c) Cement treated sand and expanded polystyrene (EPS) beads EPS beads are heated with steam to expand 50 times its original size. Cement is included to bind the cohesionless sand and EPS beads. | Backfill material for use in highway embankments in soft soil areas Compression Strength = 800 KPa Unit Weight = 10 kN/m³ |
| d) Clays Modified with Recycled Crumb Rubber Kaolin clay and bentonite were used as soils for modification. From the weight of the soil, 2-4 % of rubber crumbs are used to give maximum strength. | Soil modification Max. dry density = 1296 kg/m³ Max. Strength = 482 kPa |
| e) Blast furnace slag The slag in liquid for is cooled and then transported to a crushing and screening plant where it is further processed into various products including aggregates. | As fill material for subgrade, sub-base or base. Particle Density = 2,550 — 2,650 kg/m³ LA abrasion = 37 — 43% OMC = 8 — 12% RM 50.10 /metric tonne |
| f) Geofoam Polymerization of styrene monomer is followed by impregnation of the polymerized polystyrene beads with a blowing agent. Styrene monomer and water is charged to the reaction kettle equipped with an agitator. | As fill material for highways and embankments on peat or soft soil. Min. apparent density = 15 kg/m³ Compressive stress = 60 – 110 kPa Flexural strength = 60 – 300 kPa Shear strength = 80 – 130 kPa Tensile strength = 110 – 290kPa 1.2m x 1.8m x 0.6m – RM 300.0 |
3.1 Changing Rags to Riches (Recycling Waste Materials)

About 2 million tonnes of resins for the plastics industry are produced locally in Malaysia per annum, [10] and out of which 40% of the plastic resin are used for packaging. Polyethylene terephthalate (PET) where drinking water plastic bottles are made is the most widely recycled plastic in the world. PET is a plastic resin and a form of polyester that is formed by combining two monomers: modified ethylene glycol and purified terephthalic acid. PET plastic bottles, commonly small, portable 500ml and 1500ml sizes, are considered safe and reliable for food contact use. PET is used for numerous types of packaging for many foods, including everything from ketchup, peanut butter, soft drinks, and juices to beer, wine and spirits, [11]. In an online environmental awareness page, The World Counts, and under its Bottled Water Waste Facts [12], it mentions that more than 100 million plastic bottles are used up in the world every day and only 1 out of 5 bottles end up being recycled. Thus 80% of the plastic bottles end up being buried in landfills, and it takes approximately about 700 years for a PET plastic bottle to start decaying. Thus, realising the magnitude of the harm waste plastic bottles can cause to the environment leads innovating sustainable use of these materials in the construction industry. One of the sustainable mats being produced utilises the waste plastic bottles in block form.

4. Exploration of the masonry arch concept

According to Northern Architecture [13], masonry bridges in the United Kingdom has over 120 designs and most have already exceeded the Department of Transport's design life of 120 years and therefore must be considered as an archive of good practice and proportion. The masonry arch concept is based on an arch bridge shaped as a curved arch and supported on abutments at each end. This is illustrated in Figure 4. Arch bridges work by transferring the weight of the bridge and its loads as vertical abutment support reactions and also partially into a horizontal thrust restrained by the abutments at either side. This is also synonymous with the lintel and column construction in structures. Both structures remain stable without any settlement even though they traverse a void beneath them. Traditional masonry arches are generally durable, (by virtue of its unique fit to size construction technique) and somewhat resistant to settlement or undermining. However, relative to modern alternatives, such bridges are very heavy, requiring extensive foundations. They are also expensive to build wherever labour costs are high. Thus by replacing the heavier materials with lightweight fill material, the setbacks can be overcome.

![Figure 4](image)

**Figure 4.** Vertical bricks laid in the arch of the bridge and most bridges like the Erriff bridge are aged over 150 years [13]
5. Conclusions
Developing sustainable technologies to minimise problematic road embankment settlements is becoming more crucial, especially in finding a balance between having a long term solution, going green and constructing at an affordable cost. Understanding the measure of impact that construction designs can have on the settlement of embankments leads to an advance in the research of alternative materials and innovative design concepts. However, ideas and concepts should eventually crystallize, thus the research team is set on working to develop a sustainable technology based on the masonry arch concept.

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